Hazard, Ground Motions, and Code-Based Structural Assessment: A few Proposals and yet Unfulfilled Needs.

I. Iervolino
Dipartimento di Ingegneria Strutturale,
Università degli Studi di Napoli Federico II, Naples, Italy.

ABSTRACT:
Code-based structural assessment via nonlinear dynamic analysis requires seismic input believed to be a representation of the seismic threat to the site with respect to the limit-state of interest. Codes often are only slightly more specific than that, except prescribing to match a design spectral shape. Therefore, in record selection, several options, hearsays and beliefs may render the job especially hard for the analyst or, on the other side, heuristically simple, yet potentially inadequate to the scope. This paper, given the current European codes' procedures, tries to discuss some tools which may help to address some basic issues related to seismic input selection. In fact, some recent achievements are reviewed first, these include: automated selection of real record sets; design earthquake maps from hazard disaggregation; conditional hazard maps to include *secondary* ground motion intensity measures (IMs) in definition of seismic action; and the use of alternate types of spectrum matching records. Furthermore, possible advancements, desirable to be accounted for by future codes, are also discussed: advanced ground motion IMs, and near-source pulse-like records. Only hints are given herein, while pointing to other papers most of them presented at this same conference.

Keywords: Seismic input, Eurocode, dynamic analysis, intensity measures, performance-based seismic design.

1. INTRODUCTION

The basis of record selection is the target spectrum, which is the reference for the determination of design seismic actions. A rational design target should be representative of the seismic hazard at the site of the construction; therefore, the uniform hazard spectrum (UHS), or an approximation of it, is often used as the design spectrum[1]. The UHS is built entering the elastic spectral acceleration (for several structural periods, T, hazard curves with a specified probability of exceedance of (e.g., 10% in 50 years), and plotting the corresponding ordinates (Sa) versus T.

Given the UHS for the limit-state of interest (i.e., the specified exceedance probability or the return period, Tr) most advanced practice today, which may require aid by a seismologist, would select a set of records reflecting the *likely* magnitudes, distances, and other earthquake parameters thought to drive the probabilistic seismic hazard analysis (PSHA) for the site, and which are believed to matter with respect to structural response. Finally, the records are usually manipulated to match the UHS, individually or in average sense, at the period of the first mode of the structure (Fig. 1.1). The engineer will subsequently run time-history analysis for each accelerogram and observe the structural response. If the average exceeds a certain limit, he may conclude the structure does not withstand the design ground motion.

International codes, at least in principle, may be seen as not very far from that. In fact, once the target spectrum has been defined, the main criterion is that the records have to match it in a range of periods. For example, Eurocode 8 (CEN, 2003) states[2]: *in the range of periods between* $0.2T_1$ *and* $2T_1$*, where* T_1 *is the fundamental period of the structure in the direction where the accelerogram will be applied, no value of the mean 5% damping elastic spectrum, calculated from all time histories, should be less than*

---

[1] Recently, alternatives to UHS, were proposed (e.g., Baker and Cornell, 2006); in fact, the UHS, being an envelope of spectra of several different events, may be not representative of any earthquake.

[2] Other minor requirements apply; see Iervolino et al. (2008) for details.

90% of the corresponding value of the 5% damping elastic response spectrum. Moreover, accelerograms should be *adequately qualified with regard to the seismogenetic features of the sources* […]. Records used in the structural analysis may be: *real, artificial or obtained by simulation of seismic source, propagation and site effects*. Finally, if the sample size of the record set is at least seven, the analyst may consider as design value the average structural response to the ground motions.

In applying code prescriptions, some issues may impair the job of the practitioner in defining the seismic action. For example, it may be hard to select real records matching on average the design spectrum in a broad range of periods; on the other hand it has been not completely proven, at least to date, that artificial and synthetic signals, which may have the advantage of being perfectly spectrum matching, are appropriate for code-based structural analysis. Finally, it is unlikely that the engineer is able to qualify the input ground motions with respect to the seismological features of the sources driving the hazard.

In the following some easy-to-adopt tools, intended as attempts to reconcile code-based record selection to the practice discussed above, are proposed and some still open issues are discussed.

