Unscaled, scaled, adjusted, and artificial spectral matching accelerograms: displacement- and energy-based assessment.

Flavia De Luca, Iunio Iervolino, Edoardo Cosenza.
DIST – Dipartimento di Ingegneria Strutturale, Università degli Studi di Napoli Federico II, Via Claudio 21, 80125, Napoli.

Keywords: Real records, Scaling factor, Aritificial accelerograms, RSPMatch 2005.

ABSTRACT
Different procedures to obtain sets of spectral matching records for nonlinear dynamic analysis of structures were compared in term of post-elastic structural response. Six typologies of records were considered: unscaled real records, real moderately linearly scaled, real significantly linearly scaled, real adjusted by wavelets, artificial generated by two different procedures. 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 of a case-study site in Italy. Elastic-plastic with hardening non-degrading SDOF systems were used to evaluate the nonlinear response for the compared records at different non-linearity levels; demand spectra in term of peak and cyclic response were derived for different strength reduction factors.
Results of the analysis show that artificial or adjusted records may underestimate, at high non-linearity levels, the displacement related non linear response if compared to real records, especially those unscaled which are considered as a benchmark herein. Conversely, if the cyclic response is considered, artificial record sets show a more evident overestimation of the demand, while wavelet-adjusted do not display significant bias. Finally the two groups of linearly scaled records seem to show no systematic bias for both types of response considered.

1 INTRODUCTION

Seismic assessment of structures via non-linear dynamic analysis requires proper seismic input selection. Seismic codes suggest different procedures to select ground motion signals, most of those assuming spectral compatibility to the elastic design spectrum as the main criterion. On the other hand, practitioners have several options to get input signals for their analysis; e.g., various types of synthetic, artificial, real or real manipulated records (Bommer and Acevedo, 2004).

Codes usually acknowledge the use of different types of records and may provide additional criteria or limitations for each of those. In the new Italian seismic code (CS.LL.PP., 2008), for example, artificial records should have duration of at least 10 seconds in their pseudo-stationary part, and they cannot be used in the assessment of geotechnical structures. Synthetic generated by simulation of earthquake rupture process should refer to a characteristic scenario for the site in terms of magnitude, distance and source seismological characteristics; real records should reflect the seismic *dominating* the hazard at the site. However, practitioners not always can accurately characterize the seismological threat to generate synthetic signals or it is not possible to find a set of real records that fit properly code requirements in term of a specific hazard scenario (Convertito *et al*., 2009).

In fact, despite in the last decades the increasing availability of databanks of real accelerograms, the most sound representation of ground motions, has determined a spread use of this type of records to characterize seismic input, it may be very difficult to successfully apply code provisions to real record sets, especially those regarding spectral compatibility if appropriate tools are not available (Iervolino *et al*., 2008).

This is why the relatively easy and quick generation of artificial records, perfectly compatible with an assigned design spectrum, has become very popular for both practice and research purposes.

More recently, procedures to get the spectral compatibility of real records by wavelets adjustment were proposed (Hancock *et al.* 2006). This kind of manipulation is an extension of the more simple linear scaling of real records to modify (e.g., amplify) the spectral shape to get a desired intensity level (Iervolino e Cornell, 2005).

Although, several studies tried to assess the *reliability* of each of these procedures (e.g., Schwab *et al.*, 2006) their conclusions seem to rely too much on the working assumptions used for the comparison, that is, the benchmark and the structural response considered.

This work tries to address the spectral matching issue from the structural point of view in terms of non-linear displacement and cyclic responses, having as reference a code design spectrum.

Six categories of 28 accelerograms each of those comprised of four sets have been considered:

- Unscaled real records (URR);
- Moderately scaled real records (SF5);
- Significantly scaled real records (SF12);
- Wavelet-adjusted real records (RSPMatch);
- Type - 1 artificial records (Belfagor);
- Type - 2 artificial records (Simqke);

The basis of this study is the elastic pseudo-acceleration design spectrum, that is, all sets are compatible with the elastic design spectrum for a case study in southern Italy (see following section). To this aim a large number of single degree of freedom (SDOF) systems with an elastic-plastic with hardening behavior were considered with different strength reduction factors to get variable non-linearity levels.

As structural response measures or engineering demand parameters (EDPs) the peak inelastic displacement, the ductility demand and the equivalent number of cycles have been considered to relate the structural response to both peak and energy content of ground motion (Iervolino *et al.*, 2006; Manfredi, 2001).

Analyses aimed at comparing the bias, if any, associated to each typology of records in the three EDPs with respect to the unscaled real ground motions which are considered as a benchmark.

2 CLASSES AND RECORDS

Six categories of records have been selected assuming the same target spectrum evaluated according the new Italian seismic code for a case-study site (Avellino, southern Italy) having as geographical coordinates: lat. 40.914, long. 14.78. The 5% damped elastic spectrum considered is that related to the life-safety limit state of an ordinary construction with a nominal life of 50 years on A-type (stiff) soil class; see CS.LL.PP. (2008) for details.

For each category four spectrum compatible sets of seven records have been selected (if real) or generated (if artificial). Assuming sets of seven records acknowledges the Italian and Eurocode 8 prescriptions allowing to consider the mean structural response from non-linear dynamic analyses if at least seven records are employed.

In the following the selection or generation results are briefly reviewed.

2.1 URR - Unscaled real records

The sets of unscaled real records have been selected using Rexel 2.31 (beta), software which allows to select combinations of seven records contained in the European Strong Motion Data Base, which on average match an arbitrary or code-based elastic spectrum (Iervolino *et al.*, 2009a).

Providing to the software the geographical coordinates of the site and the limit state of interest it was possible to select 4 sets of record each of those matching on average the target spectrum in the 0.15s-2.0s range. Magnitude and source-to-site distance range between 5.6-7.8 and 0km-35km. In Figure 1 the four sets' means are represented along with individual records and target spectrum. All the set averages are within [-10%, + 30%] tolerance range with respect to the target spectrum, and in most of the compatibility interval they approximate very well the design spectral shape.

