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ISSARS: AN INTEGRATED SYSTEM FOR STRUCTURAL ANALYSIS AND EARTHQUAKE RECORDS SELECTION

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Abstract. *Despite the major advancements in earthquake engineering research and the novelty of most modern seismic codes, the selection of the earthquake ground motions used for the design or assessment of structures in the framework of structural analysis still induces significant dispersion in the calculated dynamic response of structures. For this reason, the current study presents a new, freely available, computational system developed for improving the reliability of the code-based earthquake record selection and scaling procedure, as a means to reduce the resulting structural response scatter. Through a set of preliminary criteria, related to the magnitude, epicentral distance, soil conditions, intensity measure (i.e., PGA), components of excitation (2D or 3D) and structural system (building or bridge), the proposed algorithm searches through internet the entire PEER-NGA Strong motion Database for appropriate seismic records and then ranks them in terms of their spectral matching to a target response spectrum within a prescribed frequency range. A key feature of the software is that it implements the new Application Programming Interface (API) of the computer program SAP2000 and proceeds in applying the selected records to the finite element model that the designer is assumed to have prepared at the background. In this way, both the variation of the response quantities in the time domain and the relative structural response dispersion under various records are automatically retrieved. The presentation concludes with a demonstration regarding the assessment of a real, irregular in plan, multi-storey, RC building, where the importance of adopting a structure-specific earthquake record selection process is highlighted.*

1 INTRODUCTION

During the last decades, elastic and inelastic dynamic analyses have been made feasible for the design and assessment of complex structures with thousands of degrees of freedom, thanks to the rapid evolution in computational processing power and the enhancements in engineering software. As a result, the vast majority of modern seismic codes prescribes the application of the response history analysis as an equally eligible method to assess the response of a structural system. However, current research work [1]-[3] has demonstrated that among all possible sources of uncertainty stemming from the structural and soil material properties, the design and analysis assumptions and the earthquake-induced ground motions, the latter seems to affect most seriously the structural response variability, as determined by the dynamic analyses. Therefore, the selection of a "reliable" set of earthquake ground motions for conducting response history analysis becomes an important prerequisite as it affects the reliability of the procedure as a whole.

This truly complex task, which is still undertaken by the engineers without detailed seismic code guidelines, cannot be accomplished without understanding the fundamental concepts behind selection and scaling of earthquake records and their implication in the predicted structural response. For this reason, numerous alternative methods have been proposed for enhancing the reliability of the earthquake records selection and scaling process, most of them being summarized recently by Katsanos et al. [4].

Quite typically, implicit parameters such as the earthquake magnitude M and the source-to-site distance R are widely used as preliminary criteria combined with desirable filters that are related to the soil conditions of the site of interest, code or seismic hazard prescribed levels of different intensity measures, as well as of the seismotectonic environment features (i.e. the source mechanism, the path of seismic waves, strong-motion duration). Nevertheless, the concurrent application of all the above parameters significantly restricts the number of the records eligible for selection and thus relaxation of these criteria may be inevitable to ensure a reasonable number of records for dynamic analyses. Furthermore, research work has shown that application of site-specific M-R criteria did not reduce the structural response discrepancy in various structural systems, while highlighted the relative independence of nonlinear response on the distance (e.g. [2, 5 and 6]) with the exception of cases where the cumulative damage measures are of interest [7] or for structures where the contribution of higher modes is significant [2].

As the most common earthquake record selection procedures involve spectral matching of the average response spectrum of the records to be used, with a target, code-prescribed or seismic hazard-defined elastic response spectrum [8, 9], or even a conditional mean spectrum [10], recent work evolved to develop methods for quantifying (e.g. [11, 12]) and/or optimizing [13,14] this spectrum compatibility.

Especially in case of the performance-based design approach, the selection of acceleration time series is considered with the goal of accurate prediction of the structural response at a specified ground motion intensity measure, IM. The Peak Ground Acceleration of records and some other characteristic parameters (i.e. the spectral acceleration, SA) have been used as suitable IMs (e.g. [2]). Nevertheless, advanced intensity measures, including information about the spectral shape and structural characteristics, are expected to be preferable for records selection and scaling procedures resulting in a more accurate and reliable estimate of the seismic demand [6,15,16].

Despite the aforementioned state-of-the-art evolution in this quite recent research field, a rather rough framework is prescribed by most of the modern seismic codes concerning the motions to be used for time history analysis while most of the aforementioned record selection methods proposed in the literature have not yet been incorporated in the codes. Furthermore, specific guidelines of the codes have been proven either inadequate or misleading [17]. In fact, most of the current earthquake resistant codes share a lot of similar provisions, thus revealing that most probably, specific selection provisions have been widespread among seismic codes used in other parts of the world without systematic review, needless to say, quantification of their implications in structural design and assessment [8].

Along these lines, this paper presents a new, freely available, computational scheme for selecting and scaling earthquake records which aims at maximizing both the applicability and efficiency of the code-based earthquake record selection procedure, while minimizing the potential scatter that is commonly induced in structural response. More specifically, the proposed Matlab-based software **ISSARS** (**I**ntegrated **S**ystem for **S**tructural **A**nalysis and **R**ecord **S**election) utilizes the extensive PEER-NGA ground-motion database to form suites of records complying with specific criteria while exhibiting spectral matching with a user defined target spectrum. These suites of records, which have been ranked based on their compatibility with the design spectrum, can be further used as the required seismic loading for the dynamic analyses of a structural model studied. This is made feasible by using the Applications Programming Interface (API) of the finite element program SAP2000 [18] to run numerical analyses at the background and quantify the produced discrepancy of structural response as a part of the earthquake record selection process.

To this end, the scope of the paper is to present the integrated, computational system developed that permits:

(a) the rapid code-based selection of earthquake records required for the design and assessment of buildings and bridges, that are characterized by best matching with a target response spectrum at specific structural periods and;

(b) the automatic prediction of the impact that the selected suites can have on the dispersion of the structural response of the specific structure under study. This can be used as an additional criterion before finally approving an eligible earthquake record suite.

An illustrative example regarding the application of the current integrated system for the case of a real, irregular in plan, multi-storey, RC building, in Thessaloniki, Greece is also presented in order to highlight the above advantages. The description of the computational framework and the application case study are presented in the following.

2 CODE-BASED FRAMEWORK FOR EARTHQUAKE RECORD SELECTION

As already mentioned, the computational framework developed aims to maximize the applicability and efficiency of the code-based earthquake record selection procedures with emphasis on those prescribed in Eurocode 8, Part 1 for buildings, Eurocode 8, Part 2 for bridges [19] and NEHRP Recommended Seismic Provisions for New Buildings and Other Structures [20], abbreviated in the following as FEMA P-750. According to EC8 Part1, the seismic motion to be used for response history analysis may be either artificial, simulated or recorded, depending on the application nature and the information available at the location of the structure. It is notable that the use of artificial records is described in more detail in EC8 Part1 compared to the use of real and simulated records. FEMA P-750 and EC8 Part2 limit the use of simulated seismic motions only in cases of inadequate number of real accelerograms, the latter being selected in terms of magnitude, fault distance and source mechanisms that control the hazard at the site of interest. The source mechanism and path characteristics are also adopted as preliminary criteria, while EC8 Part1 imposes compatibility with the soil category at the location of the building studied.

Concerning the spectral matching procedure, FEMA P-750 guidelines are almost identical to those in EC8 Part2 for bridges; in particular, the SRSS spectrum is determined by taking the square root of the sum of squares of the 5%-damped elastic spectra of each selected component of the horizontal motions and then, the average values of the SRSS spectra of the individual earthquakes define the final average spectrum. Spectral matching is imposed within the period range $0.2T_1 – 1.5T_1$ where T_1 is the fundamental period of the structure. On the other hand, EC8 Part1 requires that the mean 5%-damped elastic spectrum, calculated from all the response spectra of the individual records, has to be compatible with the target spectrum. However, the period range of the foreseen spectral matching is wider (i.e., $0.2T_1$ - $2T_1$). The comparative presentation of the above criteria is made in Table 1.

