ON GROUND MOTION DURATION AND ENGINEERING DEMAND PARAMETERS

Edoardo COSENZA[1], Iunio IERVOLINO[1] and Gaetano MANFREDI[1]

ABSTRACT

Impact of records features in nonlinear demand assessment is a controversial issue in earthquake engineering. What Engineering Demand Parameter (EDP) is best correlated with ground motion duration related measures has not been thoroughly addressed yet. The study presented in this paper approaches the problem investigating whether duration matters by statistical analyses of significant study cases. Twenty four SDOF structures have been designed for the purpose, considering several oscillation periods, backbones and ductility levels. Six different EDP's, ranging from kinematics ductility to equivalent number of cycles, have been considered.

Nonlinear analyses deal with ordinary records, therefore soil site and specific near fault effects, such as directivity-induces pulses, are avoided during selection. One class of accelerograms is chosen to represent three specific duration scenarios, and another class is randomly selected from a large catalogue. Responses to different records sets are evaluated in each of the study cases.

Time-history median results are formally compared by statistical hypothesis test to asses the difference, if any, between non linear demands of the sets of records. Incremental Dynamic Analysis (IDA) curves are used to qualitatively assess duration effects as function ground motion Intensity Measure (IM), while quantitative impact of duration on EDP's is assessed by means of fragility curves.

Keywords: Duration; Energy; Engineering Demand Parameter; Incremental Dynamic Analysis; Hypothesis test; Fragility curves.

1 INTRODUCTION

1.1 Motivation and framework

Duration issues in earthquake engineering deal both with capacity and demand. Definition of duration related capacity measures is a non-trivial issue, while it is not clear what EDP is affected by duration (CSMIP, 1993). The latter is approached in this study; aim is showing from a general prospective whether duration matters in nonlinear seismic demand analysis.

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Goal is pursued by investigating significant cases; SDOF periods are chosen to be representative of each of the four elastic design spectrum branches. Yielding strength is set to get two different ductility levels, comparatively "high" and "low". Evolutionary and non-evolutionary backbones are considered to simulate very different structural behaviors.

Real records sets have been chosen to be representative of three selected duration scenarios; other randomly selected accelerograms have been made available to perform statistical comparisons. Running nonlinear analyses of the SDOF structures, under the designed sets, allows monitoring six different demand measures expected to be differently sensitive to the duration content of ground motion. To establish if duration is an issue among different EDP's of the same structure, hypothesis test response are used; to investigate more deeply how it plays a role in demand analysis trend, and how quantitatively it affects differently structural response among different SDOF, IDA analyses and fragility curves are developed.

This complex experiments space may be helpful in clarifying that "it depends" whether duration matters in nonlinear seismic analysis. Importance of duration changes strongly as function of the chosen EDP while the general conclusion holds with the same EDP across all structural configurations.

1.2 Duration measures used in this study

Total duration of ground motion is a not unique definition quantity, while empirical observations show how it is an important ground motion feature affecting the structural response.

In this study, structural damage evaluation is related to number and amplitude of plastic cycles induced by seismic excitation. I_D factor, introduced by Cosenza and Manfredi (1997) is a good predictor for computation of plastic cycles demand (Cosenza and Manfredi, 2000; Manfredi, 2001) and then it's used in the present study as the duration related index for records. It's defined as in (1) being related to the energy content of ground motion but also with energy dissipated by structural response.

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

In Eq. 1 a(t) is the acceleration time-history of the ground motion, PGA and PGV are the peak ground acceleration and velocity respectively and t_E is the effective duration of the seismic event. Other definitions of duration indexes are available in literature, as said, hence, the problem is the definition of the earthquake duration in relation with the main energy contents (Cosenza and Manfredi 2000). With regard to this aspect, Trifunac and Brady have defined the effective duration t_D as the time elapsed between the 5% and the 95 % of the root mean square acceleration RMSA; Kawashima and Aizawa (1989) have introduced the bracketed duration t_B as elapsed time between the first and last acceleration excursion greater than a percentage of PGA. Trifunac and Novikova have proposed a more refined determination of t_D as the sum of the record intervals with a total amount of RMSA greater than the 90 per cent. In the following comparison of I_D with other duration measures is reported for the records herein used.