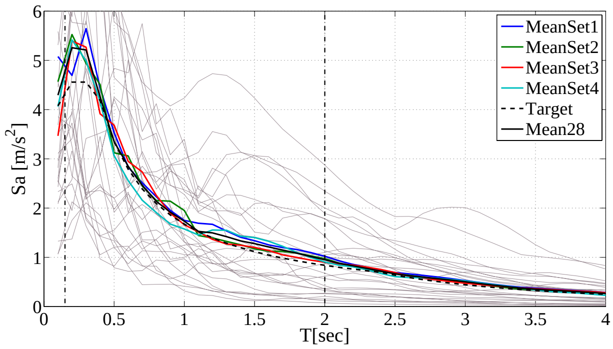

Figure 1. Unscaled records acceleration elastic spectra.

Each sets has a different average deviation δ, Equation (1), from the target spectrum equal respectively to 0.163 for set_1, 0.134 for set_2, 0.152 for set_3 and 0.141 for set_4.

$$\delta = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{Sa_{o,med}(T_i) - Sa_s(T_i)}{Sa_s(T_i)}\right)^2} \qquad (1)$$

In Equation (1) $Sa_{o,med}(T_i)$ represents the pseudo-acceleration ordinate of the average real spectrum corresponding to the period T_i, while $Sa_s(T_i)$ is the value of the spectral ordinate of the code spectrum at the same period, and N is the number of values within the considered range of periods (Iervolino *et al.*, 2008).

URR sets have no registrations in common and come from 17 different events.

2.2 Real scaled records

Also linearly scaled records have been selected with Rexel 2.31. In particular two categories of 4 scaled records sets each, differing for the mean scaling factor (SF), have been selected: (i) SF equal to 5; (ii) and SF equal to 12. The intent is to compare response to records moderately and significantly scaled.

The range of periods in which there is spectral compatibility is the same of URR.

2.2.1 SF5

In the same magnitude and distance ranges chosen for unscaled records, four set of seven compatible accelerograms each of those has a mean SF equal to 5 thanks, to a specific option of the REXEL 2.31 software, were selected, Figure 2. The 28 different records (9 records in common with URR) come from 15 earthquake events (10 of them are in common with URR). In this case the deviations of each set are smaller than unscaled ones, as expected for scaled records (Iervolino *et al.*, 2008 and 2009a); respectively equal to 0.082 for set_1, 0.087 for set_2, 0.069 for set_3 and 0.089 for set_4.

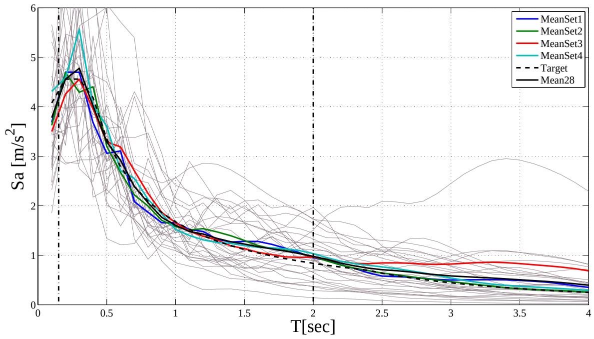

Figure 2. Scaled records SF5 acceleration elastic spectra.

2.2.2 SF12

Using REXEL three sets of seven records whose medium SF was 12, were defined. Because it was not possible to find another set with the desired characteristics, the fourth set of seven accelerograms was "manually" selected so that its deviation and its scaling factor were similar to the other three software-aided selected records.

These four sets have no event in common with the URR sets and come from 17 different events.

In this case deviations of each set are still smaller than unscaled records ones and comparable to deviation of the SF5 sets, Figure 3.

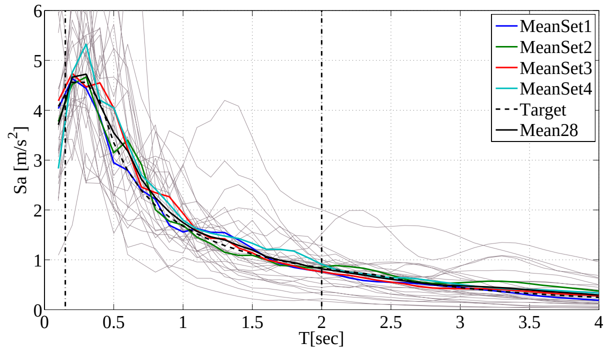

Figure 3. Scaled records SF12 acceleration elastic spectra.

2.3 RSPMatch - Wavelet adjusted records

RSPMatch2005 software (Abrahamson, 1992, Hancock *et al.* 2006) has been used to modify the sets of real unscaled records; in this case the adjustment procedure was simply aimed at reducing dispersion of records respect to the target one. The procedure has been pursued only for the 5% damping factor in the range of period [0.15s-2.0s] in which records were already compatible on average and without the application of any linear scaling factor, Figure 4.

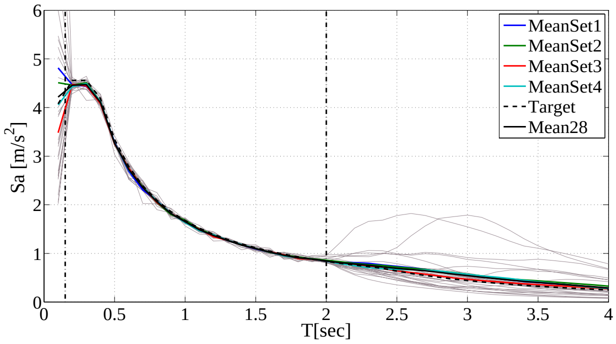

Figure 4. Wavelet adjusted records acceleration elastic spectra.