Seismic code	Selection criteria	Ensemble Spectrum	Spectral matching period range	Lower bound
EC8 Part1	source mechanism, soil type	mean of individual spectra	$0.2T_1$ - $2T_1$	$0.9 \cdot SA_{design}$
EC8 Part2	source mechanism, M, R	mean of SRSS spectra	$0.2T_1$ - $1.5T_1$	$1.3 \cdot SA_{design}$
FEMA P-750	source mechanism, M, R	mean of SRSS spectra	$0.2T_1$ - $1.5T_1$	$1.17 \cdot SA_{design}$

Table 1: Earthquake record selection and spectral matching criteria prescribed in the seismic codes studied herein.

FEMA P-750 also specifies that each one of the recorded ground motions can be scaled by different factors as a means to facilitate spectral matching, while Eurocode 8 prescribes the use of a unique scaling factor, uniformly applied to all the selected records. In addition, both Eurocode 8 and FEMA P-750 share identical provisions concerning the post-processing of the structural analysis results. More specifically, they require that the maximum of the structural response quantities arising from the individual response history analyses has to be used as the design value, when the number of records n is between $3 \le n \le 6$, while the average of the response quantities from all analyses has to be computed in case that more than 7 records are used.

3 OVERVIEW OF THE PEER-NGA STRONG MOTION DATABASE

The computational framework developed for earthquake record selection and structural analysis utilizes online the PEER-NGA Next Generation Attenuation strong-motion database [21,22] (PEER-NGA, Copyright © 2005, The Regents of the University of California, available in http://peer.berkeley.edu/peer_ground_motion_database). Currently, the data-set consists of 3551 publicly available, three-components seismic records (i.e., about 10650 individual earthquake acceleration time series) that have been recorded during 173 shallow crustal earthquakes from active tectonic regions world-wide. As can be seen in Figure 1, most of these earthquakes have occurred in California. The corresponding seismic events range in magnitude from 4.2 to 7.9 and cover epicentral distances in the range 0.2km-600km (detailed distribution is illustrated in Figures 2 and 3).

Besides the magnitude and the distance, the earthquake database contains basic information about the seismic source including date and time of the event, hypocenter location, faulting mechanism, seismotectonic environment and others. Detailed data about 1600 strong-motion stations are also provided (i.e. site characterizations, surface geology, shallow subsurface conditions, the location of the instrument inside the structure's installation place). Furthermore, each acceleration time-history has been corrected for the response of the strong-motion instrument itself and filtered out the noise included. As a result, all the above features of the NGA-Strong Motion Database enable to conduct a reliable and efficient searching for "suitable" earthquake accelerograms among the thousands of available records.

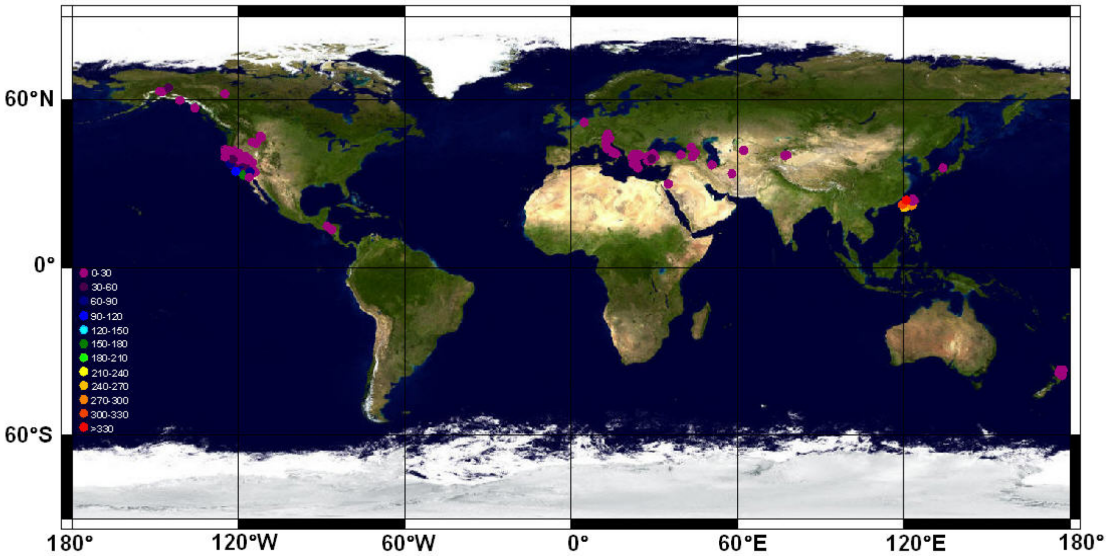


Figure 1: World map illustrating the distribution of the seismic events associated to the 173 earthquakes stored in the PEER-NGA database (distribution computed based on the information available online in http://peer.berkeley.edu/peer_ground_motion_database).

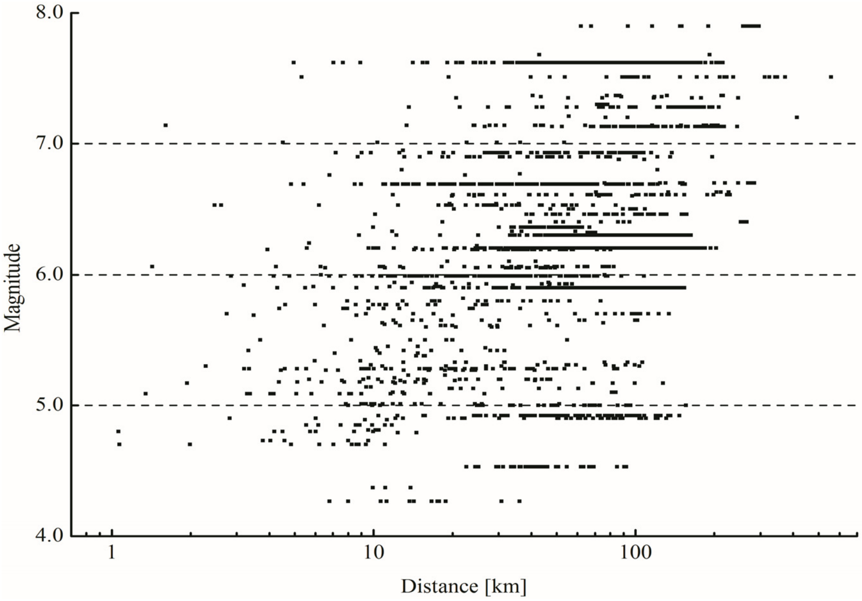


Figure 2: Magnitude and Distance distribution of strong motion records available in the PEER-NGA database (distribution computed by the ISSARS software based on the information available online in http://peer.berkeley.edu/peer_ground_motion_database).

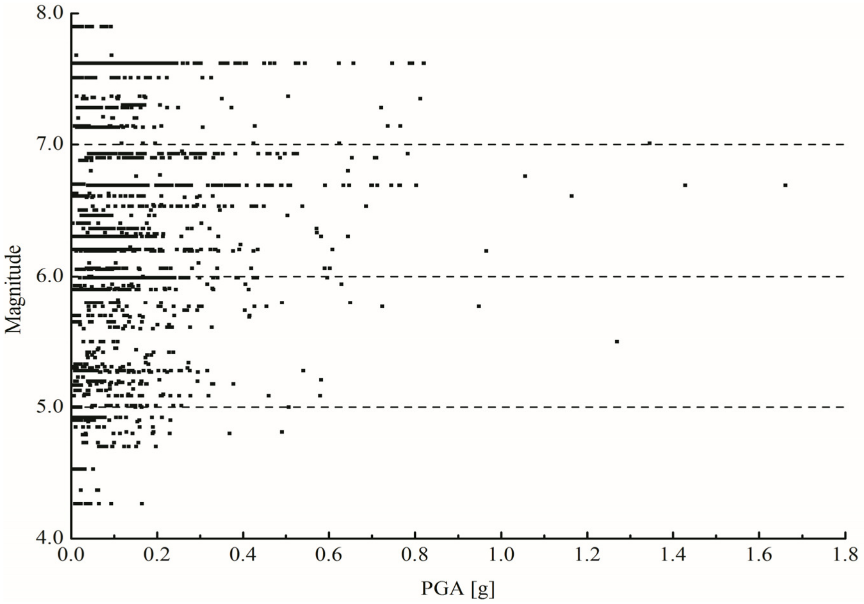


Figure 3: Magnitude and Peak Ground Acceleration distribution of strong motion records available in the PEER NGA database (distribution computed by the ISSARS software based on the information available online in http://peer.berkeley.edu/peer_ground_motion_database).

