Compared seismic response of degrading systems to artificial and real records

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ABSTRACT:
In the paper different procedures to obtain sets of spectral matching records for nonlinear dynamic analysis of structures are compared in terms of nonlinear seismic response. Six classes of records were considered: unscaled real records, real moderately linearly scaled, real significantly linearly scaled, real adjusted by wavelets, artificial generated by means of two different procedures. The study is spectral shape-based, which means that all the record set match in some sense the same target spectral shape. In a previous study the authors considered elastic-plastic with hardening single degree of freedom systems; herein two other backbones and hysteretic loops were employed. In general, it is found that artificial or adjusted records may underestimate 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 seem to not display significant differences. Finally the two groups of linearly scaled records seem to show no systematic bias for both types of response considered.

Keywords: Spectral matching, real records, scaling factor, artificial accelerograms, RSPMatch2005

1. INTRODUCTION

Seismic assessment of structures via nonlinear dynamic analysis requires proper seismic input selection. Seismic codes suggest different procedures to select ground motions, most of those assuming spectral compatibility to the elastic design spectrum as the main criterion (Iervolino et al. 2008). On the other hand, practitioners have several options to get input signals for their analyses; 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 earthquake 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 fits properly code requirements in terms 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 motion, 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 fast generation of artificial records, via *random vibration* procedures, perfectly compatible with an assigned design spectrum, has become very popular for both practice and research purposes. More recently, algorithms to get the spectral compatibility of real records by wavelets adjustment were proposed (Hancock et al. 2006).
This work tries to address the spectral matching issue from the structural point of view in terms of

nonlinear peak and cyclic responses, having as reference a code-based design spectrum. Six classes of 28 accelerograms, each of those comprised of four sets were 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), more details about selection procedure can be found in a more comprehensive work of the authors (Iervolino et al. 2010a).
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. Single degree of freedom (SDOF) systems with both degrading hysteretic loops and softening backbones were considered with strength reduction factor (R) equal to four. As structural response measures or engineering demand parameters (EDPs), ductility normalized with respect to R and equivalent number of cycles were considered to relate the structural response to both peak and energy content of ground motion (Iervolino et al. 2006). Analyses aimed at comparing the differences, if any, associated to each typology of records in the two EDPs with respect to the unscaled real ground motions which are considered as a benchmark.
With the same classes of records the elastic perfectly plastic with hardening SDOF (EPH) was considered in a previous study (Iervolino et al 2009a), to which the conclusion found herein are compared.

2. RECORDS

As reference a target spectrum built according to the new Italian seismic code for a case-study site (Avellino, southern Italy) having as geographical coordinates: lat. 40.914, long. 14.78, was considered. 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 class of records described above, four spectrum compatible sets of seven[1] records were selected (if real) or generated (if artificial). In the following the selection or generation of the sets are briefly reviewed, details may be found in Iervolino et al. (2010a).

2.1. URR, Unscaled real records

The sets of unscaled real records were selected using REXEL, freely available at http://www.reluis.it/, a software which allows to select combinations of multi-component real ground motion records, contained in the European Strong-Motion Data Base (ESD – http://www.isesd.hi.is/) and in the Italian Accelerometric Archive (ITACA – http://itaca.mi.ingv.it/ItacaNet/), which on average match an arbitrary elastic spectrum (Iervolino et al., 2010b). Providing to the software the geographical coordinates of the site and the limit state of interest, it was possible to select four sets of records. In Fig. 2.1a the four sets are represented. All the averages of the sets approximate very well the design spectral shape.

2.2. SF, Scaled real records

Also linearly scaled (amplitude scaling) records were selected with REXEL. In particular two classes of four scaled records sets each, differing for the average scaling factor (SF), were selected: (1) SF = 5; (2) and SF = 12. The intent is to compare the responses to records moderately and significantly scaled. The range of periods considered is the same as per URR.

[1] Assuming sets of seven records acknowledges the Italian and Eurocode 8 (CEN 2003) prescriptions allowing considering the mean structural response from nonlinear dynamic analyses if at least seven records are employed.