2.4 *Artificial records*

Generally speaking, generation procedures for artificial accelerograms are based on random vibration theory and the spectral matching is carried out iteratively adjusting in the amplitude Fourier spectrum (Pinto *et al.* 2004).

The two software selected for this study generate different kind of signals: the first one, Belfagor (Mucciarelli *et al.*, 2004) produces non stationary signals; the second one Simqke (Gasparini and Vanmarke., 1976) produces a stationary signal that is after enveloped in a trapezoidal shape.

2.4.1 *Belfagor records*

Belfagor software (Mucciarelli *et al.*, 2004) generates non stationary signals by using variable Fourier amplitudes empirically evaluated from Sabetta and Pugliese (1996); in fact, the code asks for reference M, R and soil type even if the spectrum to match is a code spectrum as in this case in which the target was a Newmark-Hall shaped spectrum.

Therefore, 28 accelerograms have been generated separately for the purpose of this study. They all have the same duration, 21.48 seconds and a time step of 0.005. There is a short difference with the minimum duration that Italian code assigns for artificial records (25 seconds).

Records have been arranged in four sets of seven records, Figure 5.

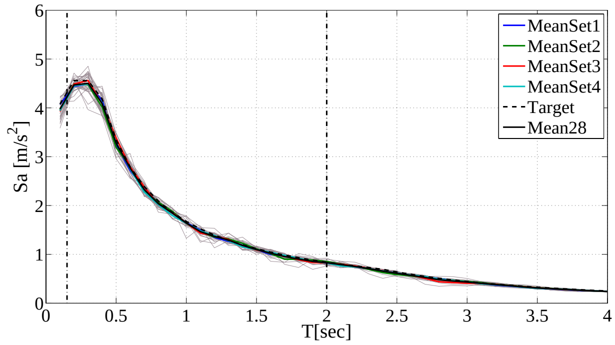

Figure 5. Belfagor records acceleration elastic spectra.

2.4.2 *Simqke records*

A second group of four sets of artificial records have been generated by Simqke (Gasparini and Vanmarke 1976). This well-known software generates groups of stationary artificial record such as they fit the target spectrum. In this case 28 records have been generated together and after they have been separated in four groups of seven (Figure 6), they fully respect the Italian code's provisions in terms of duration of both stationary and non-stationary parts.

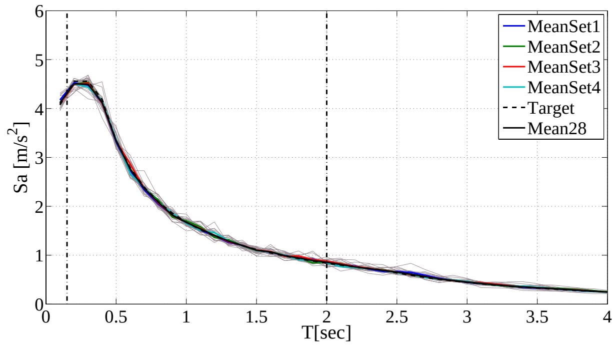

Figure 6. Simqke records acceleration elastic spectra.

2.4.3 *Integral ground motion parameters*

Each accelerogram of the six categories was processed to evaluate characteristic parameters other than the spectral shape. Average values of Arias intensity (I_A), Equation (2), and Cosenza and Manfredi index (I_D), Equation (3), (Cosenza *et al.* 1993), computed as the mean on the sample of 28 records for each category, are reported in Figure 7.

$$I_A = \frac{\pi}{2 \cdot g} \int_0^{t_E} a^2(t)\,dt \qquad (2)$$

$$I_D = \frac{2 \cdot g}{\pi} \frac{I_A}{PGA \cdot PGV} \qquad (3)$$

Real records both scaled and unscaled have close mean values of I_D as well as RSPMatch adjusted records. Both categories of artificial records display higher values of I_D.

Simqke records show very high I_A and consequently I_D values. The Simqke generation process seems to be not able to reproduce characteristic Arias intensities of real events.

Belfagor records, because of the empirically procedures based on the attenuation law better replicate real records characteristic values.

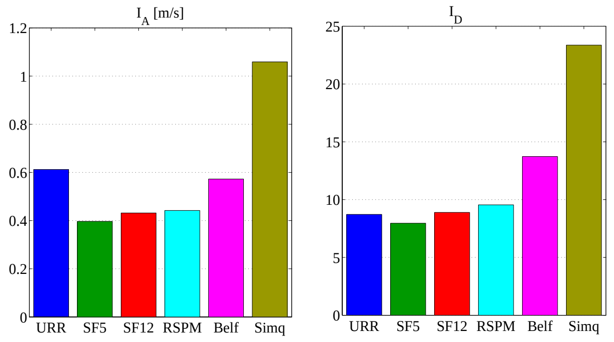

Figure 7. Average values of I_A and I_D computed as mean value of 28 records.

3 ANALYSES AND DEMAND MEASURES

All records selected for each category were used as an input for non-linear dynamic analyses applied to 20 elastic and SDOFs, whose periods vary linearly from 0.1 to 2 seconds. All SDOFs have an elastic-plastic with hardening backbone; post-yield hardening ratio has been assumed as 0.03 of the initial stiffness.

To have a response that ranges from mildly inelastic to severely inelastic behavior three reduction factors (R) were selected: 4, 6, and 10. Note that the peak value elastic deformation experienced by an elastic structure is a ground-motion specific quantity. Therefore, one can achieve the same value of R either for each record in a dataset (*constant R* approach) or on an average sense for all the records referring R factor to the target spectrum matched (*constant strength approach*). It has been adopted a constant strength approach, to simulate the effect of different sets of accelerograms to the same structure. However, it should be emphasized that the two different approaches can lead to different conclusions (Bazzurro *et al.*, 2004).