4 OVERVIEW OF THE COMPUTATIONAL FRAMEWORK DEVELOPED

The computer program ISSARS has been developed in Matlab programming environment, utilizing a series of scripts assembled and coordinated within a graphical environment. It consists of two major modules, (a) the Ground-Motion Selection Module, which is oriented to search for suitable seismic waves that comply with specific criteria and target spectrum, and (b) the Structural Analysis Module which enables automated finite element analysis of the structure under study and quantification of the record set-depended structural response scatter. Additionally to the above, an auxiliary visualization module permits the quick visualization of the generated response spectra, their means as well as the target spectrum. These modules are described in more detail below.

4.1 Ground-Motion Selection Module

The earthquake magnitude, M, and the epicentral distance, R, of the seismic events, the peak ground acceleration, PGA, of the strong-motion records as well as the site classification, S, of the recording instruments constitute the preliminary criteria for records searching through the web-based NGA-Strong Motion Database. Most of these seismological parameters, which are familiar to the structural engineers, are usually determined either through a site-specific deterministic seismic hazard analysis, SHA, or resulted from the disaggregation of a probabilistic SHA. Apart from the above criteria, both the earthquake name and the region of the seismic event can be used as a means to further refine the searching criteria.

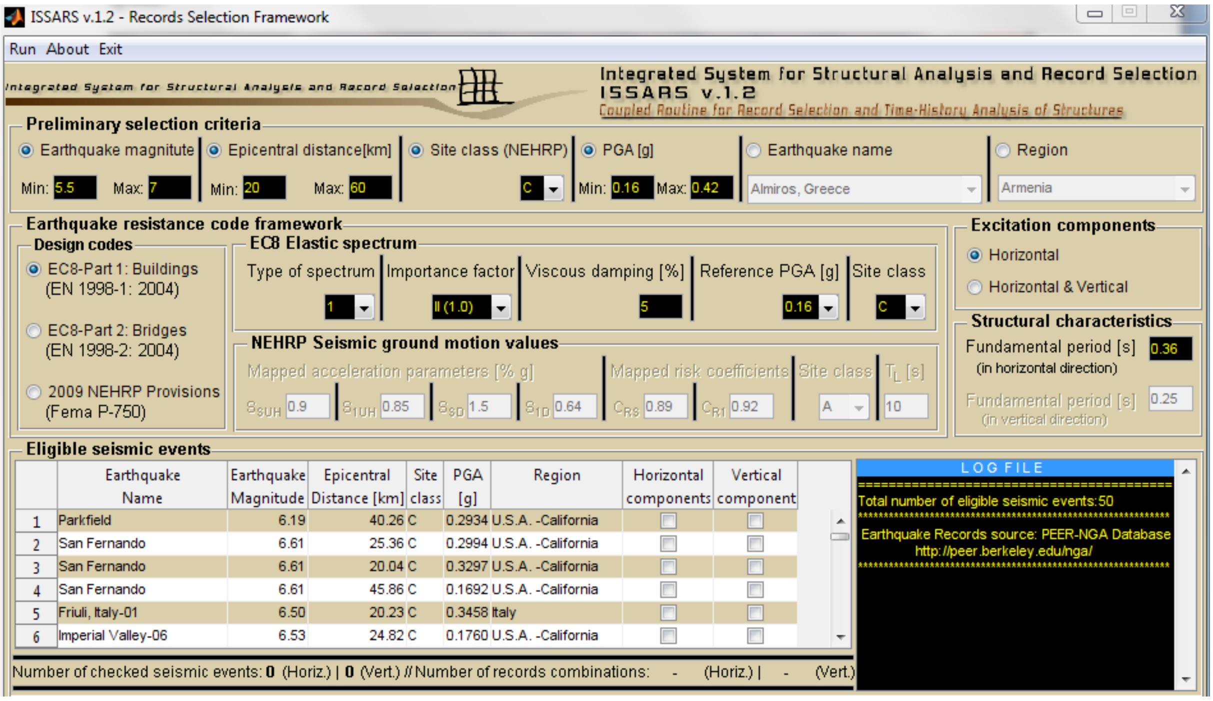
After the establishment of the preliminary seismological criteria, the algorithm core script requires the determination of the seismic code-based parameters, which are necessary for the calculation of the target response spectrum and the consecutive implementation of the spectral matching procedure. Since both Eurocode 8 (including Part1 and Part2) and FEMA P-750 provisions can be considered, the present software may be used for the design or assessment of structures both in Europe and the U.S.

In the first case of applying the Eurocode 8 procedure for selecting earthquake records, the calculation of the elastic, damped, code spectrum involves the definition of: (a) the spectrum type, (b) the importance factor of the structure studied, (c) the site classification, (d) the viscous damping and (e) the reference peak ground acceleration. On the other hand, the determination of the FEMA P-750-based target spectrum requires, apart from site classification, some characteristic seismic ground motion values, such as, the mapped uniform-hazard ground motion parameters (S_{SUH}, S_{1UH}), the mapped risk coefficients (C_{RS}, C_{R1}), the mapped deterministic ground motion parameters (S_{SD}, S_{1D}) as well as the mapped long-period transition period (T_L). Regardless of the seismic code adopted, the fundamental dynamic characteristics of the structure under study have also to be defined.

Based on the aforementioned preliminary criteria and spectrum-related parameters, ISSARS connects to the online PEER-NGA-Strong Motion Database [21] and defines the eligible seismic events (Figure 4). The user chooses any number *s* (or the entire group) of the compatible motions and the records are grouped into appropriate suites ("bins") of *m* records. The number of the suites formed, $N_{tot.suites}$, is given by the following factorial formula:

$$N_{tot.suites} = \binom{s}{m} = \frac{s!}{m!(s-m)!} \tag{1}$$

The number *m* of records forming each suite of ground motions is taken by default equal to 7 according to Eurocode 8 and FEMA P-750 provisions about the minimum value of strong-motions that allows for the definition of the design response value as the average of the response quantities from all the analyses. This number can be easily modified through the code scripts. However, it has to be noted that for cases that $m>7$, it is quite possible that the fit of the average spectrum of the suite to the target one will be eventually inferior, unless the list of the selected seismic events is relatively large. Kottke and Rathje [23] showed that if *m* exceeds 10, a larger list of records than 70 may be necessary to achieve adequate spectral convergence. Such a number of records is often difficult to be achieved given the multiple selection criteria applied while at the same time leads to an increased number of response history analyses.