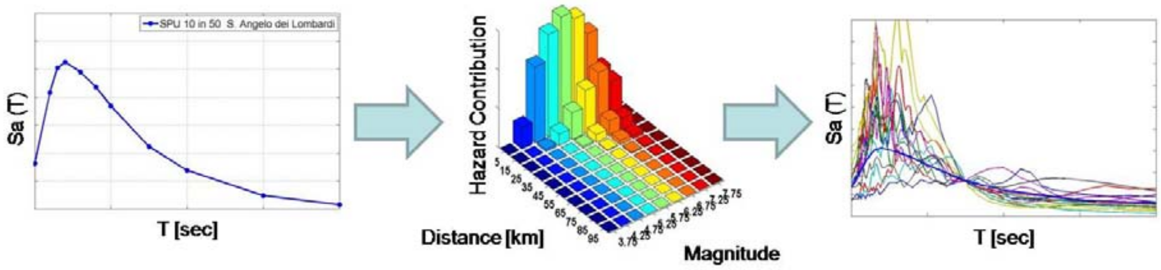


Figure 1.1. Steps to define seismic action according to the hazard at the site; from left to right: UHS for the limit-state of interest, hazard disaggregation for the spectral ordinate at the period of the first mode of the structure, selection of a set of records compatible to disaggregation and matching the target spectrum at that same period.

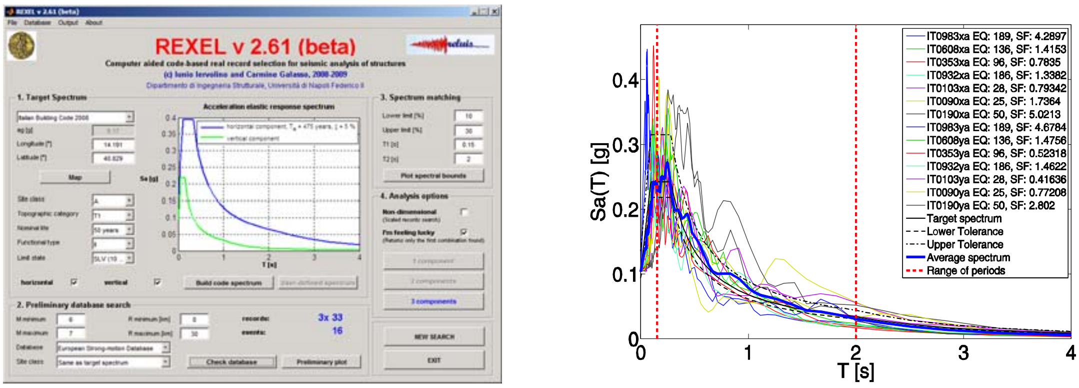
2. AIDING SELECTION OF SPECTRUM MATCHING REAL RECORDS

International seismic guidelines, concerning the use of real records for nonlinear dynamic analysis of structures, have been found not easily applicable by practitioners (Iervolino et al., 2008a). This is related to both the difficulty in rationally connecting the ground motions to the hazard at the site and the selection criteria, which often do not favor the use of real records, but rather various types of spectral matching signals (see Section 5). To overcome some of these obstacles, a software tool for computer aided real records selection, namely REXEL, was developed (Iervolino et al., 2010a and 2010b).

REXEL, allows to search for suites of waveforms, currently from the European strong motion database and the Italian accelerometric archive, compatible to spectra either user-defined or generated according to some European seismic codes. The computer program was developed to search for combinations of seven accelerograms compatible on average. It is also possible to reflect, in selection, the characteristics of the source and site, in terms of magnitude, epicentral distance, and soil classification. In particular, REXEL searches for combinations of: (i) 7 1-component accelerograms; (ii) 7 pairs of 2-components recordings; (iii) 7 triplets of accelerograms which include the two horizontal and the vertical components. For all cases the average spectrum matches the target in an arbitrary range of periods and with assigned tolerances.

An important feature of REXEL is that the first combinations returned is likely to be that with the smallest scattering of individual spectra with respect to the reference spectrum. This allows having combinations whose spectra are similar to reference spectrum, then reducing the record-to-record spectral variability within a set, which is a desirable feature if one has to estimate the seismic demand on the basis of 7 analyses only. Finally, REXEL 2.61 beta Fig. 2.1 (left) allows obtaining combinations of accelerograms compatible with the target spectrum which do not need to be scaled, but it also allows choosing sets of accelerograms compatible with the reference spectrum if linearly scaled in amplitude.

