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Ground motion duration effects on nonlinear seismic response

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SUMMARY

The study presented in this paper addresses the question of which nonlinear demand measures are sensitive to ground motion duration by statistical analyses of several case studies. A number of single degree of freedom (SDOF) structures were selected considering: (1) four oscillation periods; (2) three evolutionary and non-evolutionary hysteretic behaviours; (3) two target ductility levels.

Effects of duration are investigated, by nonlinear dynamic analysis, with respect to six different demand indices ranging from displacement ductility ratio to equivalent number of cycles. Input is made of six real accelerogram sets representing three specific duration scenarios (small, moderate and large duration). For all considered demand quantities time-history results are formally compared by statistical hypothesis test to asses the difference, if any, in the demand concerning different scenarios. Incremental dynamic analysis curves are used to evaluate duration effect as function of ground motion intensity (e.g. spectral acceleration corresponding to the SDOF's oscillation period). Duration impact on structural failure probability is evaluated by fragility curves.

The results lead to the conclusion that duration content of ground motion is statistically insignificant to displacement ductility and cyclic ductility demand. The conclusions hold regardless of SDOF's period and hysteretic relationship investigated.

KEY WORDS: duration; demand; time-history; hypothesis test; fragility

1. INTRODUCTION

Conclusive evidence is still not available to accept or reject the hypothesis that ground motion duration is an important seismological characteristic for seismic demand assessment [1]. Aim of the work herein presented shows from a general perspective whether duration matters on nonlinear structural response. This goal is pursued analysing a series of single degree of freedom (SDOF) systems. Structural features considered to be meaningful for investigation

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are: (1) oscillation period; (2) force–deformation or hysteresis relationship; and (3) target ductility. For each of these factors the following ranges were considered: four periods (from 0.1 to 4 s); three nonevolutionary and evolutionary hysteretic loops; and two yielding strengths to get ductility levels comparatively 'high' and 'low'.

Six sets of real ground motion records are selected to be representative of three different duration scenarios: 'small duration', 'moderate duration' and 'large duration'. Structural response is evaluated, by nonlinear dynamic analysis, in terms of six different demand indices [2]. To conclude whether duration is an issue for all the considered demand measures, time-history results are compared by conventional hypothesis test. To investigate how duration plays a role in demand analysis and failure probability, incremental dynamic analysis (IDA) [3] and fragility curves are developed.

Analyses show that influence of duration on seismic response depends on the chosen demand measure; as expected, energy-related indices are very sensitive to it. The less obvious result is that duration is statistically insignificant to displacement ductility ratio and cyclic ductility regardless of the structural configuration considered.

1.1. Duration-related measure used in this study

Empirical observations and analytical studies show how cyclic structural damage is related to energy released during ground shaking. More than 30 definitions of seismic duration are available in literature [4] trying to measure such damage potential [5–7]. Trifunac and Brady [8] define the effective duration t_D as the time interval between the 5 and 95% of the root mean square acceleration (RMSA). The latter is shown in Equation (1) where t_E is the total duration of the seismic event

$$\text{RMSA} = \left[\frac{1}{t_E}\int_0^{t_E} a^2(t)\,\mathrm{d}t\right] \tag{1}$$

A refined determination of the effective duration (t_n) is proposed by Trifunac and Novikova [9] as the sum of a number (m) of intervals $\{t_i^{(1)}; t_i^{(2)}\}$ over which a given amount of the integral $\int_0^{t_E} a^2(t)\,\mathrm{d}t$ is made. To compute t_n (Equation (2)), intervals are chosen so that their sum gives the shortest possible time during which the 90% of the RMSA is achieved

$$t_n = \sum_{i=1}^{m} (t_i^{(2)} - t_i^{(1)}) \tag{2}$$

In this study, structural damage is related to number and amplitude of plastic cycles induced by seismic excitation. I_D factor (Equation (3)), by Cosenza and Manfredi [10], has been proven to be a good predictor for computation of plastic cycle demand [11]; it is related with the energy content of ground shaking but also with energy dissipated by structural response

$$I_D = \frac{\int_0^{t_E} a^2(t)\,\mathrm{d}t}{\text{PGAPGV}} \tag{3}$$

In Equation (3) $a(t)$ is the acceleration time-history, PGA and PGV are the peak ground acceleration and velocity respectively; t_E is, again, the total duration of the seismic event. Duration will be herein represented primarily in terms of I_D. Therefore, duration scenarios are made of records sampled in narrow I_D bins, and influence of this factor on the nonlinear response is investigated. To interpret results as a function of other duration measures t_D and t_n are given for the accelerograms used. Furthermore, I_D scenarios are also described in terms of these two definitions of duration.