2.2.1. SF5

Four sets of seven compatible accelerograms, each of those has a mean SF equal to 5, were selected, Fig. 2.1b. Note that the variability of the scaled sets is smaller than those unscaled, as expected (Iervolino et al., 2008 and 2009b).

2.2.2. SF12

Using REXEL, three sets of seven records whose average SF was 12, were also 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 average scaling factor was similar to the other three sets selected with the software, see Fig. 2.1c.

2.3. RSPMatch, Wavelet adjusted records

RSPMatch2005 software (Abrahamson, 1992; Hancock *et al.*, 2006) was used to modify the URR sets; in this case the adjustment procedure was simply aimed at reducing the mismatch of individual records with respect to the target. The procedure was pursued in the range of period [0.15s-2.0s] in which records were already compatible on average and without the application of any scaling factor, Fig. 2.1d.

2.4. Artificial Records

Generally speaking, generation procedures for artificial accelerograms are based on the random vibration theory (Pinto et al., 2004). The two computer programs 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) generates stationary signals that are subsequently enveloped in a trapezoidal shape.

2.4.1. Belfagor records

Belfagor generates non stationary signals by using variable Fourier amplitudes empirically evaluated. Using Belfagor 28 accelerograms were generated. They all have the same duration, 21.48 seconds and a sampling time step of 0.005 seconds. Records were arranged in four sets of seven records, Fig. 2.1e.

2.4.2. Simqke records

A second class of four sets of artificial records was generated by Simqke. This well-known software generates groups of stationary artificial records in a way they fit the target spectrum. In this case 28 records were generated together and then they were split in four groups of seven, Fig. 2.1f.

2.5. Integral Parameters

Each accelerogram of the six classes was also processed to evaluate characteristic (integral) parameters other than the spectral shape. Arias intensity (I_A), and the Cosenza and Manfredi index (I_D), (Cosenza et al. 1993), Eqn. 2.1, computed as the mean of the sample of 28 records for each class, are reported in Table 2.1. I_D is defined as a factor times the I_A divided by the peak ground acceleration (PGA) times the peak ground velocity (PGV), (Iervolino et al. 2006).

$$I_D = (2 \cdot g/\pi) \cdot I_A / (PGA \cdot PGV) \tag{2.1}$$

It is possible to see that real records, both scaled and unscaled, have close mean values of I_D as well as RSPMatch records. Both classes of artificial records display higher values of I_D. Simqke records show comparatively high values of I_A and I_D. Belfagor records compare better to real records at least in terms of I_A.

