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ISSARS: An integrated software environment for structure-specific earthquake ground motion selection

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A B S T R A C T

Current practice enables the design and assessment of structures in earthquake prone areas by performing time history analysis with the use of appropriately selected strong ground motions. This study presents a Matlab-based software environment, which is integrated with a finite element analysis package, and aims to improve the efficiency of earthquake ground motion selection by accounting for the variability of critical structural response quantities. This additional selection criterion, which is tailored to the specific structure studied, leads to more reliable estimates of the mean structural response quantities used in design, while fulfils the criteria already prescribed by the European and US seismic codes and guidelines. To demonstrate the applicability of the software environment developed, an existing irregular, multi-storey, reinforced concrete building is studied for a wide range of seismic scenarios. The results highlight the applicability of the software developed and the benefits of applying a structure-specific criterion in the process of selecting suites of earthquake motions for the seismic design and assessment.

1. Introduction

The evolution in computational power and the parallel processing capabilities of modern engineering software make nowadays the use of complicated structural analysis methods an attractive alternative for the design and assessment of structures. In contrast to the past, when the elastic static or response spectrum analysis was almost exclusively used for the seismic design of structures, the state-of-practice has progressively moved toward dynamic-elastic, nonlinear-static (i.e., single mode or multi-modal "push-over" analysis), and even nonlinear time history analysis. The latter, capturing more efficiently the hierarchy of failure mechanisms, the energy dissipation, the force redistribution among the structural members and contact issues (such as gap, impact, sliding and uplift) is preferable in cases of significant material or geometrical nonlinearities and as such, is used for the design of seismically isolated buildings and bridges or the assessment of existing structures with various degrees of damage. Elastic time history analysis is also extensively used, primarily for structures whose response is dominated by higher or closely spaced modes (mostly tall and irregular buildings and towers), or structures of high importance that are typically designed to remain elastic even for long return-period earthquake intensities (i.e., industrial facilities, power plants, dams, critical administrative buildings, etc.).

In all cases, the main task of the design procedures is to achieve more predictable and reliable levels of safety and operability against different levels of seismic intensity [1], a framework known as performance-based design and assessment. Despite the above major advances made in terms of structural analysis, the reliability of the analysis output and the subsequent structural performance prediction strongly depend on the decisions made for the selection of the seismic input used as ground excitation. Research has shown that among all possible sources of uncertainty stemming from structural and soil material properties, the modeling approximations, the design and analysis assumptions as well as the earthquake-induced ground motion, the latter has by far the highest effect on the variability observed in the structural response [2–4]. Therefore, the selection of a "reliable" suite of earthquake ground motions constitutes an important prerequisite for the reliability of the structural analysis procedure as a whole.

Nowadays, typically, the selection of earthquake records in most seismic codes and guidelines worldwide is primarily based on implicit parameters such as the earthquake magnitude, M, and the source-to-site distance, R. These parameters are defined by deterministic seismic hazard analysis, *SHA*, or by disaggregating a probabilistic site-specific *SHA* [5] and are used as the preliminary criteria for selecting an initial suite of eligible earthquake motions. Soil conditions at the site of the structure, the seismotectonic environment and other parameters (for instance, source mechanism,

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path of seismic waves and duration of the strong-motion) are used often to further sift the dataset of eligible records. However, the concurrent application of all the above parameters may significantly reduce the number of the eligible records. Thus, relaxation of these criteria may be inevitable to ensure an adequate set of motions for conducting time history analyses. The above limitations of the concurrent application of multiple criteria has also lead various researchers to investigate the relative impact of magnitude- and distance-based selection, the first found to be a more influential record selection parameter [6,7].

Another significant selection criterion is the strong motion intensity and the parameter used for its quantification. Peak ground acceleration, *PGA*, and the spectral acceleration at the fundamental period of the structure, $S\alpha\,(T_1)$, are typical examples of widely used intensity measures, *IM* (e.g., [3]). More elaborate *IMs* have also been proposed, involving the spectral shape and some structural characteristics. Such *IMs* are expected to result into a more accurate prediction of the seismic demand [8–10]. However, none of them is yet explicitly implemented in seismic code ground motion selection procedures. On the other hand, it is also common to envision convergence of the response spectra of the selected acceleration time series with a target spectrum [11–13]. This target spectrum can be specified by (a) a seismic scenario determined from a ground motion prediction relationship (e.g., [14]), (b) a seismic hazard assessment for the site of interest, (c) a conditional mean spectrum [15] or (d) the seismic code provisions. Along these lines, progress has been made for the quantification and improvement of envisioned spectrum convergence (e.g., [16,17]) as well as for controlling the standard deviation of the earthquake spectra themselves [18].