2. METHODOLOGY

2.1. SDOF systems

Three different constitutive models are herein considered to be analysed with respect to duration: (a) elastic-perfectly-plastic (EPP); (b) elastic-plastic with hardening (EPH) with a secondary stiffness which is 3% of the primary; (c) modified Clough model (MC) [12] (Figure 1). The EPP model is representative of structural situations such as welded connections steel frames without instability problems. The EPH represents generic bilinear backbones. MC is included to cover a wider range of structural cases since it is commonly used to describe the behaviour of reinforced concrete structures. It has evolutionary features, but still clearly separating the elastic behaviour to the inelastic part of the response.

Four oscillation periods are associated to each of these models: 'short' (0.1 s), 'moderate' (0.6 s), 'long' (1.5 s) and 'very long' (4 s). Chosen vibration periods are representative of different regions of the Eurocode design spectrum in order to investigate if conclusions hold in the entire spectral range.

For each SDOF, yielding strength of the hysteretic loop is adjusted to get two target ductility levels. Yielding values are computed dividing the Eurocode elastic spectral strength, corresponding to the period of interest, by a factor of 3 (DL3) and 6 (DL6) (damping is always 5% of critical). Therefore, 3-models $\times$ 4-periods $\times$ 2-ductility or 24 SDOF systems are considered in the analyses; SDOF configurations are summarized in Table I.

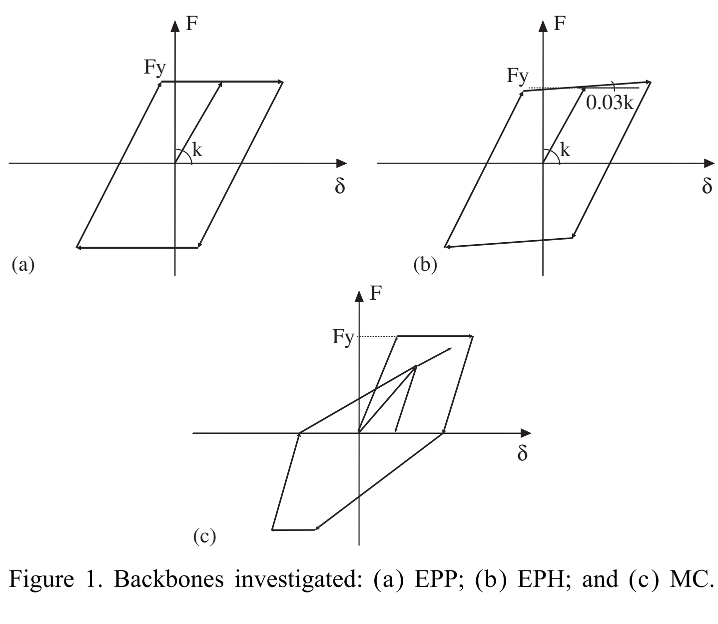

Figure 1. Backbones investigated: (a) EPP; (b) EPH; and (c) MC.

Table I. Investigated SDOFs.

	Period (T)																							
	0.1 s						0.6 s						1.5 s						4 s					
Hysteresis	EPP		EPH		MC		EPP		EPH		MC		EPP		EPH		MC		EPP		EPH		MC	
Ductility (DL)	3	6	3	6	3	6	3	6	3	6	3	6	3	6	3	6	3	6	3	6	3	6	3	6

2.2. *Nonlinear demand measures*

In the following, the six demand measures selected are described. Some indices exclusively account for lateral displacement or dissipated energy, others consider both quantities. Displacement ductility (Equation (4)) is the ratio of the peak ($\delta_{\max}$) and yielding (δ_y) displacements.

$$D_{\text{kin}} = \frac{\delta_{\max}}{\delta_y} \tag{4}$$

The cyclic ductility (Equation (5)) is defined as the sum of maximum negative and positive inelastic displacement (in absolute values) over yielding displacement.