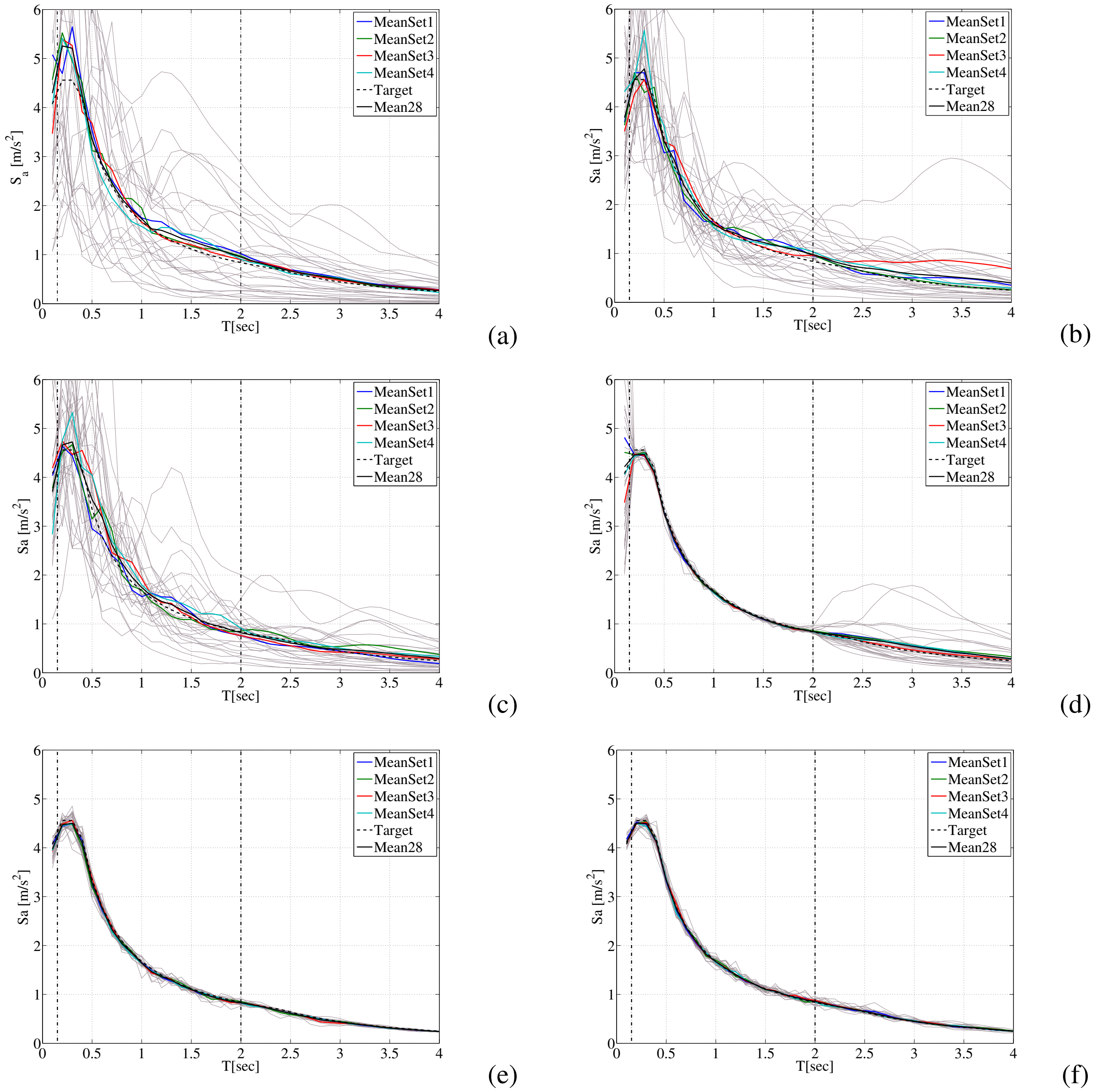

Figure 2.1. URR (a), SF5 (b), SF12 (c), RSPMatch (d), Belfagor (e), Simqke (f) acceleration response spectra.

Table 2.1. Average values of I_A and I_D for the considered classes of records

	URR	SF5	SF12	RSPMatch	Belfagor	Simqke
I_A [m/s]	0.61	0.40	0.43	0.44	0.57	1.1
I_D	8.72	7.96	8.89	9.55	13.72	23.47

3. ANALYSES AND STRUCTURAL RESPONSE MEASURES

All records selected for each class were used as an input for nonlinear dynamic analyses applied to inelastic SDOFs, whose periods (T) vary linearly from 0.1 to 2 seconds. Inelastic SDOFs are characterized by two different backbones and hysteretic loops: the first group of SDOFs (EPP) is characterized by an elastic perfectly plastic backbone and cyclic degrading (Clough and Johnston 1966), the second group (ESD) is characterized by a softening backbone and Takeda hysteretic loop (Takeda et al 1970), as shown in Fig. 3.1.

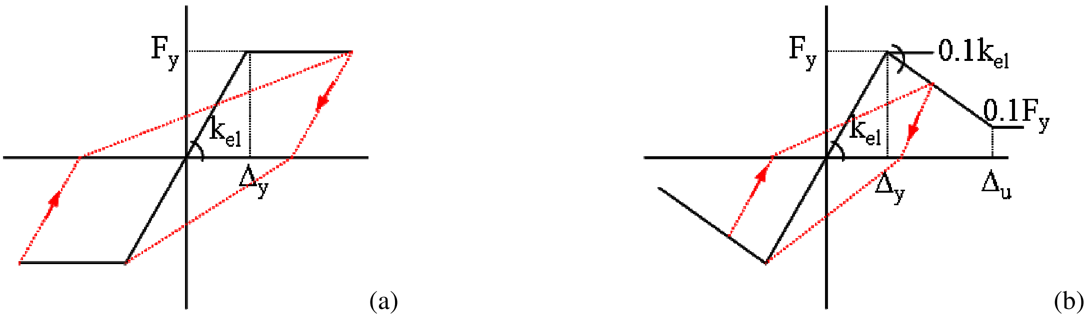

Figure 3.1. SDOF backbone curves: EPP (a) and ESD (b).