2 METHODOLOGY

2.1 Study Cases

Study cases are made of four SDOF periods with three different backbones, each of those designed to have two target ductility levels. Demand on the twenty four SDOF structures defined in such way is investigated in terms of six EDP's. Influence of I_D is assessed by hypothesis test (Iervolino and Cornell, 2004); by statistical comparison of demand coming from different sets characterized by different I_D.

Trend of demand as function of intensity measure (IM) (e.g. spectral acceleration, Sa) (Fig. 1) is assessed by Incremental Dynamic Analysis (Vamvakistos and Cornell, 2002) since I_D insensitive to amplitude scaling of records. All records in the sets are individually scaled to get the desired spectral acceleration level for all the EDP's then the median of results is plotted versus spectral acceleration. If results for sets with different I_D are kept separated the three resulting curves provide a qualitative picture of differences in EDP's of I_D.

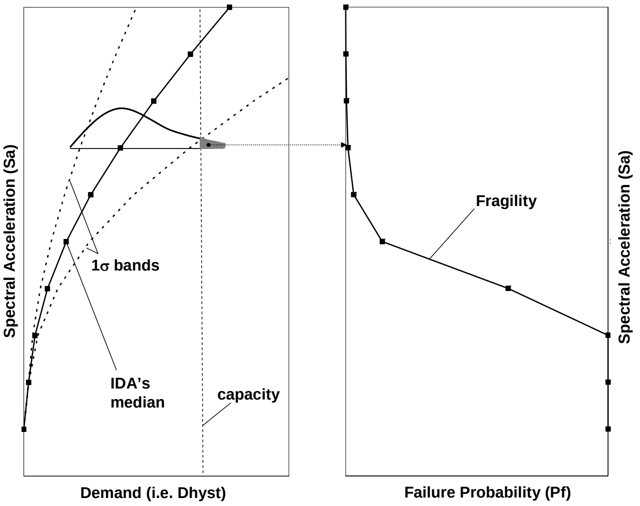
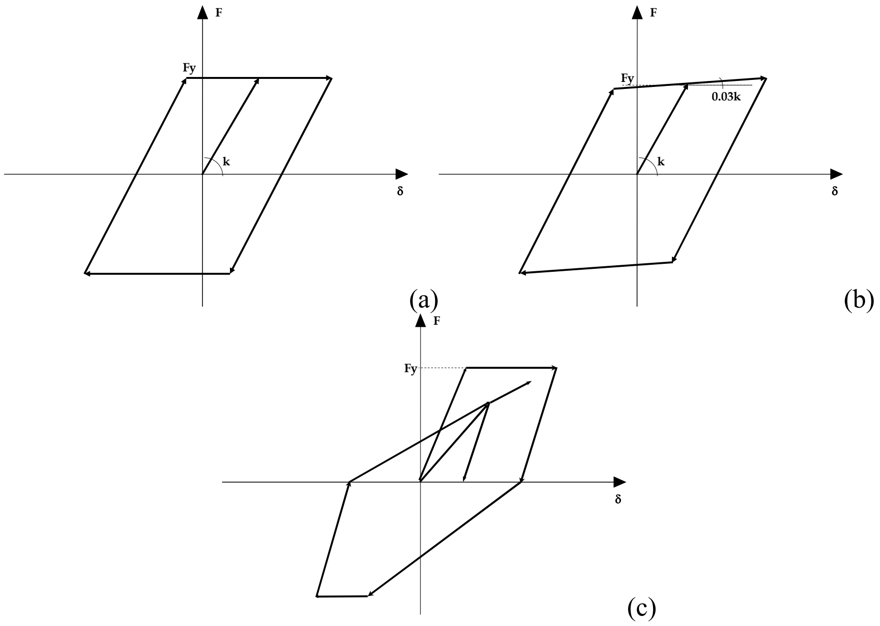


Figure 1. IDA's based fragility example (T = 0.6 s - Elastic Perf. Plastic SDOF).

Assuming lognormal distribution of the results of different records around median of IDA curve (Fig. 1) and fixing a threshold representative of the structural capacity, is possible to build up fragility curves for each set, those are representative of the I_D value specific for the set they refer to.