Preliminary selection criteria

● Earthquake magnitute Min: 5.5 Max: 7
● Epicentral distance[km] Min: 20 Max: 60
● Site class (NEHRP) C
● PGA [g] Min: 0.16 Max: 0.42
○ Earthquake name Almiros, Greece
○ Region Armenia

Earthquake resistance code framework

Design codes
● EC8-Part 1: Buildings (EN 1998-1: 2004)
○ EC8-Part 2: Bridges (EN 1998-2: 2004)
○ 2009 NEHRP Provisions (Fema P-750)

EC8 Elastic spectrum
Type of spectrum: 1
Importance factor: II (1.0)
Viscous damping [%]: 5
Reference PGA [g]: 0.16
Site class: C

NEHRP Seismic ground motion values
S_{SUH} 0.9
S_{1UH} 0.85
S_{SD} 1.5
S_{1D} 0.64
C_{RS} 0.89
C_{R1} 0.92
Site class A
T_L [s] 10

Excitation components
● Horizontal
○ Horizontal & Vertical

Structural characteristics
Fundamental period [s] (in horizontal direction) 0.36
Fundamental period [s] (in vertical direction) 0.25

Eligible seismic events

	Earthquake Name	Earthquake Magnitude	Epicentral Distance [km]	Site class	PGA [g]	Region	Horizontal components	Vertical component
1	Parkfield	6.19	40.26	C	0.2934	U.S.A. -California	☐	☐
2	San Fernando	6.61	25.36	C	0.2994	U.S.A. -California	☐	☐
3	San Fernando	6.61	20.04	C	0.3297	U.S.A. -California	☐	☐
4	San Fernando	6.61	45.86	C	0.1692	U.S.A. -California	☐	☐
5	Friuli, Italy-01	6.50	20.23	C	0.3458	Italy	☐	☐
6	Imperial Valley-06	6.53	24.82	C	0.1760	U.S.A. -California	☐	☐

Number of checked seismic events: **0** (Horiz.) | **0** (Vert.) // Number of records combinations: - (Horiz.) | - (Vert.)

```
LOG FILE
==========================================
Total number of eligible seismic events:50
*****************************************************
Earthquake Records source: PEER-NGA Database
http://peer.berkeley.edu/nga/
*****************************************************
```

Figure 4: Preliminary seismological criteria, Code-based parameters and list of eligible seismic events.

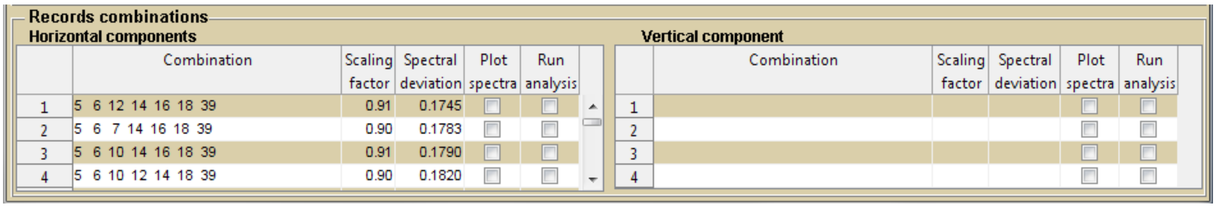
Having formed all the eligible suites of m records, the average spectra for each suite are calculated and the appropriate scaling factors sf_{avg} (unique for each suite), required to comply with the spectral matching criteria (Table 1), are computed as follows:

$$sf_{avg} = \left\{ \min\left(\frac{Sa_{avg}(T_i)}{Sa_{target}(T_i)} \right) \right\}^{-1}, \quad i = 1 \ to \ N \tag{2}$$

where $Sa_{avg}(T_i)$ is the ordinate of the average response spectrum of the records suite corresponding to the period T_i, Sa_{target} is the spectral acceleration of the code spectrum derived at the same period and N is the number of values within the code-imposed range of periods (Table 1). The suites, which consist of scaled of motions, are then ranked according to their "goodness-of-fit" to the target spectrum. The level of spectral matching between the scaled average spectra of the record combinations and the target spectrum is quantified by the expression of the normalized root-mean-square-error, *NRMSE*, also used by Iervolino *et al.* [24].

$$NRMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{S_{avg}(T_i) - S_{target}(T_i)}{S_{target}(T_i)} \right)^2} \tag{3}$$

The final list of the eligible suites of m records, appropriately ranked according to the spectral matching criterion of Eq. (3), is shown in Figure 5. Additionally, the algorithm provides an extensive output data file that includes all related input data (i.e. the preliminary seismological criteria, the seismic code parameters and the dynamic characteristics of the structural system under study) and the associated meta-data concerning the eligible seismic events and their acceleration time series as well as the final hierarchy of the suites formed (Figure 6).



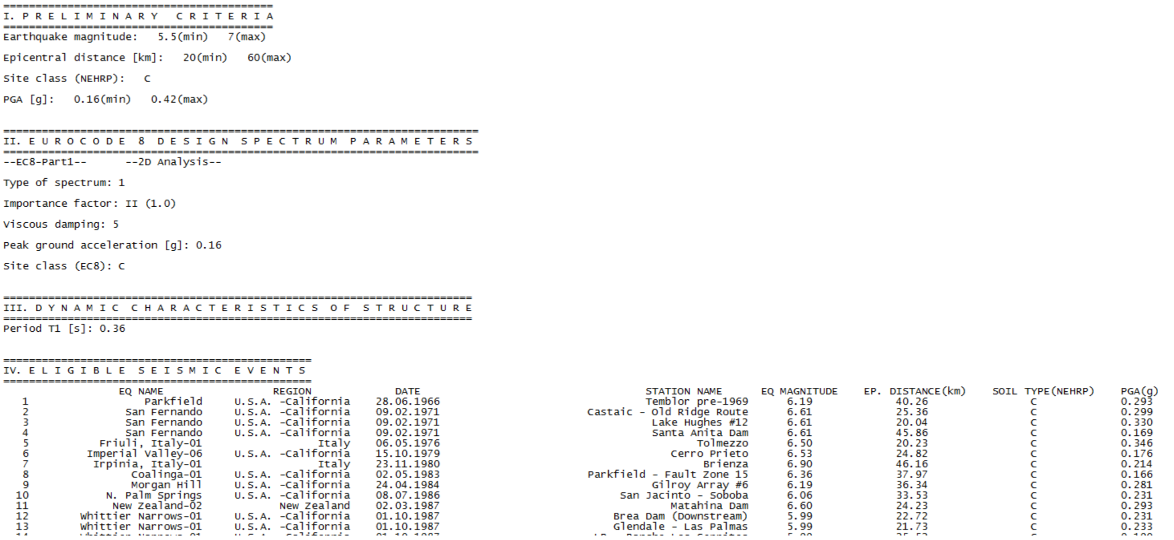
Horizontal components

	Combination	Scaling factor	Spectral deviation	Plot spectra	Run analysis
1	5 6 12 14 16 18 39	0.91	0.1745	☐	☐
2	5 6 7 14 16 18 39	0.90	0.1783	☐	☐
3	5 6 10 14 16 18 39	0.91	0.1790	☐	☐
4	5 6 10 12 14 18 39	0.90	0.1820	☐	☐

Vertical component

	Combination	Scaling factor	Spectral deviation	Plot spectra	Run analysis
1				☐	☐
2				☐	☐
3				☐	☐
4				☐	☐

Figure 5: Final list of the ground motion suites formed, as they are ranked according to the spectral matching criterion of Eq. (3).



```
==========================================
I. P R E L I M I N A R Y   C R I T E R I A
==========================================
Earthquake magnitude:   5.5(min)   7(max)

Epicentral distance [km]:   20(min)   60(max)

Site class (NEHRP):   C

PGA [g]:   0.16(min)   0.42(max)

=========================================================================
II. E U R O C O D E  8  D E S I G N  S P E C T R U M  P A R A M E T E R S
=========================================================================
--EC8-Part1--      --2D Analysis--

Type of spectrum: 1

Importance factor: II (1.0)

Viscous damping: 5

Peak ground acceleration [g]: 0.16

Site class (EC8): C

========================================================================
III. D Y N A M I C  C H A R A C T E R I S T I C S  O F  S T R U C T U R E
========================================================================
Period T1 [s]: 0.36

================================================
IV. E L I G I B L E  S E I S M I C  E V E N T S
================================================
                EQ NAME              REGION           DATE                               STATION NAME     EQ MAGNITUDE    EP. DISTANCE(km)    SOIL TYPE(NEHRP)    PGA(g)
  1              Parkfield    U.S.A. -California   28.06.1966                        Temblor pre-1969       6.19             40.26               C             0.293
  2           San Fernando    U.S.A. -California   09.02.1971                Castaic - Old Ridge Route       6.61             25.36               C             0.299
  3           San Fernando    U.S.A. -California   09.02.1971                        Lake Hughes #12       6.61             20.04               C             0.330
  4           San Fernando    U.S.A. -California   09.02.1971                        Santa Anita Dam       6.61             45.86               C             0.169
  5       Friuli, Italy-01                  Italy   06.05.1976                               Tolmezzo       6.50             20.23               C             0.346
  6     Imperial Valley-06    U.S.A. -California   15.10.1979                           Cerro Prieto       6.53             24.82               C             0.176
  7      Irpinia, Italy-01                  Italy   23.11.1980                                Brienza       6.90             46.16               C             0.214
  8            Coalinga-01    U.S.A. -California   02.05.1983                Parkfield - Fault Zone 15       6.36             37.97               C             0.166
  9            Morgan Hill    U.S.A. -California   24.04.1984                        Gilroy Array #6       6.19             36.34               C             0.281
 10         N. Palm Springs    U.S.A. -California   08.07.1986                    San Jacinto - Soboba       6.06             33.53               C             0.231
 11        New Zealand-02            New Zealand   02.03.1987                           Matahina Dam       6.60             24.23               C             0.293
 12     Whittier Narrows-01    U.S.A. -California   01.10.1987                  Brea Dam (Downstream)       5.99             22.72               C             0.231
 13     Whittier Narrows-01    U.S.A. -California   01.10.1987                  Glendale - Las Palmas       5.99             21.73               C             0.233
```