It is to recall that the peak elastic deformation experienced by an elastic structure is a ground-motion specific quantity. Therefore, one can achieve the same value of the strength reduction factor (R), either for each record in a dataset (*constant R* approach) or on an average sense for all the records, that is, relating the R factor to the target spectrum matched (*constant strength approach*) as in Eqn. 3.1, where $Sa_{e,t}$ is the elastic acceleration ordinate in the target code spectrum at the period of the SDOF and *m* is its mass. The latter approach was considered herein, to simulate the effect of different sets of accelerograms on the same structure; in particular R was chosen equal to four.

$$F_y = Sa_{e,t}(T) \cdot m/R \tag{3.1}$$

EDPs chosen were selected to investigate both peak and cyclic seismic response. Displacement-based parameters is the kinematic ductility (D_{kin}), Eqn. 3.2, evaluated as the ratio of the peak inelastic displacement ($Sd_{R=i}$) and the yielding displacement (Δ_y), and then normalized with respect to R. Cyclic response related parameter is equivalent number of cycles (N_e) was also considered (Manfredi 2001). It includes the hysteretic energy (E_H) normalized with respect to the largest cycle ($A_{plastic}$), decoupling ductility demand (already considered above) and cyclic demand, Eqn. 3.3.

$$D_{kin} = Sd_{R=i}/\Delta_y \tag{3.2}$$

$$N_e = E_H/A_{plastic} \tag{3.3}$$

4. RESULTS

Elastic displacement spectra, evaluated as mean value on 28 records for each class, are first compared to the target spectrum transformed from pseudo-acceleration, Fig. 4.1a.
Fig. 4.1b reports the ratio of the average spectrum of the class and the code spectrum, that is, the deviation of each class (Sd_{el}) with respect to the target spectrum ($Sd_{el\text{-}target}$), as it may help to understand the nonlinear results presented in the following. Although all classes are spectrum matching, real records spectra show the largest deviation with respect to the target. This is because real records match the target on average, while for the other three classes (adjusted and artificial records) each single records matches closely the target (see Fig. 2.1).

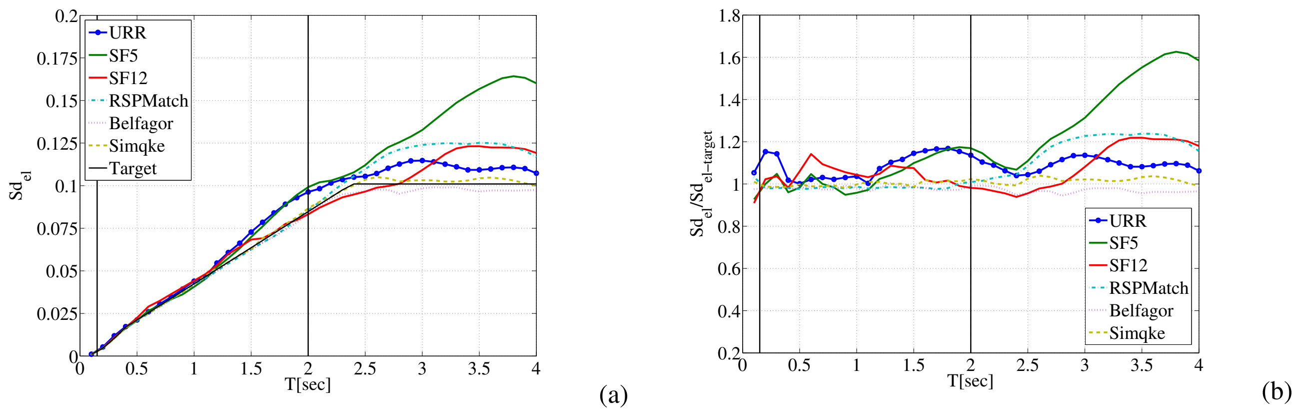

Figure 4.1. Average values of elastic displacement (a) and ratio to the target spectrum for the record classes (b).