As an example of the record suites the software returns, a 2-components combinations selected for a site in southern Italy is given in Fig. 2.1 (right).



Italian Building Code 2008
Longitude (°) 14.191
Latitude (°) 40.829
Site class A
Topographic category T1
Nominal life 50 years
Limit state SLV
M minimum 6
M maximum 7
R minimum [km] 0
R maximum [km] 30
Database European Strong-motion Database
Site class Same as target spectrum
records: 3x 33
events: 16
Lower limit [%] 10
Upper limit [%] 30
T1 [s] 0.15
T2 [s] 2
Non-dimensional ☐
I'm feeling lucky ☑

Figure 2.1. Image of the software graphic user interface (left) and a combination found for a site in Italy in the case of 2-components ground motions (right); see Iervolino et al. (2010a) for details.

3. IDENTIFYING THE DESIGN EARTHQUAKES

As discussed above, in the most advanced codes, the UHS is the basis for the definition of design seismic actions on structures. On the other hand, accelerograms to be employed in structural analysis, not only are recommended to match such a spectrum, but also to be compatible with the earthquake source features relevant for the site of interest. This may be intended as indentifying the *design earthquakes*, which may be done via disaggregation of PSHA. In fact, once the UHS has been defined, it is possible to identify one or more values of magnitude (M), source-to-site distance (D) and *epsilon*[3] (ε) providing the largest contributions to the hazard in terms of exceeding a specified Sa value.

Disaggregation results depend on the hazard level being disaggregated (Tr), and on the structural period the spectral acceleration refers to. In fact, UHS for different Tr are characterized by different design earthquakes and, within the UHS for a given Tr, short and long period ranges may display different M, D and ε from disaggregation. Therefore, useful tools for record selection may be maps, which for several probabilities of exceedance of spectral ordinates at structural periods of interest to earthquake engineering, map the design earthquakes from disaggregation. An example is given in Chioccarelli et al. (2010) where, disaggregation of 10% in 50 years hazard for the whole Italy, and for structural periods equal to 0 sec (peak ground acceleration, PGA) and 1.0 sec is presented. Disaggregation for these two periods is intended to help in identifying design earthquakes for the short and moderate/long period ranges of the UHS related to the life safety limit-state of ordinary constructions. In Fig. 3.1 these maps are partially given. They report, for each site and for Sa(1 sec), the first two design earthquakes in terms of M and D; in fact, the most of sites hazard is contributed by more than a single earthquake source.

4. HAZARD-CONSISTENT INCLUSION OF ADDITIONAL IMS IN SELECTION

Acceleration-based IMs (e.g., spectral ordinates) have been shown to be important and useful in the assessment of structural response of buildings. However, there are cases in which it is desirable to account for other ground motion intensity measures (IMs), while selecting records. For example, although it is generally believed that, under some hypotheses, integral IMs associated to duration are less important for structural demand assessment with respect to peak quantities of ground motion, there are cases in which the cumulative damage potential of the earthquake is also of concern.

An easy yet hazard-consistent way of including secondary IMs in record selection is represented by the *conditional hazard maps*; i.e., maps of secondary ground motion intensity measures conditional, in a probabilistic sense, to the design hazard for the primary parameter. To illustrate the conditional hazard concept, in the study of Iervolino et al. (2010c) the joint distribution of PGA and a parameter which may account for the cumulative damage potential of ground motion, was investigated.

---

[3] A measure of how much a record's parameter is away from the median value provided by an attenuation law.