2.1.1 SDOF periods and backbones

Four different periods SDOF systems have been considered, *short* (0.1 sec), *moderate* (0.6 s), *long* (1.5 sec) and *very long* (4 sec) in order to investigate if conclusions come to at moderate periods seem to hold at extremes. Chosen periods are representative of different branches of the Eurocode design elastic spectrum. For each of the periods two yield strengths are selected dividing the elastic strength by a factor of 3 (DL3) and 6 (DL6) according to the design spectrum; damping is 5% of critical. Backbones investigated are: elastic perfectly plastic (EP) first as example case and elastic-plastic with hardening (EPH) which avoid possible instability of the first one (Fig. 2). Plus, a stiffness degrading model is considered such as modified Clough (MC) (Mahin and Bertero, 1981).



(a) (b) (c)

Figure 2. Backbones Investigated: EPP (a); EPH (b); MC (c).

EPP model is a non evolutionary model as EPH; they're representative of peculiar structural situation such as welded connections steel frames without instability problems. EPP model is not evolutionary or degrading. Modified Clough model is evolutionary in terms of elastic stiffness; it has been added to the analyses to cover a larger range of structural cases keeping it simple: still clearly separating elastic phase to inelastic phase.

2.1.2 Engineering Demand Parameters

Different demand measures are differently sensitive to earthquake duration, assess whether duration matters for EDP's is the main goal of the study. Has been shown poor correlation of duration indexes with displacement demand, while is of certain interest to see what happens changing the collapse criterion. Demand measures considered are: kinematics ductility (Dkin); cyclic ductility (Dcyc); plastic fatigue (Fp, b = 1.8); plastic fatigue (Fp, b = 1.5); hysteretic ductility (Dhist). Equivalent number of cycles (Ne) has also been considered since it's well correlated with the energy measure adopted in this study. Details about EDP definitions herein used may be found in Krawinkler and Nassar (1992), Cosenza et al. (1993), Fajfar and Vidic (1994) and Cosenza and Manfredi (2000). Fig. 3 summarize study cases, each dot is a particular designed SDOF structure. All SDOF's in Fig. 3 are investigated in terms of all six EDP's listed above.

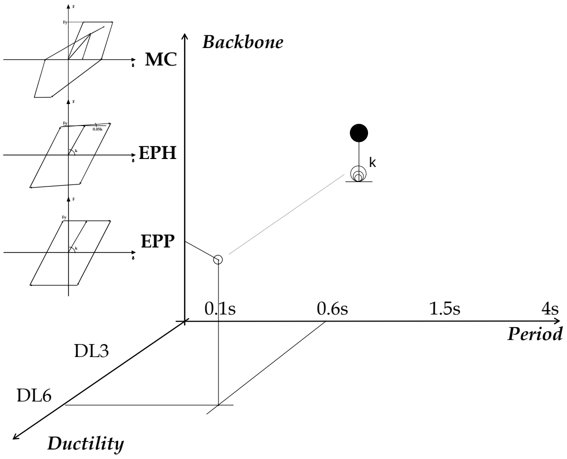


Figure 3. SDOF's analysis space.

2.2 Accelerograms

All the records herein considered came from the Pacific Earthquake Engineering Research Center (PEER) database, so that we may assume they all are processed the same. However all the accelerograms in both of the groups of sets have been selected with some boundary conditions in order to better reduce the influence of those factor that are not in the objective of the study. In particular only records from C-D NEHRP soil classes and coming from free field or one story building instrument housing have been considered. These features make the records definable as ordinary, avoiding site and housing response effects. Moreover, for addressing the selection issue the records belong to the far field so that come from stations at over 25 km in distance in order to better avoid directivity pulse-type effects.

2.2.1 Class of target sets

Similarly to what presented in Iervolino and Cornell (2004) the target sets for the record selection study are designed to be representative of specific scenarios; i.e. duration. Three sets of 20 records each have been set up to be I_D specific in the median (I_D = 5, I_D = 13, I_D = 20). Scatter around the median values are due to unavailability of enough records with required features in the database, this scatter will affect results especially in I_D = 20 sets where it is stronger.