$$D_{\text{cyc}} = \frac{-\delta_{\min} + \delta_{\max}}{\delta_y} \tag{5}$$

These two demand definitions only account for lateral displacements. If hysteretic behaviour is also contributing to structural damage, the plastic fatigue should be introduced (Equation (6)):

$$F_{\text{p}} = A \sum_{i=1}^{n} \left(\frac{\delta_{\max,i}}{\delta_y} - 1 \right)^b \tag{6}$$

F_{p} includes ductility ($\delta_{\max,i}/\delta_y$) of all plastic cycles (n) through a weighting factor (b) accounting for their amplitude; A is a parameter depending on monotonic loading. It is easy to recognize that F_{p} is intermediate between displacement and energy-based demand measures. For large b values plastic fatigue asymptotically tends toward displacement ductility ratio since only larger cycles are taken into account. If $b=1$ all the cycles are weighted the same independently of their amplitude, in this case plastic fatigue coincides with hysteretic ductility (D_{hyst}) or normalized hysteretic energy. The latter can be computed by Equation (7), where E_{H} is the dissipated hysteretic energy and F_{Y} is the yielding strength

$$D_{\text{hyst}} = \frac{E_{\text{H}}}{F_{\text{Y}} \delta_y} + 1 \tag{7}$$

Since the equivalent number of cycles (N_{e}) also clearly accounts for hysteretic behaviour, it is included in the analyses. (Equation (8) gives N_{e} for the EPP backbone.)

$$N_{\text{e}} = \frac{E_{\text{H}}}{F_{\text{Y}}(\delta_{\max} - \delta_y)} + 1 \tag{8}$$

One can see that demand measures considered range progressively from displacement-based (D_{kin}) to energy-based (D_{hyst}) considering two different plastic fatigues ($b = 1.8, 1.5$). Further details about these indices and their ability to capture nonlinear behaviour may be found in References [13–18].

It may be considered pointless to investigate duration effect (which is expected to be strong) on energy-related demand quantities. However, obtaining this self-evident result in the framework of analyses presented is necessary; it confirms that the study is well conducted in the light of less obvious findings as independence of displacement ductility and cyclic ductility on duration.

2.3. Duration scenarios

Accelerograms for nonlinear time-history analyses are selected to be representative of specific duration scenarios. Herein, three bins of 20 records are defined to have specific median I_D ($I_D \approx 5$ 'small duration', $I_D \approx 14$ 'moderate duration', $I_D \approx 22$ 'large duration'). Characteristics of bins are shown in Figure 2 where I_D is represented versus t_D and t_n.

The primary purpose of selection is to have records featuring durations representative of the scenarios; to this aim it is desirable to have the lowest scatter possible around the median I_D in each bin. This aids in defining the duration scenarios without uncertainty. Lack of data with the required features in the chosen catalog (see Section 2.3.1) leads to a certain dispersion which is given in Table II; I_D standard deviation is fairly low in the I_D5 and I_D14 bins while it is greater in the I_D22 group. This scatter leads to a lower gap between the I_D14 and I_D22 bins, which is reflected in the corresponding demand curves and fragilities, but it does not affect the general conclusions of the study.

The scenarios are defined in terms of I_D but they may also be represented in terms of effective duration. The I_D5, I_D14 and I_D22 sets feature 13, 20, 30 s average t_D and 7, 12, 16 s average t_n, respectively (Table II).

Each of these three groups is split in two of size-10 sets in order to increase the number of significant cases to compare. The six size-10 sets, named: I_D5a, I_D5b, I_D14a, I_D14b, I_D22a and I_D22b, are listed in Appendix A and may be easily retrieved from Pacific Earthquake Engineering Research Center database at http://peer.berkeley.edu/smcat/. List of records

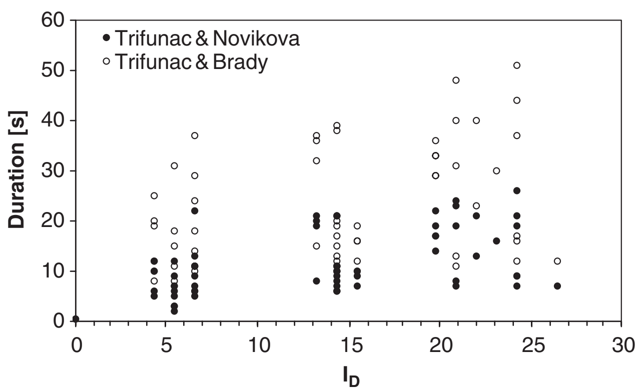

Figure 2. I_{D} versus other duration definitions in the target sets.