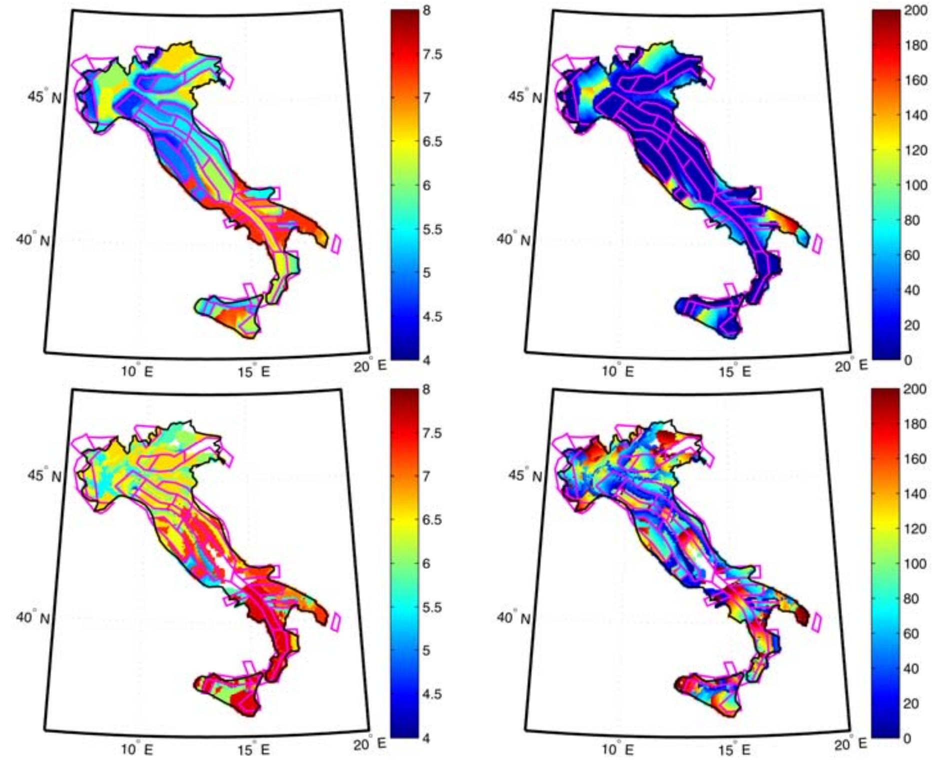


Figure 3.1. Italian map of first (upper panels) and second design earthquakes (lower panels) in terms of M (left) and D (right) for Sa(1.0sec) with a 10% hazard in 50 years; adapted from (Chioccarelli et al., 2010).

The chosen energy related measure is the so-called *Cosenza and Manfredi index* (I_D), Eqn. (4.1), the ratio of the integral of the acceleration squared to the PGA and peak ground velocity (PGV).

$$I_D = \frac{1}{PGA \cdot PGV} \int_0^{t_E} a^2(t)\,dt \tag{4.1}$$

A ground motion prediction relationship was retrieved for I_D. Subsequently, the residuals have been tested for correlation and for joint normality, which allowed obtaining the probabilistic distribution of the logs of I_D conditional to PGA. In fact, the conditional mean $\left(\mu_{\log_{10}I_D|\log_{10}PGA,M,R}\right)$ and standard deviation of $\log_{10}I_D$ $\left(\sigma_{\log_{10}I_D|\log_{10}PGA}\right)$ given that $\log_{10}PGA = z$ are given in Eqn. 4.2, where they are a function of: the average and standard deviation from attenuation relationship of I_D $\left(\mu_{\log_{10}I_D};\sigma_{\log_{10}I_D}\right)$; the correlation coefficient between the logs of PGA and I_D (ρ); and the average and standard deviation from attenuation relationship of PGA $\left(\mu_{\log_{10}PGA|M,R};\sigma_{\log_{10}PGA}\right)$. Because the conditional distribution of I_D and PGA depends on the I_D attenuation and from the PGA attenuation, it also depends on magnitude and distance; e.g., the design earthquakes.

$$\mu_{\log_{10}I_D|\log_{10}PGA,M,R} = \mu_{\log_{10}I_D|M,R} + \rho \cdot \sigma_{\log_{10}I_D} \frac{z - \mu_{\log_{10}PGA|M,R}}{\sigma_{\log_{10}PGA}}; \quad \sigma_{\log_{10}I_D|\log_{10}PGA} = \sigma_{\log_{10}I_D}\sqrt{1-\rho^2} \tag{4.2}$$

These results have been used to compute the distribution of I_D conditional to PGA with a return period of 475 years in the Campania region (southern Italy); i.e., the life-safety design PGA on rock. Conditional hazard maps in Fig. 4.1, provide information on the values of I_D (referring to two different percentiles) which should be taken into account given the PGA hazard.
Note that the conditional hazard concept may be, in principle, extended to any pair of IMs.