3.1 Engineering demand Parameters

EDPs chosen have been selected to investigate both peak and cyclic seismic response. Displacement-based parameters are: (i) the ratio of the peak inelastic displacement ($Sd_{R=i}$) to the elastic target spectral displacement ($Sd_{el-target}$), Equation (4); and the displacement ductility (D_{kin}) evaluated as the ratio of the peak inelastic ($Sd_{R=i}$) and yielding displacement (Δ_y), Equation (5).

$$\frac{Sd_{R=i}}{Sd_{el-target}} \tag{4}$$

$$D_{kin} = \frac{Sd_{R=i}}{\Delta_y} \tag{5}$$

The equivalent number of cycles (N_e) was also considered. It considers the hysteretic energy (E_H) normalized with respect to the largest cycle, separating ductility demand (already considered above) and cyclic demand, Equation (6).

$$N_e = \frac{E_H}{F_y \cdot \left(Sd_{R=i} - \Delta_y\right)} \tag{6}$$

4 RESULTS AND DISCUSSION

4.1 Displacement ratio to the target spectrum

In this section the ratio between displacement and elastic target spectrum is presented as mean value on 28 records pooled per typology. Figure 9 gives the ratio for R equal to 1, that is, the deviation of each typology with respect to the target spectrum, as it may help to understand the non-linear results. Figures from 10 to 12 show the average trends for a specific R.

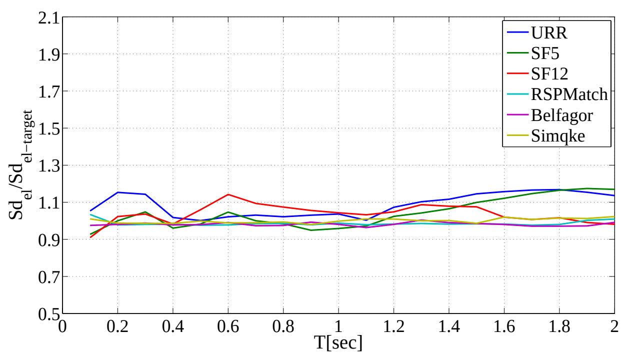

Figure 9. Elastic ratio with target elastic spectrum for each category (28 records).

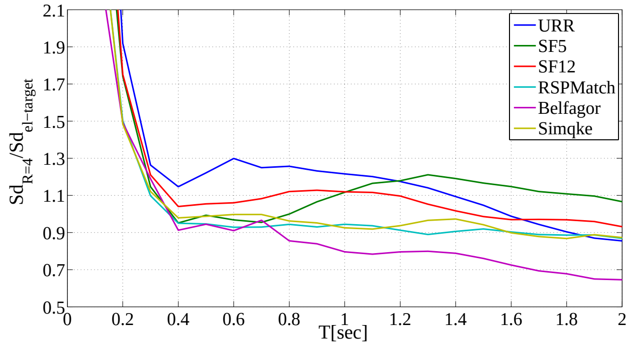

Figure 10. R = 4 ratio with target elastic spectrum for each category (28 records).

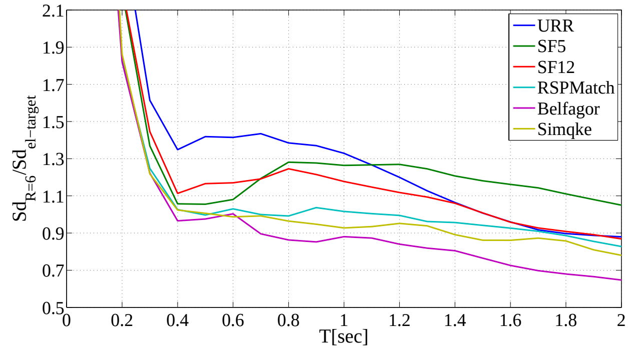

Figure 11. R = 6 ratio with target elastic spectrum for each category (28 records).

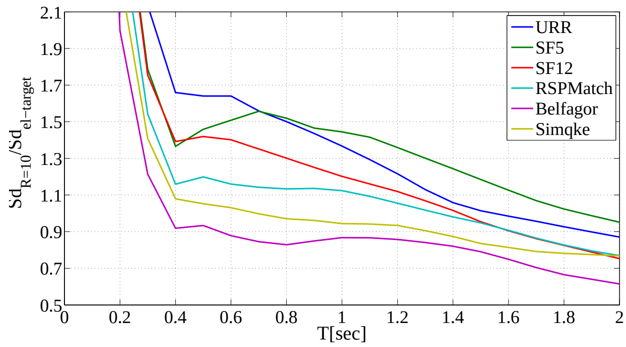

Figure 12. R = 10 ratio with target elastic spectrum for each category (28 records).

Generally, the adjusted and artificial records seem to show a systematic underestimation of the displacement ratio if compared to the URR for the higher non-linearity levels, and at least in the range of period of interest for the most of common structures.

SF5 and SF12 have a less systematic behaviour with period, this is probably related to the larger variability of individual records within a set, and seems to be qualitatively comparable to the URR. Values above unity shown systematically by Belfagor records lead to average inelastic displacement lower than elastic.

Hypothesis tests, for example, may help assess to quantitatively the significance of these results.

In Appendix (Figure A1) the ratio is plotted for each of the four sets illustratively for R equal to 6, this is to assess how much the pooled trends match the individual sets trends.

4.2 Ductility demand

While the inelastic to elastic ratio of the previous section provides a relative measure, the kinematic ductility may be useful to assess the absolute displacement demand. From Figure 13 to Figure 15 the same trend observed above may be found, that is, artificial or adjusted may records show underestimation with respect to URR only at high non-linearity levels.

In Appendix (Figure A2) the trends are given for the individual sets within each typology. It is confirmed that scaled sets may be considered similar to the URR.

Ductility demands for each category are very close to each other for R equal to 4; increasing reduction factors lead to the same trend found for displacement ratio. In this case URR ductility demand, for R equal to 10 in the moderate periods range, is two times that of Belfagor records.