Table II. Record sets features.

	Small duration—I_D6	Moderate duration—I_D14	Large duration—I_D22
Median I_D	5	14	22
Standard deviation I_D	0.9	0.7	2.0
C.O.V. I_D	0.16	0.05	0.10
Average t_D (s)	14	20	30
Average t_n (s)	7	12	16

includes I_D and duration in terms of both t_D and t_n. All accelerograms come from the same catalog so that uniform processing may be assumed.

2.3.1. Records selection process. Specific studies [19, 20] show that, for nonlinear demand assessment purposes, no particular care is required in selecting records with respect to magnitude and distance if accelerograms are scaled to a common intensity level (e.g. first mode spectral acceleration). Herein, prudently, the size-10 sets are characterized by average moment magnitude from 6.4 [M] to 6.7 [M], then the maximum gap between two sets is 0.3 [M]. Distance is considered to be even less important than magnitude; therefore, records used in this study come from a broad range of distances (which here is intended as the closest distance to fault rupture). However, one can see that average distances of sets are in the range of 70–90 km, so that defined sets can be considered similar in terms of magnitude or distance.

Other selection constraints help to reduce the influence on results of those factors that are not in the objective of the study. Only stiff soil accelerograms recorded on free field or on one-storey buildings are considered. To avoid directivity pulse-type effects records belong to the far field; to this aim distance is greater than 25 km. Finally, to reduce correlation due to event commonality within the defined sets, it is desirable to have the records coming from different events. This requirement conflicts with the purpose of having sets well defined in terms of duration due to limits of catalogue. The compromise was to limit to no more than two records per set coming from one event and limiting as much as possible the event overlapping among different duration scenarios. Accelerograms have been chosen randomly among those meeting the listed requirement.

2.4. Analyses

The SDOF cases are analysed by nonlinear time-history with the described sets as input. As first step, influence of I_D is evaluated by conventional hypothesis test [21] on nonlinear demand resulting from different duration scenarios. The null hypothesis is that record sets featuring different duration give the same median demand if scaled to a common spectral acceleration level (e.g. overall median); if the hypothesis cannot be rejected one can conclude that duration is insignificant for the considered demand measure.

Scaling of compared record sets is important because duration is correlated with magnitude, so for a given distance an increase in magnitude will also produce an increase in duration and lateral displacement. Therefore, in general one could observe correlation between duration and lateral displacement. Scaling of records to a common spectral acceleration (Sa) lead to

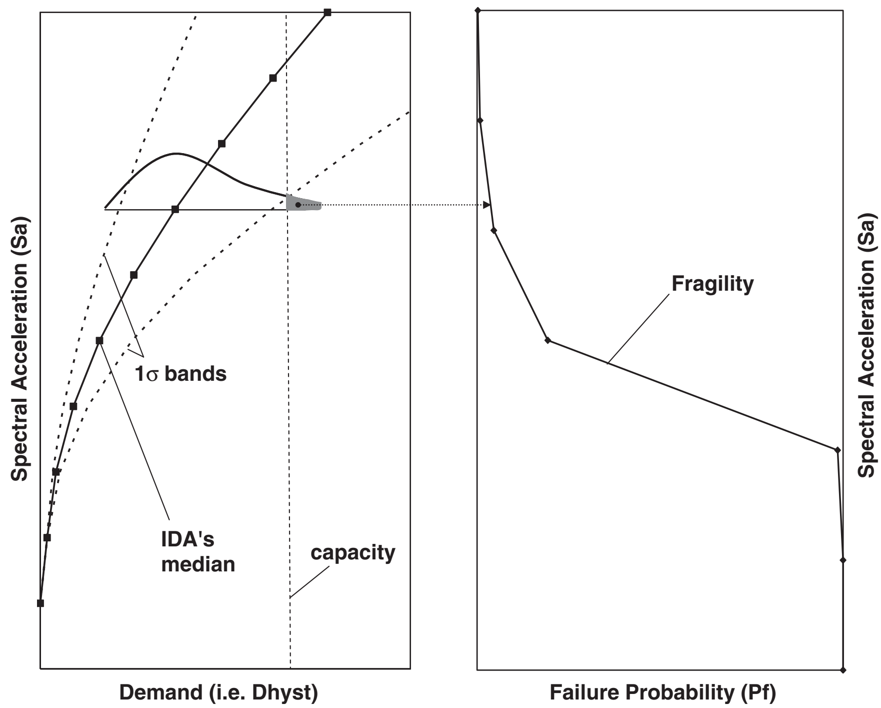

Figure 3. IDA-based fragility example ($T = 0.6$ s—EPP SDOF).

conclusions about duration effects on inelastic behaviour provided that the ground motions produce same elastic demand.