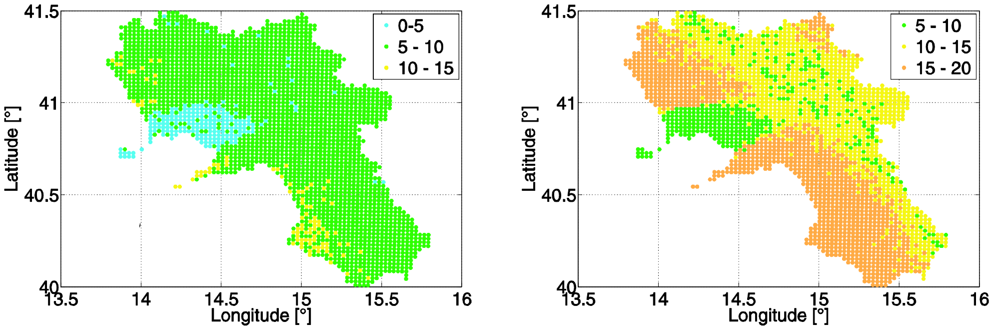


Figure 4.1. Hazard map in terms of median I_D conditional to PGA with a 10% in 50 years exceeding probability on rock in the Campania region (southern Italy) (left); hazard map in terms of I_D with a 10% exceedance probability conditional to PGA with a 10% in 50 years exceeding probability on rock; adapted from Iervolino et al. (2009c).

5. THE NEED FOR VALIDATING (NON-REAL) SPECTRUM MATCHING RECORDS

Spectrum matching records as those artificial or adjusted by wavelets, are an attractive alternative with respect to real records for code based record selection because their perfect compatibility with the design target and ease of generation. However, to date, it has not finally proven they are equivalent to real records with respect to estimating the structural response, which are considered as a benchmark by many. To this aim, the simple study presented by De Luca et al. (2010) compared different procedures to obtain sets of spectral matching accelerograms for nonlinear dynamic analysis of structures in terms of inelastic seismic response. Six classes of records were considered: original (unscaled) real records (URR), real records moderately linearly scaled (SF5), real records significantly linearly scaled (SF12), real records adjusted by wavelets (RSPMatch), artificial waveforms generated by two computer programs (Belfagor, Simqke). The study is spectral shape-based, that is, all the considered sets of records, generated or selected, match individually (artificial and adjusted) or on average (real records) the same design spectrum for a case-study site in Italy.

Three kinds of single degree of freedom (SDOF) systems, non-degrading and non-evolutionary, non-degrading and evolutionary, and both degrading and evolutionary, were used to evaluate the nonlinear response to the compared records. Demand spectra in term of peak and cyclic responses were derived for different strength reduction factors (Rs). Results of the analyses (see Fig. 5.1 for an example) show that artificial or adjusted accelerograms may underestimate, in some cases and at high nonlinearity levels, the displacement response in terms of kinematic ductility (D_{kin}), if compared to original real records, which are considered as a benchmark. However, this conclusion does not seem to be statistically significant. Conversely, if the cyclic response is considered in terms of equivalent number of cycles, N_e, artificial record classes show a significant overestimation of the demand, which does not show up for wavelet-adjusted records. The two classes of linearly scaled records do not show systematic bias with respect to those unscaled for both types of structural response considered.

A similar, if not greater, need for validation holds for synthetic records obtained by simulation of earthquake physics, which are interesting to engineers who want to play with design scenarios.

6. FINDING MORE INFORMATIVE IMS WITH RESPECT TO STRUCTURAL RESPONSE

It has been discussed that codes basically only assign the spectral shape. In fact, $Sa(T_1)$ is the perfect predictor for the response of elastic SDOF systems, and a good predictor for elastic multi-degree of freedom (MDOF) systems dominated by the first mode of vibration, associated to the T_1 period, and studies have found that, in some case, structural response may be not particularly sensitive to magnitude and distance given $Sa(T_1)$. However, it does not provide information about the spectral shape in other regions of the spectrum, which may be important for the nonlinear behavior (beyond T_1) or for structures dominated by higher modes (before T_1). As a consequence, in general, the structure is sensitive to different spectral values in a large range of periods. This is why codes assign spectral compatibility for the average spectrum of a record set in period intervals.