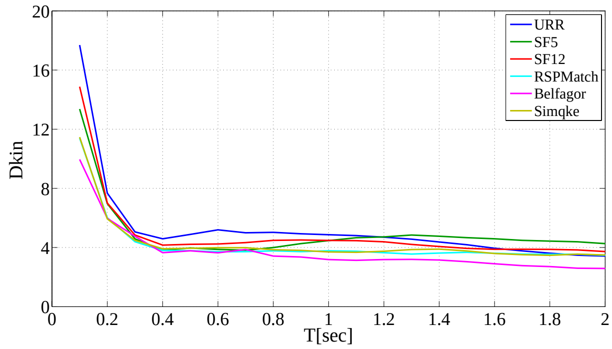

Figure 13. R = 4 ductility demand

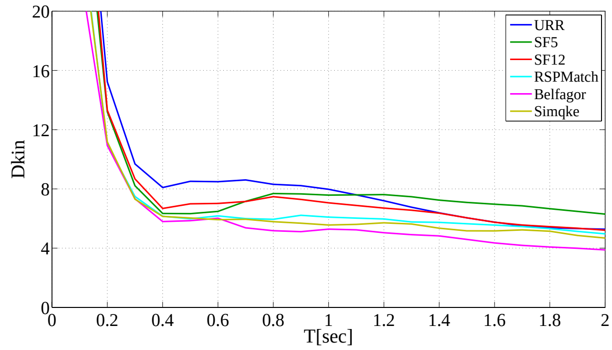

Figure 14. R = 6 ductility demand

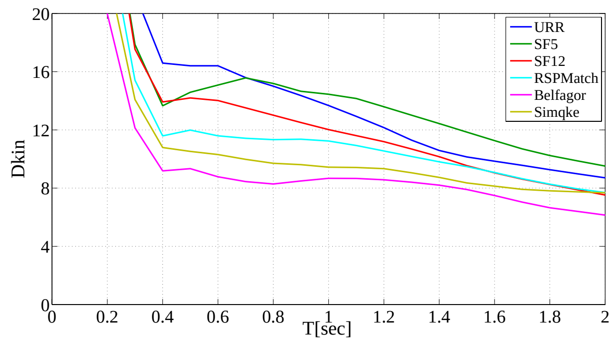

Figure 15. R = 10 ductility demand

4.3 *Equivalent number of cycles*

More evident conclusions may be found when analyzing the trends of the equivalent number of cycles (Figure 16 to Figure 18). In fact, for all the non-linearity levels, a strong overestimation in terms of cyclic response may be observed for both adjusted and artificial records. In this case Simqke records show the highest N_e values that in some cases can get over the 200% with respect to the URR; Belfagor records have the same trend, although with a lower bias. Wavelet-adjusted records do not show a detectable bias in terms of N_e. In Appendix (Figure A3) the trends are given for the individual sets within each typology.

It is to note that these trends could be predicted by the integral parameters discussed above; i.e., the I_D values of the sets. Figure 19 to Figure 21 show N_e versus I_D for the individual records for selected periods and only for R equal to 6. For artificial records (more evidently for Simqke records) the high values[1] of I_D seem to agree with the high N_e values.

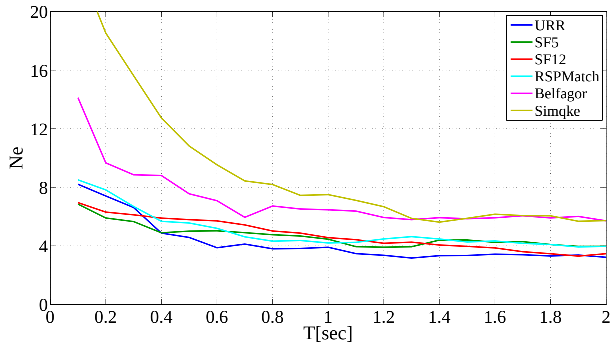

Figure 16. R = 4 equivalent number of cycles

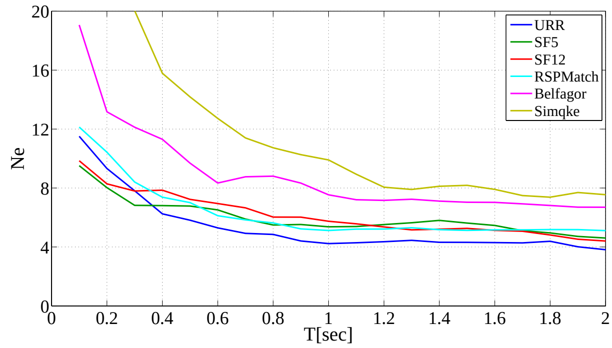

Figure 17. R = 6 equivalent number of cycles

[1] Note that the likely I_D values for the test site conditional to the design acceleration are 5.3 as median, 3.5 and 8.2 as 16% and 84% percentiles (Iervolino *et al.*, 2009b), indicating that the artificial records have unlikely integral parameters although they are spectral matching.

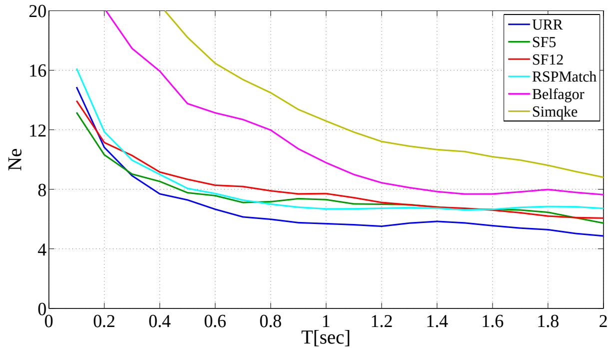

Figure 18. R = 10 equivalent number of cycles

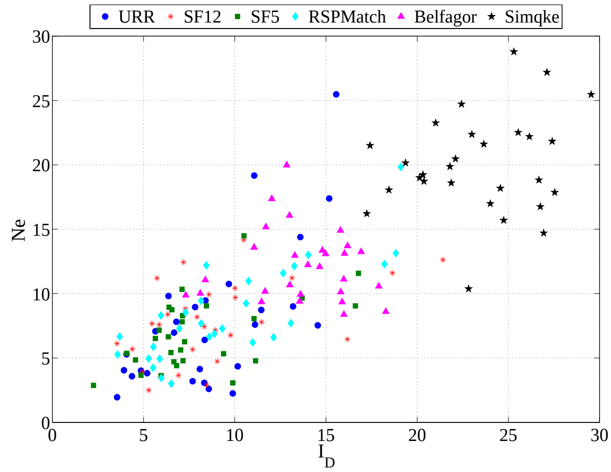

Figure 19. N_e versus I_D for R = 6 and T = 0.3 seconds evaluated for each record of each category.