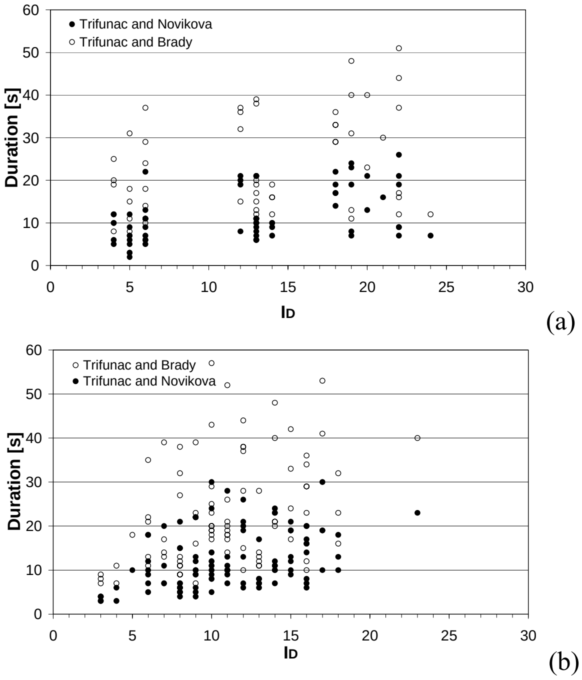


Figure 4. I_D vs. duration in the T (target sets) (a) and A (arbitrary sets) (b).

Duration characteristics of target sets are shown in Figure 4(a) where I_D is represented versus other duration definitions (Trifunac and Brady, 1975; Trifunac and Novikova, 1994). In order to best represent what might occur in the future and to reduce correlation due to event commonality, it is desirable to have the records in each set coming from different events. This requirement conflicts with the desire to have a large sample. Target sets have been split in two of size ten which is the order of magnitude used in recommended earthquake engineering practice, but also to formally compare different sets with the same I_D. The size ten sets are named: T5a, T5b, T13a, T13b, T20a and T20b can be easily retrieved in the PEER on-line database.

2.2.2 Class of arbitrary sets

While part of the analysis is comparing sets with different specific I_D, has been considered useful to compare target set to sets randomly selected records which are not subjected to catalog limits and may give another proof if duration is an issue or not. These sets were chosen effectively randomly (in terms of I_D) from the catalog. The *arbitrary sets* are ten sets of ten records each. The records in each set are chosen randomly (without replacement) first from the list of events and then from the available distances within a certain event to the degree possible. Features of arbitrary sets are shown in Figure 4(b).The record samples used in this study have been found having correlation of about 40-45% between I_D and other duration measures.

3 RESULTS AND DISCUSSION

Selected result are presented in the following; for sake of brevity only analyses regarding one SDOF can be shown and only target-sets results can be reported; discussion of other study cases may be found elsewhere (Iervolino et al., 2004). The SDOF T = 0.6 s with the elastic-perfectly-plastic backbone has been chosen to be discussed since this period may be of special interest for earthquake engineering applications, while the EPP backbone is one of the most commonly used in this kind of study. However, is remarkable that conclusions hold similarly for all others SDOF and backbones study cases and for arbitrary class of sets, which can’t be published here since they would require considerably longer discussion.

3.1 Hypothesis Tests

Testing the hypothesis that duration “doesn’t matter” for EDP means that responses from different sets, characterized by different I_D, should give virtually the same results. This statistical equivalence for each structural case can be assessed by statistically testing the ratio of the estimated medians (i.e. geometric mean) of the results of nonlinear analyses. In the following relations the ratio of the estimated median responses of two generic set (x, y) is defined as z in (1) while the estimation of the standard error can be evaluated β.

$$z = \frac{\bar{\theta}_x}{\bar{\theta}_y}; \beta_z = \sqrt{\frac{\sigma^2{}_x}{n_1} + \frac{\sigma^2{}_y}{n_2}} \tag{2}$$

In (2) n_1 and n_2 are the sample sizes of the compared sets; σ_x and σ_y are the standard deviations of the natural logarithms of the two compared sets. Under the assumption that the responses are lognormal: the natural log of the responses ratio (z) divided by β is distributed as a student-T with 18 degrees of freedom. The Null Hypothesis of the test is

H_o: responses of different sets are virtually the same

To the proof of this hypothesis we can associate a statistical significance level, which corresponds to the risk of rejecting H_o when it is, in fact, correct.