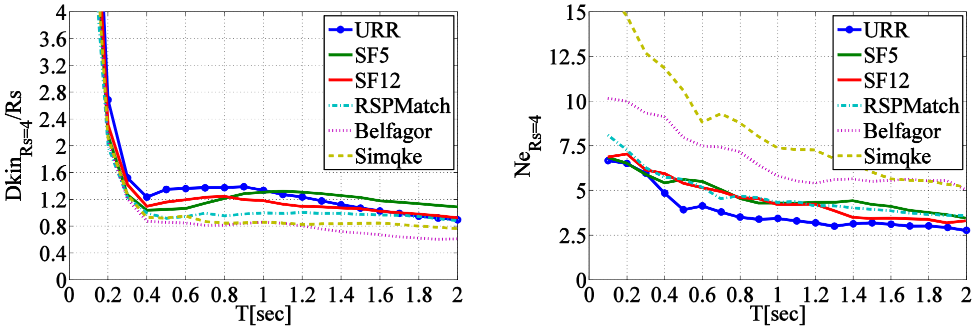


Figure 5.1. Example of ductility (left) and equivalent number of cycles (right) elastic-plastic SDOF demands normalized by the strength reduction factor (Rs equal to 4); adapted from De Luca et al. (2010).

Regarding individual record selection, then, it may be useful to use IMs representative for the spectral shape. These are under investigation currently as Sa_{avg} (the geometrical mean of spectral ordinates in a range of periods $T_1,\ldots,T_N$). A simple yet effective improvement of Sa_{avg} is the geometrical mean normalized it by $Sa(T_1)$. In fact, a new parameter named N_p (Eqn. 6.1) may be introduced; see Bojórquez and Iervolino (2010). The information carried by N_p is that if it is close to one on average for a set of records, it is expected the average spectrum to be about flat in the range between $T_1,\ldots T_N$. If N_p is lower than one a negative slope is expected and vice-versa. As an example, the average spectra for two group records and N_p values, considering $T_N = 2T_1$, are given in Fig. 6.1. N_p is independent of the scaling level of the record, and, most importantly, it helps to improve the knowledge about the spectral shape in a range of periods of interest to nonlinear structural response; thus, it may be an useful secondary IM.
Selecting records on the basis of the individual spectral shape may help in increasing the efficiency of structural demand estimation. This is important because, currently, the very small number of records to be employed and the large record-to-record variability of response, may give a poor confidence in the structural assessment, which means that response to two sets nominally equivalent may be different. This kind of IMs, therefore, candidates for the next generation of procedures for record selection.

$$N_P = Sa_{avg}\left(T_1,\ldots,T_N\right)/Sa\left(T_1\right) \qquad (6.1)$$

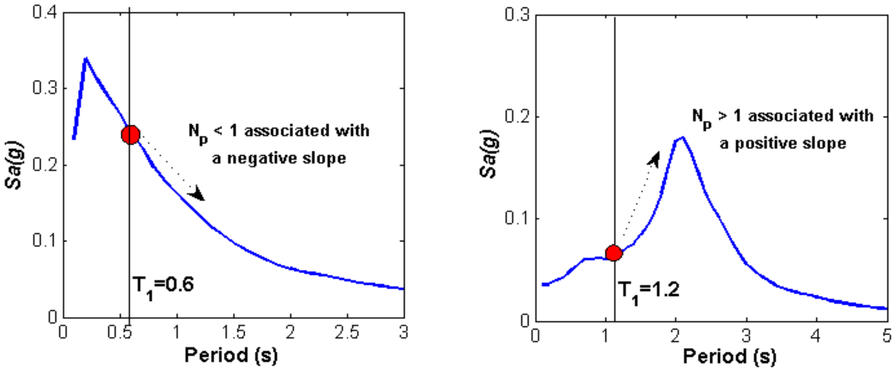


Figure 6.1. Mean elastic response spectra with $N_p = 0.39$ (left), and 1.9 (right); Bojórquez and Iervolino (2010).

7. THE NEAR-SOURCE PULSE-LIKE RECORDS ISSUE

It is well known that in the case of an earthquake, ground motion recorded at near-source sites may be subjected to rupture *directivity* effects which result in a low frequency full cycle velocity pulse at the beginning of the signal. The occurrence of this effect depends on the rupture process and on the geometrical configuration of the fault and the site. Fig. 7.1 (left) sketches rupture directivity in the simple case of a unilateral strike-slip fault. As the rupture, which may be seen as a point source moving along the fault, goes away from the epicenter, it radiates energy in seismic waves originated at different instants. Roughly speaking, the wave fronts tend to all arrive at the same time in site 2. Conversely, in site 1, with respect to which the rupture moves away, waves tend also to arrive in different moments. Therefore, in the former case the energy is concentrated in a high amplitude and short duration (impulsive) motion (e.g., Fig. 7.1, right); while in the latter the signal is longer and of lower amplitude.