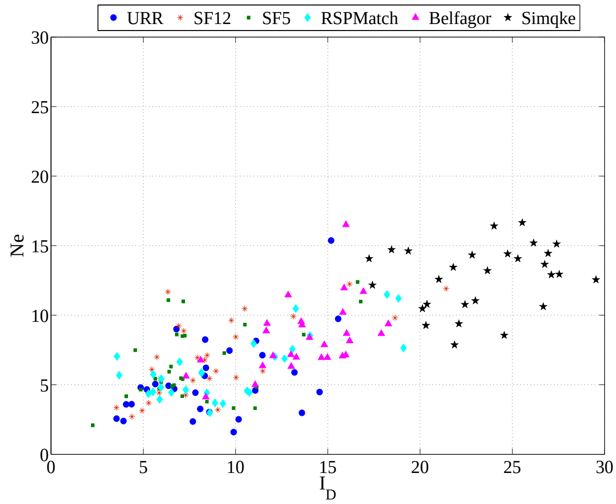

Figure 20. N_e versus I_D for R = 6 and T = 0.6 seconds evaluated for each record of each category.

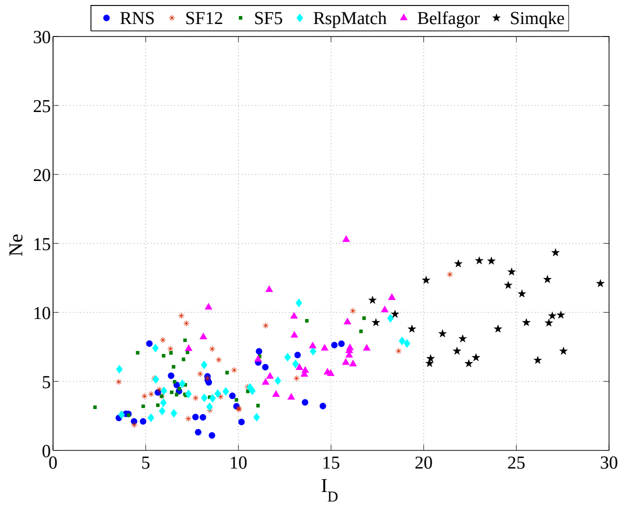

Figure 21. N_e versus I_D for R = 6 and T = 1.0 seconds evaluated for each record of each category.

5 CONCLUSIONS

In this work different ways to achieve spectral matched records have been compared in terms of post-elastic seismic response in terms of both peak displacement- and cyclic-based response measures of 20 non degrading SDOFs at different non-linearity levels.

Six typologies of records were considered: real unscaled, real with limited scaling factor, real with high scaling factor, adjusted with wavelets, and two different types of artificial records.

The benchmark was the design elastic spectrum for a case study site in southern Italy and the response to unscaled records matching it on average.

Results seem to indicate that artificial and wavelet-adjusted records may underestimate displacement and ductility demand, although this is evident only for high R values. The trends for the linearly scaled records seem to be non-systematic. Hypothesis tests may help to assess quantitatively how much these results are significant.

On the other hand, when cyclic response is of concern, artificial records show a strong overestimation with respect to real records and wavelet-adjusted records.

As a side results, it is to note that this latter conclusion could be predicted by some integral parameter of the ground motion, which therefore should be used as an additional criteria for structures in which cyclic behaviour has an important role in determining seismic performances.