Figure 6: ISSARS's output file.

The computational time, required for calculating 480700 suites of scaled records (formed for the case of 25 selected seismic events), is about 60 seconds on a 8GB RAM 1.60 GHz quad core processor. This computational efficiency permits the concurrent use of the software for multiple ranges of preliminary criteria.

4.2 Visualization Module

The results of the previous module can be visualized by calling the plot module. For each one of the formed suites of records, ISSARS provides a figure illustrating (a) the target spectrum, (b) the code-imposed lower bound of the design spectrum (necessary for the spectral matching procedure, Table 1), (c) the individual 5% damped response spectra of all records within a given suite (d) the average spectrum of the suite, and (e) the scaled average spectrum. This schematic illustration of the calculated spectra (Figure 7) enables a preliminary but useful visual assessment regarding the "goodness-of-fit" of a particular suite of records to the target spectrum, which may reveal period ranges of inappropriately unsuccessful fit that may be otherwise suppressed by the averaging *NRMSE* values of Eq. (3).

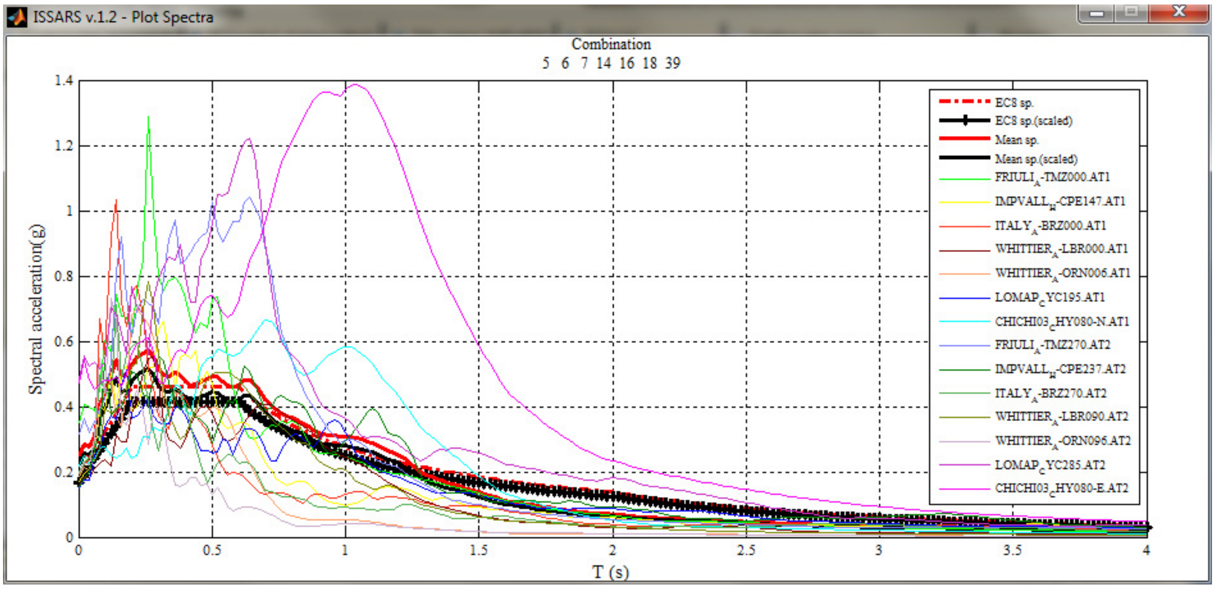
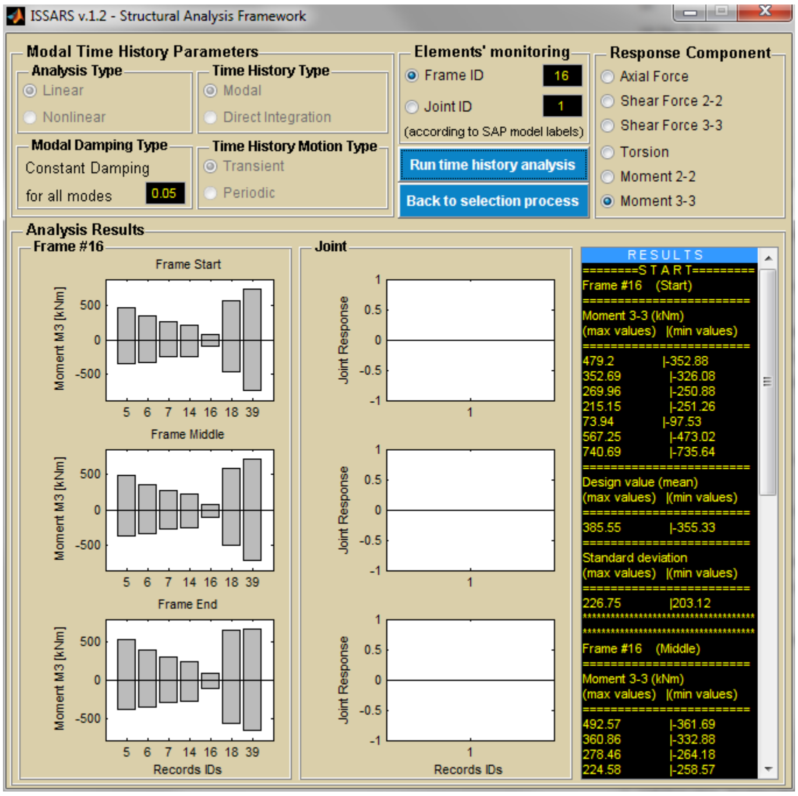


Figure 7: Sample plot of individual, average and target spectra computed for each suite.

4.3 Structural Analysis Module

Although it is not explicitly stated in modern seismic codes, one of the main objectives of selecting and scaling accelerograms is to form suites of records that will eventually induce adequately stable estimates of the predicted elastic or inelastic structural response; otherwise, the associated dispersion in response quantities may undermine the reliability of the predicted design values [25, 26]. At the same time, the consideration of the structural response variability in the decision-making procedure for selecting earthquake records is only implicitly considered by seismic codes through the rough estimate of the fundamental period and the associated period range for spectral matching.

In the computational framework developed, the discrepancy induced in the response quantities by the selection of a given suite of records, is quantified and utilized as a selection criterion itself. This is made feasible by using the recently introduced Application Programming Interface (API) of the finite element software SAP2000 [18]. This API permits the execution of specific build-in functions to run and control SAP2000 in the background, during the execution of the Matlab script, provided that the designer/engineer has developed and made available the finite element model of the structure in advance.