Several alternative or more advanced methods have been proposed for enhancing the reliability of the earthquake records selection and scaling process (as reviewed in [19]). Nevertheless, again, their main findings have not yet been reflected on the present state of practice and the corresponding drafting of seismic codes. In contrast, a somewhat simplified framework is only prescribed, without major differences among codes worldwide.

2. Motivation and objectives

Recent research has shown that the above rather oversimplified prescriptions of seismic codes and guidelines for selecting and scaling suites of motions has adverse implications for both assessment and design of structures. More precisely:

(a) the limited number of (commonly seven) records required by most guidelines and seismic codes for conducting time history analyses, undermines in advance the computation of a adequately stable estimate of the elastic or inelastic structural response [3,12,13,20].
(b) in most cases, the above variability in structural response cannot be reduced by a more accurate specification of the range of variation for the magnitude *M* or the source-to-site distance *R*, because structural response and *M*–*R* pairs have been found only partially correlated [3,8,21]. Few exceptions are structures sensitive to higher modes [3] or structures assessed on the basis of cumulative damage measures [22].
(c) the quality of spectrum convergence, which is the main selection and scaling criterion according to the seismic codes, is not explicitly ensured in a quantified manner. More specifically, the process only guarantees that the *average* response spectrum of the ground motions selected simply *exceeds* the ordinates of the target one, without considering the aleatory variability of the records or imposing an upper bound for the resulting mean spectrum of the seed records. This often leads to either unreliable estimates of structural response or overconservative design values [23].
(d) enforcement of spectral matching to periods as long as twice the fundamental period T_1 of a building, as prescribed for instance in Eurocode 8-Part 1, is made irrespectively of the structural characteristics and ductility. As a result, spectral matching is enforced in the long period range, where it is very unlikely that a low-to-moderate ductility structure will ever respond. On the other hand, this scaling at the long period range, may substantially increase the spectral ordinates of the mean spectrum of the records selected in more critical periods of vibration (i.e., close or lower than T_1) [23].
(e) even in case the designer is aware of the above issues, it is impossible to overcome them and achieve near optimal spectral matching without a specialized computational tool. Currently, useful algorithms and software have been made available for selecting and scaling seismic records [17,18,24–26] in all cases though, earthquake record selection is solely related to the fundamental period of the structure, without considering other structural or response parameters.

Given the above limitation, an improved computational scheme has been developed and is presented herein for *structure-specific* selection and scaling of seismic motions aiming to accommodate a web-based selection of earthquake records for buildings and bridges according to the European and US standards. Particularly, the proposed framework retrieves records from the PEER-NGA strong-motion database (PEER-NGA, ©2011, The Regents of the University of California, available in http://peer.berkeley.edu/peer_ground_motion_database) and forms suites that comply with specific criteria (*M*, *R*, soil type) and the spectral matching requirements of *Euro*code 8 [27] (Part1 for buildings and Part2 for bridges) or NEHRP Recommended Seismic Provisions for New Buildings and Other Structures, abbreviated in the following as FEMA P-750 [28].

The software proceeds, optionally, in filtering out, from the subset of eligible suites of motions that satisfy the code criteria and present the best matching with the target spectrum, those extreme cases that are associated with unrealistically high variability in response quantities, specifically for the structure studied. This is achieved by using the Application Programming Interface (API) functions of a widely used finite element software (SAP2000, CSI [29]) to conduct time history analyses of the structure in the computer background during runtime and quantify the induced variability in critical structural response quantities.

In this way, the ground motion suite, which is eventually selected from a long list of code-compliant suites, has the following desirable features:

(a) satisfies all the preliminary criteria (magnitude, source-to-site distance, intensity, soil class) *and* all the spectral matching provisions of current seismic codes in Europe and the US whichever is each time applicable,
(b) is characterized by *near-optimal* average spectral matching to the target spectrum (as opposed to the *minimum* spectral matching criteria prescribed by EC8 and FEMA-750),
(c) can be easily and automatically formed by *more* than seven records (which is the *minimum* number of records typically prescribed in the codes), thus improving the reliability of the mean structural response computed.
(d) ensures reasonable (i.e., not excessive) structural response variability in the most critical structural elements (i.e., typically, though not compulsorily, bending moments at the base of shear walls or lateral storey displacements). Particularly, the user can (optionally) set the desirable level of structural response variability, by assigning a threshold confidence level for the standard error of the response quantities, and thus filter-out some of the, otherwise eligible,