APPENDIX

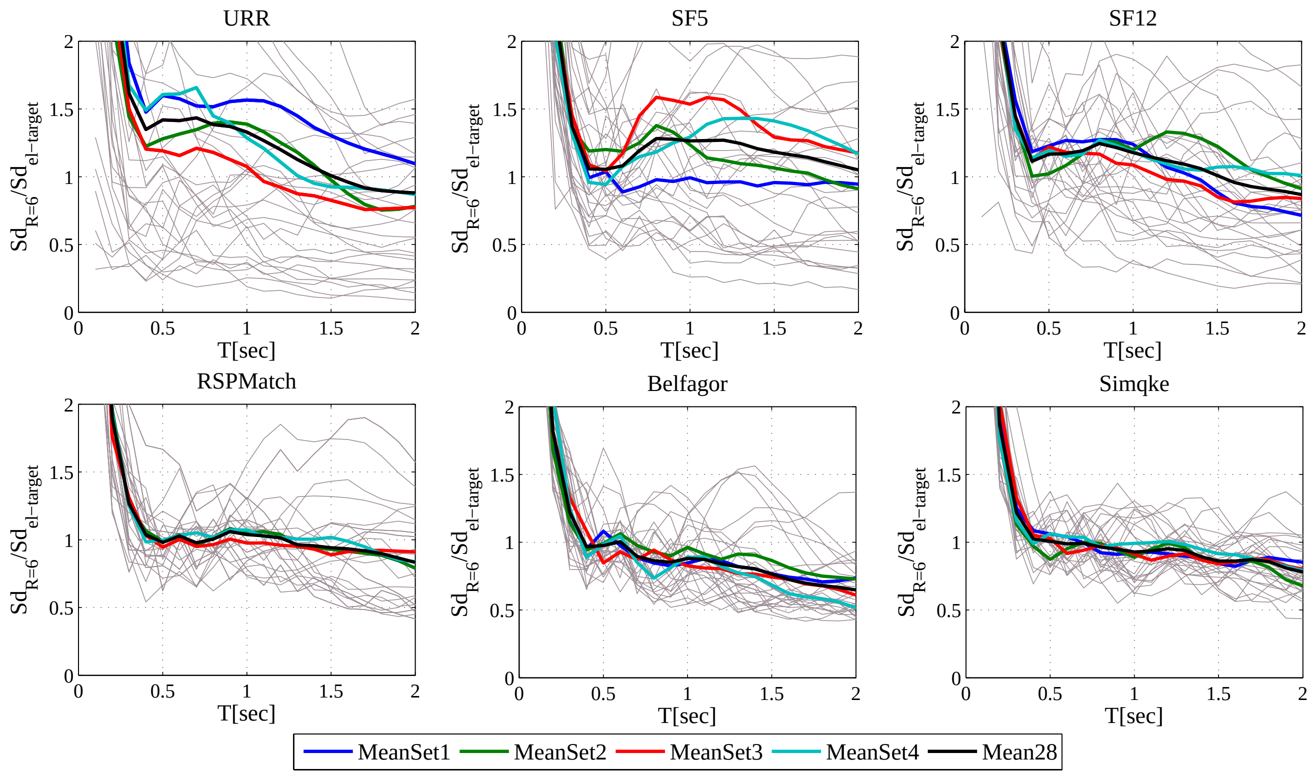

Figure A1. R = 6 ratio with target elastic spectrum evaluated for each category per set.