4.1. Peak response

Fig. 4.2 shows ductility normalized with respect to R for both the EPP systems and ESD systems. In both cases artificial records seem to show some underestimation of ductility demand with respect to URR, at least looking at the ESD results. In the moderate frequencies range, also RSPMatch records seem to underestimate the URR response. However, such underestimations, for EPP and ESD, were found to be always statistically non-significant, also at R levels higher than 4 not shown herein (Iervolino et al. 2010a). These results confirm the trend found for the EPH peak response (Iervolino et al., 2009a and 2010a).

Belfagor and Simqke records show comparable peak responses. Real scaled records, both SF5 and SF12, do not show any bias with respect to URR.

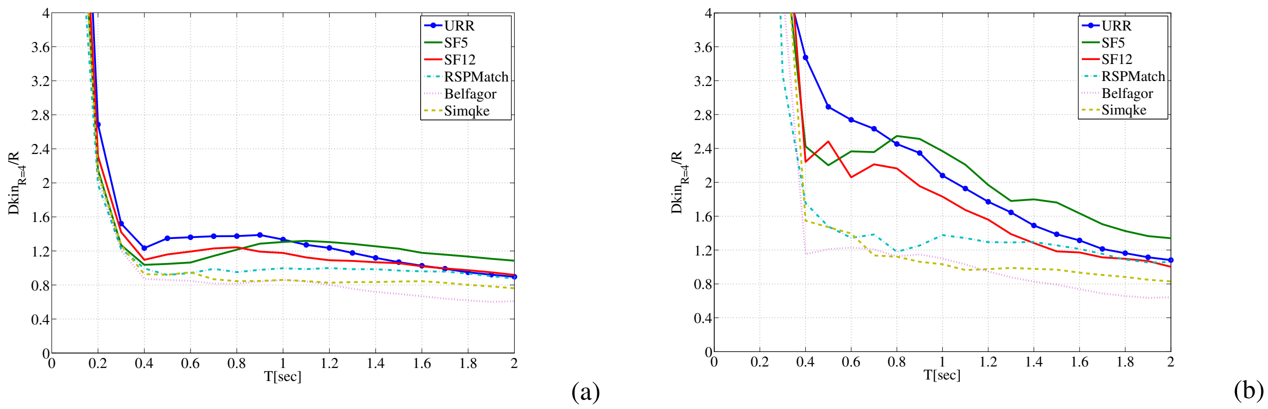

Figure 4.2. Average values of Dkin/R for EPP (a) and ESD (b) systems computed as mean value of 28 records.

4.2. Cyclic response

Fig. 4.3 shows the values of Ne for both the EPP and ESD systems. An overestimation in terms of cyclic response may be observed for both classes of artificial records. Simqke records show the largest overestimation. Belfagor results show that a generation procedure based on non-stationary characteristics of the earthquake gives more acceptable results in terms of cyclic response.

SF5 and SF12 records have, again, a non systematic trend with respect to URR, confirming that scaling procedure does not introduce any bias even if the scaling factor is large. RSPMatch records give results close to URR indicating that the wavelet adjustment seems to not affect the cyclic response. It is to note that cyclic response overestimation of artificial records is found to be statistically significant in both EPP and ESD SODFs, at several R levels, confirming the same trend found for EPH SDOFs (see Iervolino et al., 2010a).