Following tables show absolute values of $\ln(z)/\beta$ for T = 0.6 s SDOF with EPP backbone. The greater is this number the larges is the discrepancy between the responses in terms of standard error. In bold-italic are highlighted those results leading to rejection of the null hypothesis at 1.5 sigma confidence level. The matrices sub-diagonal show the comparison of different target-sets with the same median I_D; by definitions this results should be clean of rejections of null hypothesis since two sets with the same I_D are built to be statistically equivalent.

Tables 1. Hypothesis test results T = 0.6 s – EPP SDOF.

Dkin	**5a**	**5b**	**13a**	**13b**	**20a**	**20b**
5a	0.00	-	-	-	-	-
5b	0.19	0.00	-	-	-	-
13a	***2.37***	***2.07***	0.00	-	-	-
13b	0.42	0.58	***2.72***	0.00	-	-
20a	0.70	0.50	1.44	1.05	0.00	-
20b	0.49	0.28	***1.80***	0.88	0.24	0.00

Dcyc	**5a**	**5b**	**13a**	**13b**	**20a**	**20b**
5a	0.00	-	-	-	-	-
5b	0.12	0.00	-	-	-	-
13a	0.12	0.21	0.00	-	-	-
13b	***1.61***	***1.52***	1.14	0.00	-	-
20a	0.93	0.94	0.63	0.56	0.00	-
20b	0.74	0.76	0.45	0.90	0.27	0.00

Fp b=1.8	**5a**	**5b**	**13a**	**13b**	**20a**	**20b**
5a	0.00	-	-	-	-	-
5b	0.07	0.00	-	-	-	-
13a	1.25	1.07	0.00	-	-	-
13b	0.05	0.03	1.16	0.00	-	-
20a	0.94	0.80	0.25	0.87	0.00	-
20b	1.35	1.17	0.11	1.26	0.36	0.00

Fp b=1.5	**5a**	**5b**	**13a**	**13b**	**20a**	**20b**
5a	0.00	-	-	-	-	-
5b	0.02	0.00	-	-	-	-
13a	***1.54***	1.39	0.00	-	-	-
13b	0.32	0.31	1.16	0.00	-	-
20a	1.30	1.19	0.16	0.95	0.00	-
20b	***1.74***	***1.58***	0.23	1.36	0.37	0.00

Dhist	**5a**	**5b**	**13a**	**13b**	**20a**	**20b**
5a	0.00	-	-	-	-	-
5b	0.16	0.00	-	-	-	-
13a	***2.46***	***2.25***	0.00	-	-	-
13b	1.15	1.14	1.25	0.00	-	-
20a	***2.34***	***2.17***	0.01	1.20	0.00	-
20b	***2.83***	***2.59***	0.45	***1.65***	0.42	0.00

Ne	**5a**	**5b**	**13a**	**13b**	**20a**	**20b**
5a	0.00	-	-	-	-	-
5b	0.44	0.00	-	-	-	-
13a	0.28	0.73	0.00	-	-	-
13b	***2.40***	***2.66***	***2.44***	0.00	-	-
20a	***2.50***	***2.75***	***2.51***	0.38	0.00	-
20b	***3.61***	***3.76***	***3.76***	***1.63***	1.11	0.00

Tabled results show that in the case of kinematics ductility there's no evidence to reject the null hypothesis and all the values are generally close to zero meaning similar responses under different I_D sets. Hysteretic ductility and equivalent number of cycles results strongly suggest that I_D matters in nonlinear demand analysis since H_o is rejected in almost all comparisons while it cannot be rejected if two sets with the same I_D are compared. Under this prospective Dkin rejection cases results may be explained. Under the assumption that duration doesn't matter in Dkin, results should be almost clean of values above 1.5 times the standard error but, 13a is not equivalent to 13b as proven by hypothesis test of direct comparison. However, pooling 13a-13b in one set (13) and comparing it with a pooled set (5) the comparison provides $|\ln(\bar{\theta}_5 / \bar{\theta}_{13})/\beta_{5,13}| = 1.2$ which leads to no rejection.

Plastic fatigue is expected to be sensitive to I_D, but the latter is not showing in the tables. To explain that it is worth to remember that hypothesis test are built to reject the null hypothesis; if they don't, it means that there's no reason to reject which may mean that there are not enough information to do it (too large dispersions or small sample sizes). This is why IDA's and fragility analyses have been performed. Those results will show sensitivity of Fp to I_D which cannot be assessed by hypothesis test due to large standard errors.