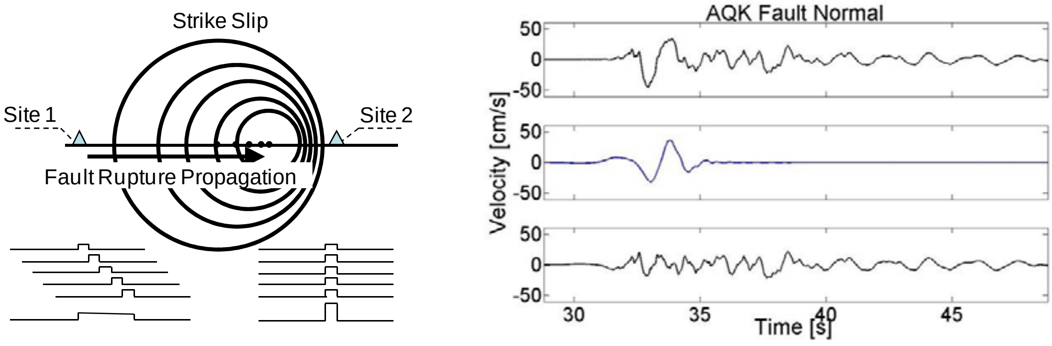


Figure 7.1. Constructive interference of waves and directivity (left); and one of the impulsive records of the recent L'Aquila (2009) earthquake (right), from the top to the bottom: velocity, time-history, extracted pulse, and residual ground motion after the pulse is removed; adapted from Chioccarelli and Iervolino (2010).

Near-source pulse-like records are of interest to structural engineering because the seismic action is expected to be peculiar with respect to non-pulse-like records, that is: (i) the elastic demand of pulse-like signals is generally larger than that of ordinary ground motions, particularly concerning the fault-normal direction; (ii) the spectral shape is non-standard with an increment of spectral ordinates in the range around the pulse period (Fig. 7.2, left); (iii) because the pulse period, T_p, is generally a low frequency one (i.e., in the same order of magnitude of that of the most of common structures) the demand can be peculiarly intense. On the other hand, current attenuation laws are not able to capture such effects well, and therefore current PSHA is not able to predict this peculiar spectral shape. This failure may possibly lead to an underestimation of the nonlinear demand. Moreover, because the inelastic-to-elastic ratio ($S_{d,i}$ over $S_{d,e}$) of near-source signals is not the same than ordinary records (Fig. 7.2, right), it is not proven the current design procedures are conservative enough in the near-source.
Therefore, this issue may be especially relevant for structural engineering applications and has to be properly accounted for. Accounting for pulse-type records in earthquake engineering practice should be reflected both in PSHA and in record selection; this is probably the main issue to be addressed in the next generation of codes (Chioccarelli and Iervolino, 2010).

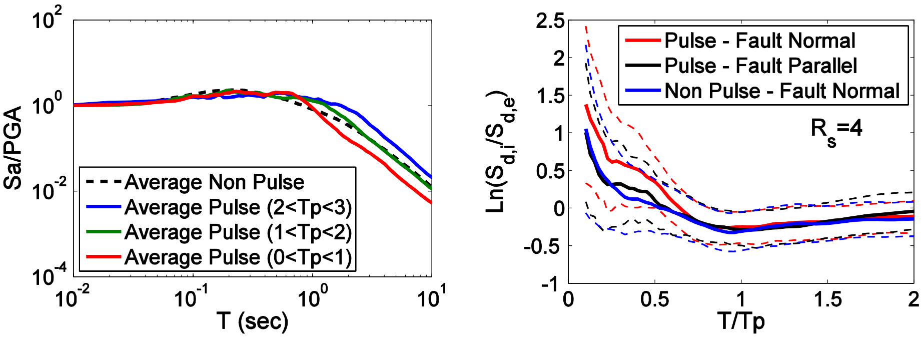


Figure 7.2. Spectral shape of pulse-like records with a "bump" around the pulse period (left); and peculiar trend of inelastic-to-elastic spectral displacement ratio for pulse-like with respect to ordinary records (right); adapted from Chioccarelli and Iervolino (2010).