Modal Time History Parameters

Analysis Type
● Linear
○ Nonlinear

Time History Type
● Modal
○ Direct Integration

Modal Damping Type
Constant Damping for all modes 0.05

Time History Motion Type
● Transient
○ Periodic

Elements' monitoring
● Frame ID 16
○ Joint ID 1
(according to SAP model labels)

Response Component
○ Axial Force
○ Shear Force 2-2
○ Shear Force 3-3
○ Torsion
○ Moment 2-2
● Moment 3-3

```
RESULTS
========S T A R T=========
Frame #16   (Start)
=========================
Moment 3-3 (kNm)
(max values)  |(min values)
=========================
479.2          |-352.88
352.69          |-326.08
269.96          |-250.88
215.15          |-251.26
73.94          |-97.53
567.25          |-473.02
740.69          |-735.64
=========================
Design value (mean)
(max values)  |(min values)
=========================
385.55          |-355.33
=========================
Standard deviation
(max values)  |(min values)
=========================
226.75          |203.12
**********************************
**********************************
Frame #16   (Middle)
=========================
Moment 3-3 (kNm)
(max values)  |(min values)
=========================
492.57          |-361.69
360.86          |-332.88
278.46          |-264.18
224.58          |-258.57
```

Figure 8: Structural Analysis Module.

Through this interactive link, response history analyses are performed using the record suites, which are defined according to the preliminary criteria set and the “goodness-of-fit” ranking system, while the Matlab-based script retrieves post-processing structural analysis data, such as the action effects (i.e. forces and displacements) maxima, monitored at the frames and joint locations (Figure 8). Another advantage of the interactive record selection procedure is that, it can be followed, regardless of the complexity of the finite element model, that is, the type of the structure, the number of degrees of freedom, its geometry, the potential for material or geometrical nonlinearities, the consideration of soil flexibility, the direction of excitation or any unconventional structural characteristic. The complexity of the structure is resolved by the designer and once the finite element model is made available to the Matlab script, the structure-specific earthquake record selection runs effortlessly.

5 APPLICATION OF THE PROPOSED COMPUTATIONAL FRAMEWORK FOR THE ASSESSMENT OF AN EXISTING RC STRUCTURE

In an attempt to illustrate the applicability of the proposed computational framework, a demonstration is presented herein for the case of an existing, multi-storey R/C building, located in Thessaloniki, Greece. The overview of the case study as well as the results derived are presented in the following.

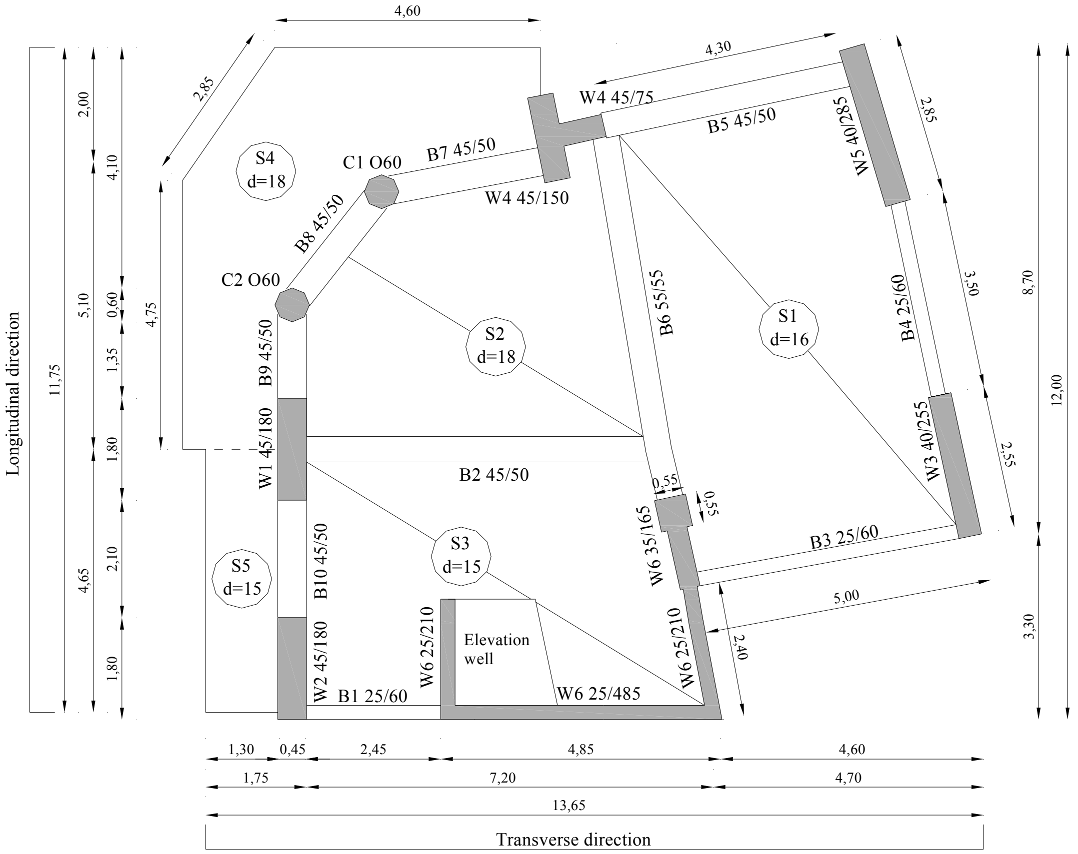


Figure 9: Plan view of the typical floor of the case study building.

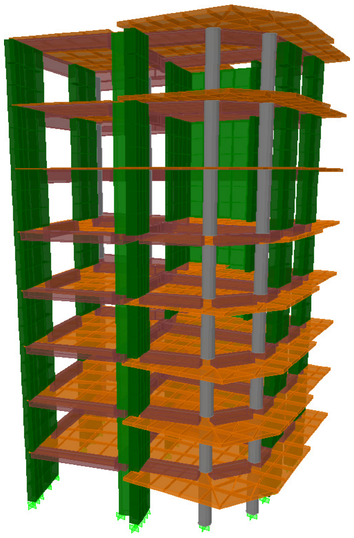


Figure 10: A 3-Dimensional finite element model of the building under study.

5.1 Case study building: Structural configuration and numerical modeling aspects

The building studied is an irregular in plan, seven-storey R/C dual system, with a pilotis and a basement, which is located in the city of Thessaloniki, in Greece, whose plan view is presented in Figure 9. The total area of the typical storey is 135.0 m^2 and the storey height is 3.0 m. The lateral strength of the building is provided by four shear walls of relatively equally dimensions and a reinforced concrete core eccentrically. The concrete class used was C20/25 (i.e., compressive strength $f_c'=20\ N/mm^2$), and St.III steel bars (i.e. yield strength $f_y'=500\ N/mm^2$) were applied for the longitudinal and transverse reinforcement. The building under study was constructed in 2008 according to the latest version of the Greek Seismic Code EAK2000 [27] which is currently in parallel enforcement with the Eurocodes. The design ground acceleration, a_g, has been set equal to 0.16g as corresponding to the lowest seismic hazard category in Greece. The soil conditions have been classified as category C according to both EAK2000 and EC8 site categorization. Figure 10 illustrates the fixed-base model [28], developed with the use of SAP2000 finite element software [18] using both frame elements for the beams and the columns and shell elements for the shear walls and slabs.