3.2 IDA Curves

Hypothesis test have been intended as preliminary results for testing target-sets behavior and made good cases for general proof of expected results. However, to assess the trend of EDP as function of spectral acceleration in the target-sets IDA's analyses have been performed; it has been possible since I_D index is insensitive to scaling by definition. Again, in the following figures IDA's trend are reported for T = 0.6 s SDOF with EPP backbone in the range of 0 to 1 [g] spectral acceleration. For the purpose of IDA, sets with the same I_D merged in one set (i.e. $T5a \bigcup T5b \equiv T5$) to increase the sample size (20 records each).

Results are reported in the median, dispersion results show broad residuals distribution particularly for T20 set where, as shown in Fig. 1a, I_D are much more disperse than other sets. Results show how I_D influence is undetectable in kinematics ductility while it becomes more and more influent moving towards hysteretic ductility where demand curves are ranked in the crescent sense of I_D. In fact, all plots refer to the same range (abscissa), then is possible to conclude, from the right shift of the curves, how the median of the demand increases progressively from Dkin to Fp and from Fp to Dhyst. This same trend has been shown, without exceptions, in all other study cases that are not reported here.

3.3 Fragility Curves

While IDA curves help in assessing qualitatively the trend of IDA in different EDP's while for quantitatively evaluate effects of duration related indexes may be useful to get fragility curves from demand analyses (Fig. 1). In fact, they incorporate not only trend information but also results dispersion effects. Fragility curves regarding kinematics ductility don't show any significant effect of I_D on the failure probability (Fig. 6); all curves provide similar probabilities of failure and are not ranked on the plot by I_D. As expected form IDA results moving to plastic fatigue and hysteretic ductility or equivalent numbers of cycles, fragilities rank by I_D level; moreover median of fragility reduces indicating an easier collapse and slope increases showing greater differences in failure probability of different I_D sets.