8. FINAL REMARKS

In the paper a few issues, regarding both improvement of current record selection procedures and needs for the next generation of codes, have been briefly reviewed. All of them revolve around the earthquake information to be accounted for in selection once the design spectrum, which is the current basis for determination of the seismic actions on structures, is given. Therefore tools for aiding the seismic input selection aim to control the spectral shape, and/or to identify other features of the signal consistent with the target spectrum and, at the same time, with the hazard (i.e., the design earthquakes, conditional hazard maps and spectral shape-based IMs).

The final goal is to improve the estimation of structural response both in terms of accuracy and efficiency. In fact, two are the underlying critical points in the most of what discussed: (i) what ground motion parameters are relevant for structural assessment other than the spectrum (accuracy); and (ii) the "enough" number of records (small in current codes with respect to record-to-record variability of nonlinear response) to be employed in structural analysis (efficiency).

Possible advancements discussed, are related to the need of accounting, in hazard analysis and record selection, for the of near-source records' characteristics. This is seen important because earthquakes are mostly damaging in the near-source region and current tools are calibrated on non-impulsive records; i.e., may be inadequate.

Finally, it is to note that the paper referred mainly to the uniform hazard spectrum as it is the current best practice to relate the design spectrum to the seismic hazard at the site; nevertheless it has some shortcomings which may impair its use as the spectrum to match in record selection, and it is likely the next generation of advanced codes will consider alternate representations of design ground motion. This could not be discussed; however, given results virtually apply to any hazard-based design spectrum.

ACKNOWLEDGEMENTS

The results presented here could not have been feasible without the students and co-workers whose effort may be not adequately reflected by the references below; they are: Eden Bojórquez, Eugenio Chioccarelli, Flavia De Luca, and Carmine Galasso. These studies also benefitted of the thoughtful stimuli of professors Edoardo Cosenza and Gaetano Manfredi, and of course, C. Allin Cornell.

REFERENCES

Baker, J.W., Cornell, C.A. (2006a) Spectral shape, epsilon and record selection *Earthquake Engineering & Structural Dynamics* **35**(9), 1077–1095.

Bojórquez, E., Iervolino, I. (2010). A Spectral Shape-based Scalar Ground Motion Intensity Measure for Maximum and Cumulative Structural Demands. *Proc. of 14th European Conference on Earthquake Engineering*, Ohrid, Republic of Macedonia.

CEN, European Committee for Standardization. (2003). Eurocode 8: Design provisions for earthquake resistance of structures, Part 1.1: general rules, seismic actions and rules for buildings, Pren1998-1.

Chioccarelli, E., Iervolino, I. (2010). Near-Source Seismic Demand and Pulse-Like Records: a Discussion for L'Aquila Earthquake. *Earthquake Engineering and Structural Dynamics.* doi 10.1002/eqe.987 (in press)

Chioccarelli, E., Iervolino, I., Convertito, V. (2010) Italian Map of Design Earthquakes from Multimodal Disaggregation Distributions: Preliminary Results. *Proc. of 14th European Conference on Earthquake Engineering*, Ohrid, Republic of Macedonia.

De Luca, F., Iervolino, I., Cosenza, E. (2010). Compared seismic response of degrading systems to artificial and real records. *Proc. of 14th European Conference on Earthquake Engineering*, Ohrid, Republic of Macedonia.

Iervolino, I., Galasso, C., Cosenza, E. (2010a). New features of REXEL 2.61 beta, a tool for automated record selection. *Proc. of 14th European Conference on Earthquake Engineering*, Ohrid, Republic of Macedonia.

Iervolino, I., Galasso, C., Paolucci, R., Pacor, F. (2010b). REXELite, online record selection for the ITalian ACcelerometric Archive. *Proc. of 14th European Conference on Earthquake Engineering*, Ohrid, Republic of Macedonia.

Iervolino, I., Giorgio, M., Galasso, C., Manfredi, G. (2010c). Improving seismic action assessment: conditional design maps for secondary intensity measures. *Proc. of 14th European Conference on Earthquake Engineering*, Ohrid, Republic of Macedonia.

Iervolino, I., Maddaloni, G., Cosenza, E. (2008). Eurocode 8 compliant real record sets for seismic analysis of structures. *Journal of Earthquake Engineering*, **12**(1):54-90.