For example, let us consider the SDOF featuring $T = 0.6$ s—EPP—DL3. To compare the I_D22a and I_D5b sets they are scaled to the same Sa corresponding to $T = 0.6$ s. The nonlinear dynamic analyses provide the medians of the six demand measures for the two sets. For each measure the median resulting from the set I_D22a is compared to the median demand of the set I_D5b. The null hypothesis is that medians are equal (i.e. duration does not matter).

The test gives a direct response to the question: *which of the chosen demand measures is sensitive to durations*? The findings determine in which case the null hypothesis has to be rejected. The hypothesis test gives a '*yes–no*' answer without investigating the duration's effects quantitatively. Therefore, the trend of demand as a function of ground motion intensity measure (e.g. Sa) is evaluated by IDA. To this aim, all accelerograms in the sets are individually scaled to get the desired spectral acceleration level in a given range, and then the medians of demand measures are plotted versus Sa. (I_D is insensitive to amplitude scaling of records.) If IDA curves generated with record sets representing different I_D provide increasing demand for larger I_D (given the same Sa level) it is possible to conclude that duration matters for that particular demand measure and a picture of tendency is given.

Assuming log-normal dispersion of the IDA's results of different records around the median of the IDA curve (Figure 3), and defining a threshold representative of the structural capacity, it is possible to compute fragility curves. This step further in the analyses provides information about influence of duration on failure probability including record-to-record variability and capacity information. If the duration is significant for fragility it is expected that, for the same Sa level, curves developed with records belonging to different I_D sets provide failure probability somehow proportional to it (i.e. a small I_D set gives lower failure probability than fragilities built with larger I_D records).

3. RESULTS AND DISCUSSION

In this section, hypothesis tests, IDA, and fragility analyses are discussed. For the sake of brevity only selected result are given in details. Analyses regarding the $T = 0.6$ s SDOF are shown for both target ductility levels of the two EPP and MC force–deformation relationships. Other results are given in summary form. A more detailed report of all the considered structures may be found in Reference [22].

The SDOF—$T = 0.6$s is discussed since this period may be of special interest for earthquake engineering applications; the EPP backbone is one of the most commonly used in this kind of study while the MC is analysed because it is evolutionary. It is remarkable that conclusions hold for all others SDOF study cases which cannot be published here since they would require a longer description with little incremental value to the discussion.

3.1. Hypothesis tests

If duration *does not matter* for a given demand measure, the median responses evaluated by two record sets representing different I_D scenarios should be virtually the same. Testing this means performing a statistical test on the ratio (z) of the estimated medians being equal to 1. z is defined as the median demand of a record set (x), for example I_D22a featuring $I_D \approx 22$, divided by the resulting median of another set (y) belonging to a different duration scenario (i.e. I_D5b characterized by $I_D \approx 5$)

$$z = \frac{\bar{\theta}_x}{\bar{\theta}_y} \tag{9}$$

In Equation (9), $\bar{\theta}_x$ and $\bar{\theta}_y$ are the estimated demand medians of set x and set y ($I_{D,x} > I_{D,y}$) respectively. The estimation of standard error of z can be evaluated as

$$\beta_z = \sqrt{\frac{\beta_x^2}{n_1} + \frac{\beta_y^2}{n_2}} \tag{10}$$

where n_1 and n_2 are the sample sizes of the sets x and y, respectively; β_x and β_y are the standard deviations of the natural logarithms of the sets. Under the assumption that the individual responses are lognormal the natural log of the ratio in Equation (9) divided by β_z is distributed as the Student-t with $(n_1 + n_2 - 2)$ DOF. In this case the number is 18.