5.2 Coupled earthquake record selection and structural analysis

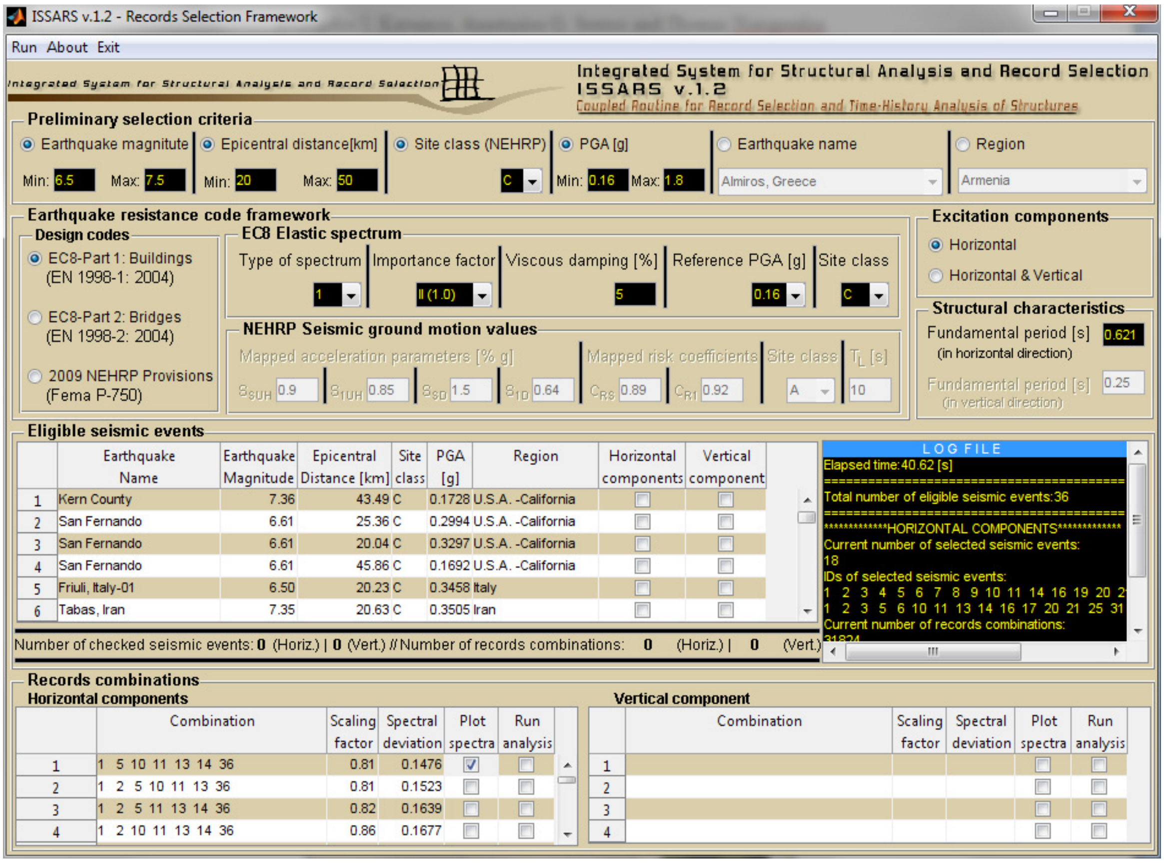
After the development of the finite element model of the building studied, a seismic scenario was determined for the seismic hazard of the particular site using the following seismological criteria: (a) earthquake magnitude, $6.5 \leq M \leq 7.5$, (b) source-to-site distance, $20 \leq R \leq 50$ (km), (c) peak ground acceleration, $PGA \geq 0.16g$ and (d) soft soil conditions, corresponding to Eurocode 8 soil category C. Regarding the target spectrum, the EC8 5% damped, elastic spectrum was defined for soil category C while the reference peak ground acceleration value was taken equal to 0.16g for the reason described previously. The fundamental period of the structure was found equal to 0.621s and was used to establish the EC8 prescribed spectral matching period range (i.e. $0.2T_1=0.12s<T<2T_1=1.24s$). Based on the above, ISSARS was performed to search online within the PEER-NGA Strong Motion Database and 36 different seismic events have been returned as eligible. Analytical description of the resulting sample is summarized in Table 2. It is notable that each one of these eligible earthquakes consists of two horizontal seismic records, which are required for the bi-directional seismic loading of the particular multi-storey R/C building.

Due to the enormous computational cost that would be required in case of calculating all the possible records suites from the 36 eligible seismic events (i.e., 8,347,680 suites of seven pairs of horizontal components of strong motions would be required), 28 different earthquakes were selected, leading to the generation of 1,184,040 suites of records (Figure 11). The required computational time for this calculation did not exceeded 120-150 s using a 8GB RAM 1.60 GHz quad core processor.

In the following, ranking of the suites of records took place in terms of their spectral compatibility to the Eurocode 8 target spectrum and according to the hierarchical concept adopted. The first suite of records, characterized by the highest matching score, was selected as the first candidate for the dynamic analysis of the structure under study. More specifically, the seven pairs of strong motions, which are included in the first suite, were automatically transferred and applied as the seismic excitation of the case study finite element model, thus, seven bi-directional, elastic response history analyses were performed in the background using the Structural Analysis Module and the built-in API functions of the SAP2000 program. The results of these consecutive analyses were returned, processed and finally presented by ISSARS (Figure 12) in the form of maximum absolute values of all response quantities at the monitored frames and joints, as well as their average values and standard deviations. The designer may also choose alternative top ranked suites of earthquake records, compare the resulting discrepancy of the computed response quantities and decide on the most representative combination (suite) of records to be eventually used for design or assessment purposes.

No.	Earthquake	Recording Station	M	R	PGA	Used
1	KC 21.07.1952	Taft Lincoln School	7.36	43.49	0.173	Yes
2	SFE 09.02.1971	Castaic-Old Ridge R.	6.61	25.36	0.299	Yes
3	SFE 09.02.1971	Lake Hughes#12	6.61	20.04	0.330	Yes
4	SFE 09.02.1971	Santa Anita Dam	6.61	45.86	0.169	Yes
5	FR 06.05.1976	Tolmezzo	6.50	20.23	0.346	Yes
6	TAB 16.09.1978	Dayhook	7.35	20.63	0.351	Yes
7	IV 15.10.1979	Cerro Prieto	6.53	24.82	0.176	Yes
8	IR 23.11.1980	Brienza	6.90	46.16	0.214	Yes
9	NZ 02.03.1987	Matahina Dam	6.60	24.23	0.293	Yes
10	LP 18.10.1989	Anderson Dam	6.93	26.57	0.238	Yes
11	LP 18.10.1989	Coyote Lake Dam	6.93	30.78	0.295	Yes
12	LP 18.10.1989	Gilro-Gavilan Coll.	6.93	28.98	0.334	Yes
13	LP 18.10.1989	Hollister-South & Pine	6.93	48.24	0.279	Yes
14	LP 18.10.1989	San Jose-S.T. Hills	6.93	20.13	0.283	Yes
15	LP 18.10.1989	Saratoga-Aloha Ave	6.93	27.23	0.382	Yes
16	CM 25.04.1992	Shelter Cove Airport	7.01	36.28	0.195	Yes
17	LAN 28.06.1992	Lucerne	7.28	44.02	0.721	Yes
18	NOR 17.01.1994	Big Tujunga, Angeles	6.69	31.55	0.200	No
19	NOR 17.01.1994	Castaic - Old Ridge R.	6.69	40.68	0.490	Yes
20	NOR 17.01.1994	Glendale - Las Palmas	6.69	29.72	0.256	Yes
21	NOR 17.01.1994	LA-City Terrace	6.69	39.15	0.267	Yes
22	NOR 17.01.1994	LA-Cypress Ave	6.69	33.25	0.206	Yes
23	NOR 17.01.1994	LA-Fletcher Dr	6.69	30.27	0.207	Yes
24	NOR 17.01.1994	LA-Temple & Hope	6.69	32.72	0.165	No
25	NOR 17.01.1994	LA-Univ. Hospital	6.69	36.47	0.349	Yes
26	NOR 17.01.1994	La Crescenta - N.Y.	6.69	27.83	0.173	No
27	NOR 17.01.1994	Lake Hughes#12A	6.69	40.65	0.215	Yes
28	NOR 17.01.1994	Lake Hughes#9	6.69	44.77	0.169	No
29	NOR 17.01.1994	Manhattan Beach	6.69	38.69	0.166	No
30	NOR 17.01.1994	Moorpark-Fire Station	6.69	31.45	0.229	No
31	NOR 17.01.1994	Pasadena-N. Sierra	6.69	44.01	0.234	Yes
32	NOR 17.01.1994	Point Mugu-Lag Peak	6.69	48.28	0.175	No
33	NOR 17.01.1994	San Gabriel-E Grand	6.69	44.32	0.209	No
34	DZC 12.11.1999	Lamont 375	7.14	24.05	0.737	Yes
35	MAN 20.06.1990	Abbar	7.37	40.43	0.505	Yes
36	HM 16.10.1999	Hector	7.13	26.53	0.306	Yes

Table 2. Description of eligible seismic events as derived by the application of the seismological criteria adopted in the current algorithm.