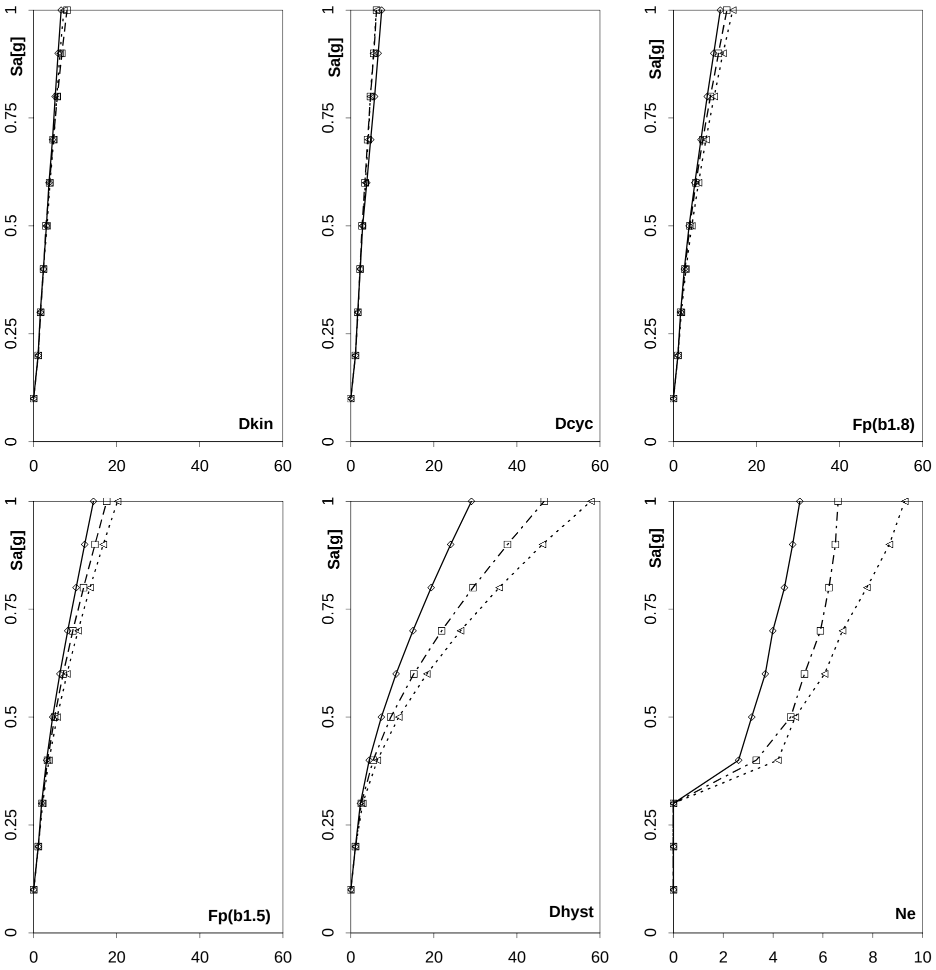


Figure 5. IDA curves for T = 0.6 s – EPP SDOF (◇ T5; □ T13; △ T20).

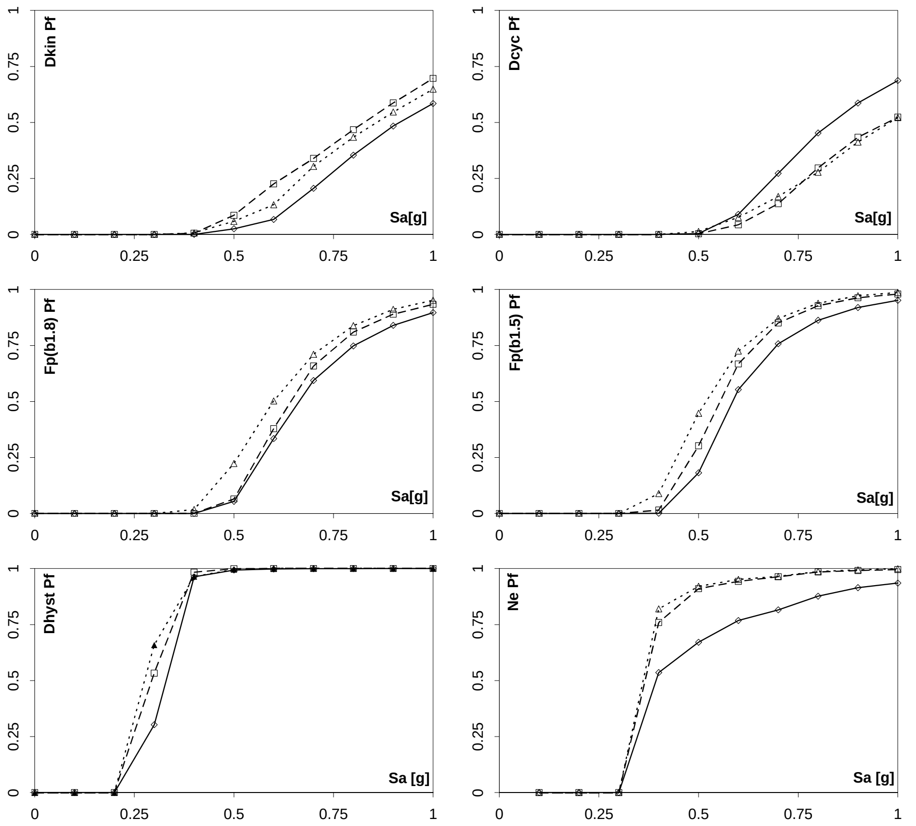


Figure 6. Fragility for T = 0.6 s – EPP SDOF (—◇— T5; --□-- T13; ···△··· T20).

4 CONCLUSIONS

Effects of duration on seismic demand analysis have been proven in general sense. Results of this study show with different information levels on a statistical basis how ground motion duration related indices affect engineering demand assessment. Influence of I_D is proven generally on a test hypothesis prospective while the demand trends and fragility assessment add quantitative features to the statements. Kinematics and cyclic ductility seem to be not affected at all by I_D where no bias in the results can be proven while plastic fatigue (low b) and hysteretic ductility demand show a systematic dependence on duration. Even if selected results have been shown, investigators found the same general conclusion for all cases in broad ranges of period from 0.1 sec to 4 sec and for very different evolutionary and nonevolutionarynondegrading backbones. Ultimately is shown how duration affects differently different EDP's regardless of the kind of structure (SDOF) considered even though backbones are not equally sensitive to duration.

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