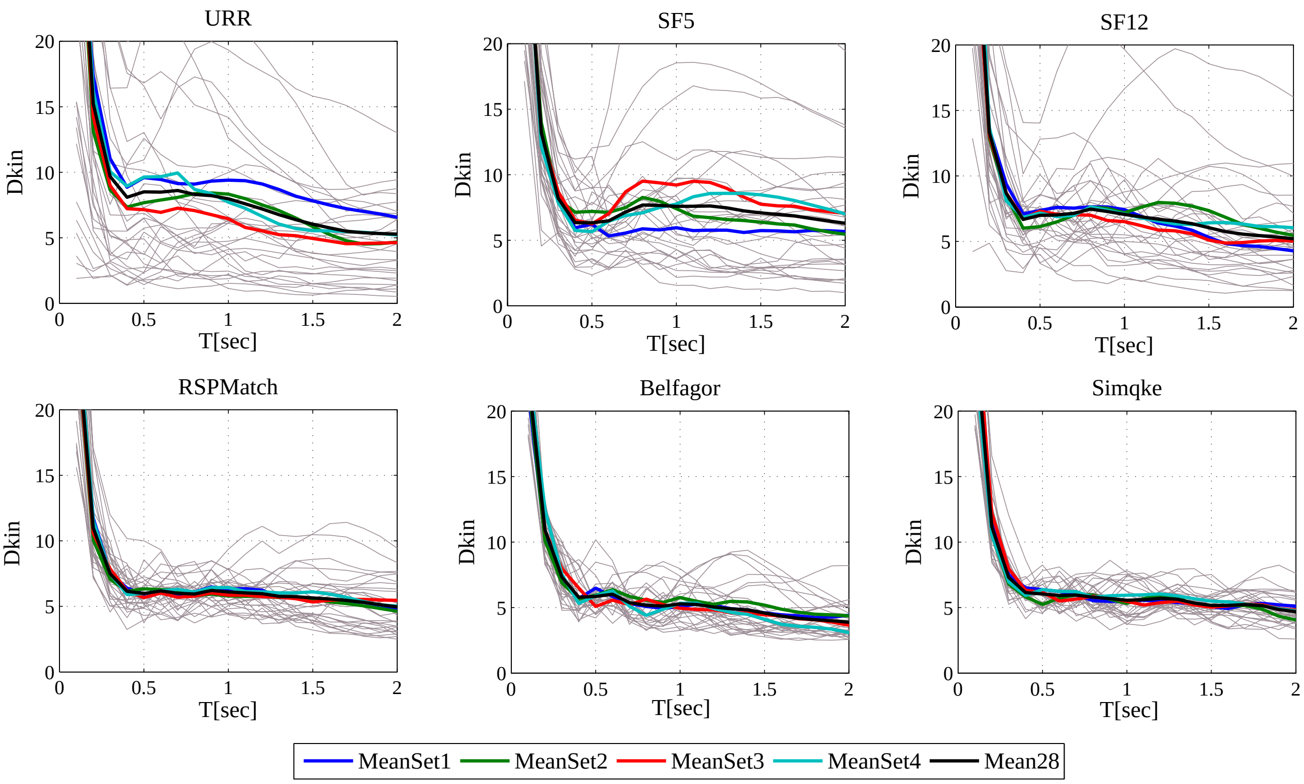

Figure A2. R = 6 ductility demand per sets

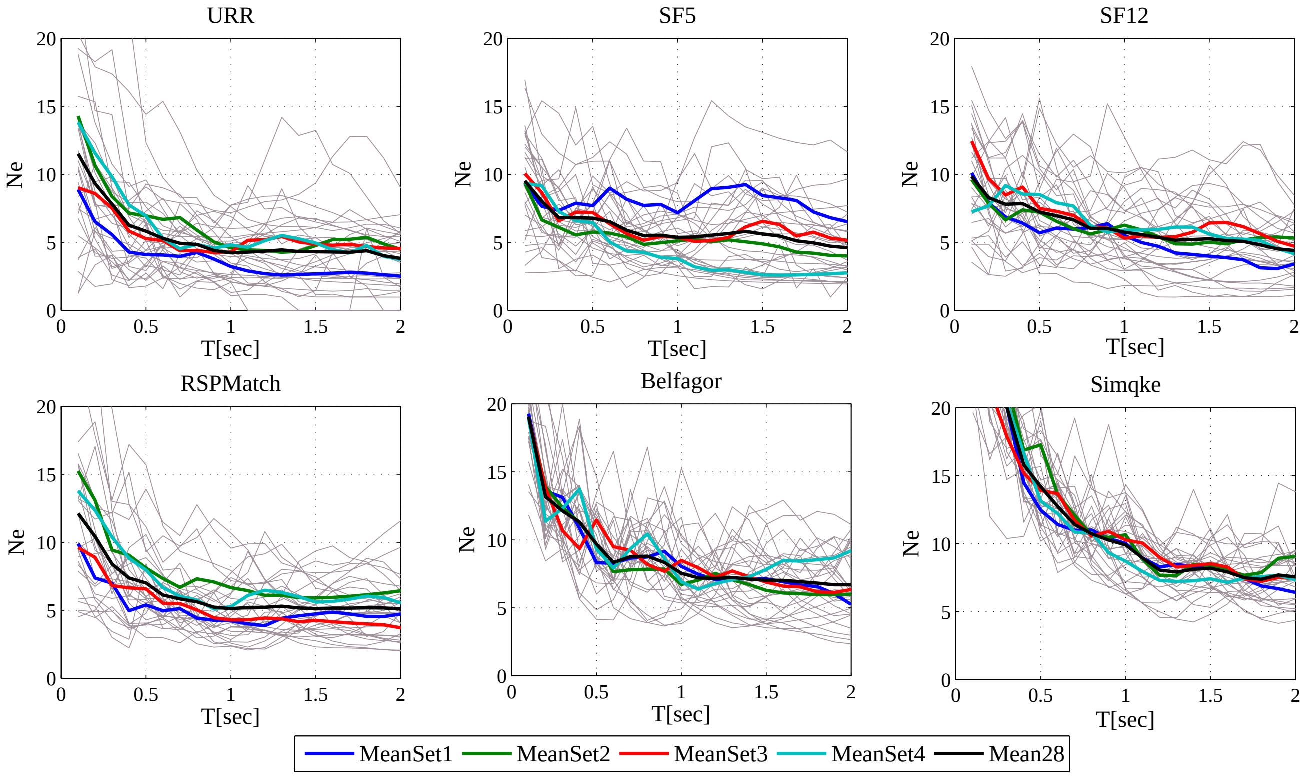

Figure A3. R = 6 equivalent number of cycles per sets.

REFERENCES

Abrahamson N.A., 1992. Non-stationary spectral matching. *Seismological research letters*. **63**(1), 30

Bazzurro P., Luco N. 2004. Post-elatic response of structures to synthetic ground motions. Report for Pacific Earthquake Engineering Research (PEER) Center Lifelines Program Project 1G00 Addenda. CA, US

Bommer J.J,Acevedo A.B., 2004. The use of real earthquake accelerograms as input to dynamic analysis. *Journal of Earthquake Engineering*. **8**(Special Issue I), 43-91.

Convertito V.,Iervolino I., Herrero A., 2009. Design earthquakes' map: an additional tool for engineering seismic risk analysis. Application to southern Apennines (Italy). XIII Convegno Anidis . **June 28-July 2, Bologna, I**.

Cosenza E., Manfredi G., Ramasco R. 1993. The Use of Damage Functionals in Earthquake-Resistant Design: a Comparison Among Different Procedures. Earthquake Engineering and Structural Dynamics, 22(10), 855-868.

CS.LL.PP.; 2009: Istruzioni per l'applicazione delle norme tecniche delle costruzioni. Gazzetta Ufficiale della Repubblica Italiana, 47.

CS.LL.PP; DM 14 Gennaio 2008: Norme tecniche per le costruzioni. Gazzetta Ufficiale della Repubblica Italiana, 29.

Hancock, J., Watson-Lamprey, J., Abrahamson, N.A., Bommer, J.J., Markatis, A., McCoy, E., Mendis, E., 2006. An improved method of matching response spectra of recorded earthquake ground motion using wavelets. *Journal of Earthquake Engineering*. **10**(Special Issue I), 67-89.

Gasparini D.A., Vanmarke E.H., 1976. Simulated earthquake motions compatible with prescribed response spectra. MIT civil engineering research report R76-4. Massachusetts Institute of Technology, Cambridge, MA.

Iervolino I., Cornell C.A., 2005 Record selection for nonlinear seismic analysis of structures. *Earthquake Spectra*, **21**(3), 685-713.

Iervolino I., Manfredi G., Cosenza E., 2006. Ground motion duration effects on nonlinear seismic response. *Earthquake Engineering and Structural Dynamics*, **30**, 485–499.

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.

Iervolino I., Galasso C., Cosenza E.,2009a. REXEL 2.31 (beta) e la selezione normativa dell'input sismico per l'analisi dinamica non lineare delle strutture. XIII Convegno Anidis. **June 28-July 2, Bologna, I**.

Iervolino I., Galasso C.,Manfredi G., 2009b. Analisi di pericolosità sismica vettoriale per parametri di picco e integrali del moto sismico. XIII Convegno Anidis. **June 28-July 2, Bologna, I**.

Manfredi G., 2001. Evaluation of seismic energy demand. Earthquake Engineering and Structural Dynamics, 35, 21–38.

Mucciarelli M., Spinelli A., Pacor F., 2004. XI Convegno Anidis. **January 25-29, Genova, I**.

Pinto P.E., Giannini R., Franchin P., 2004. Seismic reliability analysis of structures. IUSS Press Pavia.

Sabetta, F., Pugliese, A., 1996. Estimation of response spectra and simulation of nonstationary earthquake ground motions. *Bulletin of the Seismological Society of America*, **86**(2), 337-52.

Schwab P., Lestuzzi P., 2007. Assessment of the seismic non-linear behaviour of ductile wall structures due to synthetic earthquakes. *Bullettin of Earthquake Engineering,* **5**, 67-84.