Preliminary selection criteria

● Earthquake magnitute Min: 6.5 Max: 7.5
● Epicentral distance[km] Min: 20 Max: 50
● Site class (NEHRP) C
● PGA [g] Min: 0.16 Max: 1.8
○ Earthquake name Almiros, Greece
○ Region Armenia

Earthquake resistance code framework

Design codes
● EC8-Part 1: Buildings (EN 1998-1: 2004)
○ EC8-Part 2: Bridges (EN 1998-2: 2004)
○ 2009 NEHRP Provisions (Fema P-750)

EC8 Elastic spectrum
Type of spectrum: 1
Importance factor: II (1.0)
Viscous damping [%]: 5
Reference PGA [g]: 0.16
Site class: C

NEHRP Seismic ground motion values
Mapped acceleration parameters [% g]: S_{SUH} 0.9 S_{1UH} 0.85 S_{SD} 1.5 S_{1D} 0.64
Mapped risk coefficients: C_{RS} 0.89 C_{R1} 0.92
Site class: A
T_L [s]: 10

Excitation components
● Horizontal
○ Horizontal & Vertical

Structural characteristics
Fundamental period [s] (in horizontal direction): 0.621
Fundamental period [s] (in vertical direction): 0.25

Eligible seismic events

	Earthquake Name	Earthquake Magnitude	Epicentral Distance [km]	Site class	PGA [g]	Region	Horizontal components	Vertical component
1	Kern County	7.36	43.49	C	0.1728	U.S.A. -California	☐	☐
2	San Fernando	6.61	25.36	C	0.2994	U.S.A. -California	☐	☐
3	San Fernando	6.61	20.04	C	0.3297	U.S.A. -California	☐	☐
4	San Fernando	6.61	45.86	C	0.1692	U.S.A. -California	☐	☐
5	Friuli, Italy-01	6.50	20.23	C	0.3458	Italy	☐	☐
6	Tabas, Iran	7.35	20.63	C	0.3505	Iran	☐	☐

Number of checked seismic events: **0** (Horiz.) | **0** (Vert.) // Number of records combinations: **0** (Horiz.) | **0** (Vert.)

```
LOG FILE
Elapsed time:40.62 [s]
=========================================
Total number of eligible seismic events:36
=========================================
*************HORIZONTAL COMPONENTS*************
Current number of selected seismic events:
18
IDs of selected seismic events:
1  2  3  4  5  6  7  8  9  10  11  14  16  19  20  2
1  2  3  5  6  10  11  13  14  16  17  20  21  25  31
Current number of records combinations:
31824
```

Records combinations

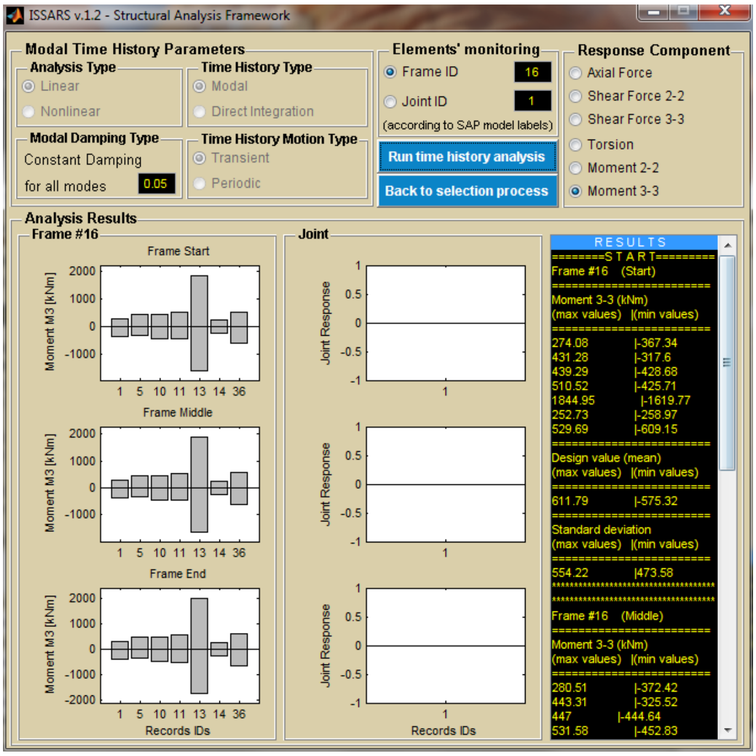
Horizontal components

	Combination	Scaling factor	Spectral deviation	Plot spectra	Run analysis
1	1 5 10 11 13 14 36	0.81	0.1476	☑	☐
2	1 2 5 10 11 13 36	0.81	0.1523	☐	☐
3	1 2 5 11 13 14 36	0.82	0.1639	☐	☐
4	1 2 10 11 13 14 36	0.86	0.1677	☐	☐

Vertical component

	Combination	Scaling factor	Spectral deviation	Plot spectra	Run analysis
1				☐	☐
2				☐	☐
3				☐	☐
4				☐	☐

Figure 11: Application of ISSARS for the case of an existing, irregular in plan, multi-storey, RC building (Ground-motion selection module)



Modal Time History Parameters

Analysis Type
● Linear
○ Nonlinear

Time History Type
● Modal
○ Direct Integration

Modal Damping Type
Constant Damping for all modes: 0.05

Time History Motion Type
● Transient
○ Periodic

Elements' monitoring
● Frame ID: 16
○ Joint ID: 1
(according to SAP model labels)

Response Component
○ Axial Force
○ Shear Force 2-2
○ Shear Force 3-3
○ Torsion
○ Moment 2-2
● Moment 3-3

Analysis Results
Frame #16
Joint

```
RESULTS
========S T A R T========
Frame #16    (Start)
========================
Moment 3-3 (kNm)
(max values)  |(min values)
========================
274.08          |-367.34
431.28          |-317.6
439.29          |-428.68
510.52          |-425.71
1844.95          |-1619.77
252.73          |-258.97
529.69          |-609.15
========================
Design value (mean)
(max values)  |(min values)
========================
611.79          |-575.32
========================
Standard deviation
(max values)  |(min values)
========================
554.22          |473.58
********************************
********************************
Frame #16    (Middle)
========================
Moment 3-3 (kNm)
(max values)  |(min values)
========================
280.51          |-372.42
443.31          |-325.52
447         |-444.64
531.58          |-452.83
```

Figure 12: Application of ISSARS for the case of an existing, irregular in plan, multi-storey, RC building (Structural analysis module).

6 CONCLUSIONS

An integrated computational system that couples the code-based earthquake records selection procedure and the structural response is developed and presented herein as a means to increase both the applicability and the effectiveness of the current state-of-the-practice in conducting response history analyses. The proposed Matlab-based algorithm utilizes the online PEER-NGA strong motion database in order to search for compliant strong motions, which are required for the seismic loading of dynamic analyses. After an initial records filtering procedure in terms of magnitude, epicentral distance, soil conditions, intensity measure, components of excitation (2D or 3D) and structural system (building or bridge), the eligible acceleration time series are grouped into numerous suites and finally ranked on the basis of their spectral similarity with the design spectrum. Through the recently released Application Programming Interface (API) of the computer program SAP2000, the selected records are applied to excite the finite element model that the designer is assumed to have prepared at the background. The variation of the response quantities in the time domain are automatically computed and the relative structural response dispersion under various records sets is assessed. The presentation concludes with a demonstration assessment of an existing, irregular in plan, multi-storey, RC building, where the importance of adopting a structure-specific earthquake record selection process is highlighted. It is deemed that the structure-specific earthquake record selection procedure presented herein is a promising alternative to the existing procedures and a significant improvement compared to the conventional application of the current seismic code provisions.

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