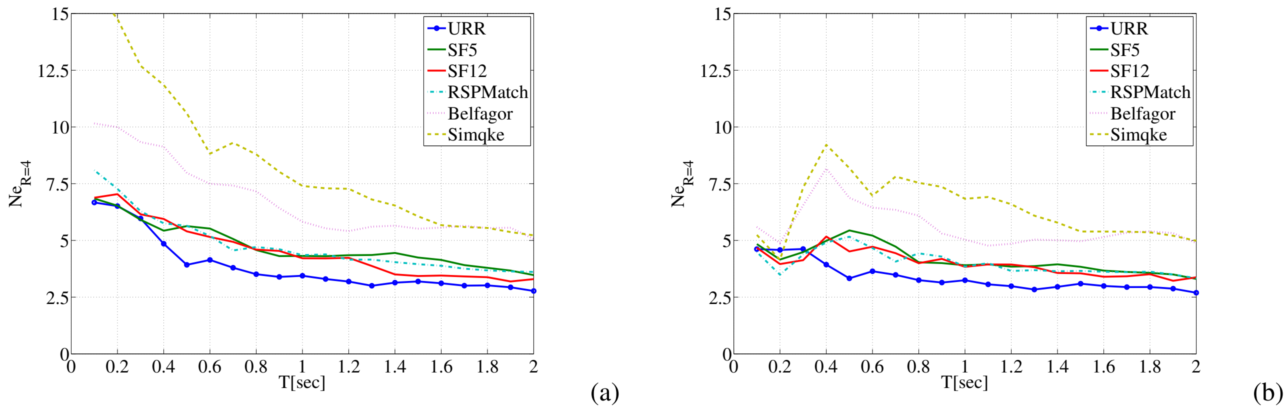

Figure 4.3. Average values of N_e for EPP (a) and ESD (b) systems computed as mean value of 28 records.

Cyclic response overestimation of artificial records was a predictable result; in fact, artificial records are characterized by higher values of integral parameters, especially I_D. Fig. 4.4 shows, as an example, the I_D versus N_e plot of each record for T equal to 0.6s, for both EPP systems and ESD systems; in both cases it is possible to note a fairly significant correlation between the two parameters. On the other hand correlation is more evident in the EPP systems with respect to the ESD systems.

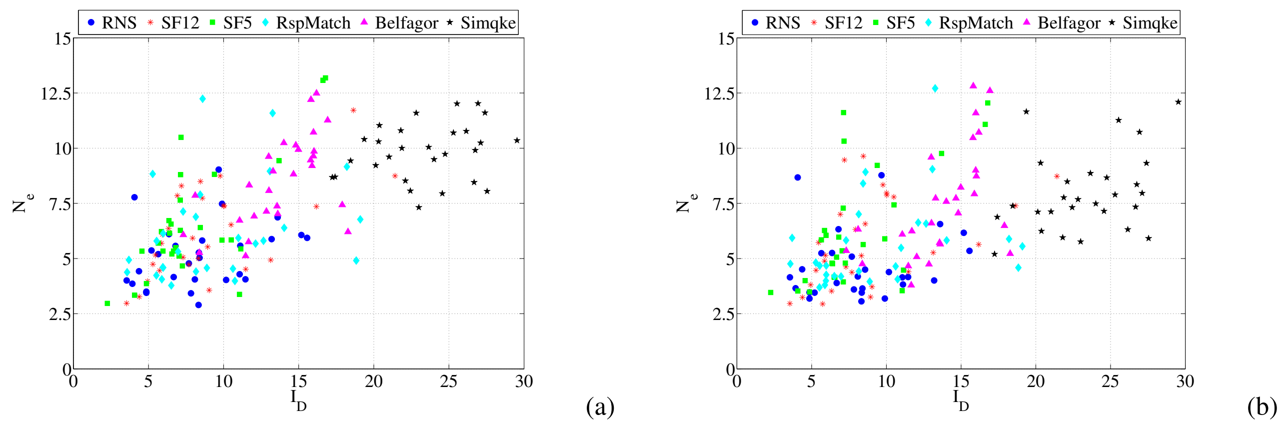

Figure 4.4. N_e versus I_D for R = 4 and T = 0.6s evaluated for system EPP (a) and ESD (b) for each record.

5. CONCLUSIONS

In this work different ways to achieve spectral matching record sets were compared in terms of both peak and cyclic of inelastic seismic response of SDOFs.

Six typologies of records were considered: real unscaled, real with limited average scaling factor, real with large average scaling factor, real adjusted with wavelets, and two different types of artificial records. The benchmarks were 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, in some cases and in a non significant way, underestimate peak displacement-related demand. 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. These conclusions could have been predicted taking into account integral parameters of ground motion, such as I_A and I_D. All the trends for the linearly scaled records seem to be non-systematic suggesting that scaling does not bias the response if the spectral shape is a control factor.

Results found herein confirm general trends found for other SDOFs analyzed in a previous study by the authors.

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