As discussed, the assumption being tested is that the z-ratio is *statistically* not different from one. It means that different duration scenarios provide the same demand given that they are scaled to a common Sa level (e.g. they provide the same elastic demand). Formally the null hypothesis, H_0, of the test is

$$H_0 : \text{median responses are equal}$$

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

$$\text{Significance level} = P[\text{reject } H_0 \mid H_0 \text{ correct}]$$

Two significance levels have been considered; they correspond to the '1.5-sigma and 2-sigma' levels (here the '1.5-β and 2-β' levels). For the two-sided Student-t PDF with 18 DOF these levels correspond to 0.152 and 0.061, respectively. Therefore to test whether one can accept the hypothesis that a pair of sets medians are equal, one needs simply to calculate the natural log of their ratio ($\ln(z)$), divide that by the estimated standard error, β_z, and confirm whether that result is 'close' to zero, where close means within ± 1.5 or ± 2.0 for the 15 and 6% significance levels, respectively. For example, the lower left-hand case in Table III —D_{kin} yields a response ratio of 0.89 whose natural log is about 0.12; the standard error is about 0.15. The former divided by the latter is 0.81 (to two significant figures). This value is less than 1.5 (or 2.0), so the equality of medians hypothesis may be accepted at the 15% (and 6%) significance level. Note that if the ratio is close to unity, an approximate check is to simply compare the deviation from unity (1.0 – 0.81 or 0.19 in this example) with 1.5 (or 2.0) times β (0.23 or 0.30 in this example). This is adequate in most cases here. Note that even if the hypothesis is true one would expect to reject it (incorrectly) in about 15% (or 6%) of the cases.

Table III shows absolute values of $\ln(z)/\beta$ for $T = 0.6$s SDOF with EPP backbone (DL3) for all demand indices considered. Those results leading to rejection of the null hypothesis at 1.5β confidence are highlighted in bold–italic. This table leads to the conclusion that, in the case of displacement ductility ratio, there is no evidence to conclude that duration is significant; in fact, all the values are generally close to zero meaning very similar responses to different I_D scenarios. Hysteretic ductility and equivalent number of cycles results strongly suggest that I_D matters in nonlinear demand analysis and H_0 is rejected in almost all comparisons.

Plastic fatigue is expected to be sensitive to duration (depending on b value), but the latter is not clearly shown in the tables. To explain this, it is worth recalling that if a hypothesis test does not reject a given null hypothesis it means that there is not enough information to support acceptance, which may be attributed to large dispersions or inadequate sample sizes. IDA and fragility curves will show sensitivity of F_{p} to I_D, which cannot be evaluated by this test.

Finally, elements in the cells below the diagonals in Table III show the comparison of different sets with the same I_D. These results are clean of null hypothesis rejections since two sets with the same I_D are virtually equivalent by definition. (For example, I_D5a and I_D5b should always give virtually the same nonlinear response if scaled to a common Sa level; such equivalence is herein confirmed for all sets.)

Table IV shows the summary of the rejection cases for the nonevolutionary backbones (all SDOF periods) at 2β significance levels. In the displacement ductility ratio case the corresponding overall rejecting fraction is 3 out of 16×12 (192) which is approximately 0.02; for D_{cyc} this ratio yields to 0.03. In both cases if these values are lower than 0.06 or 6%; then the hypothesis that duration (I_D) *does not matter*, independently of period and ductility level, and has to be accepted at 2β significance level.

At 1.5β level (Table V) the rejection fractions for displacement and cyclic ductility are 0.05 and 0.06, respectively, leading to the same conclusion of 2β. For the D_{hyst} rejection cases, fractions are 0.20 (2β) and 0.44 (1.5β); therefore, the null hypothesis has to be rejected. The

Table III. Hypothesis test results. $T = 0.6$ s—EPP SDOF, DL3.

D_{kin}	5a	5b	14a	14b	22a	22b	D_{cyc}	5a	5b	14a	14b	22a	22b
5a	0.00						5a	0.00					
5b	0.23	0.00					5b	0.38	0.00				
14a	0.01	0.16	0.00				14a	0.00	0.36	0.00			
14b	0.16	0.01	0.13	0.00			14b	0.77	1.08	0.74	0.00		
22a	0.03	0.17	0.01	0.13	0.00		22a	0.02	0.35	0.02	0.64	0.00	
22b	0.81	0.97	0.60	0.67	0.73	0.00	22b	0.21	0.54	0.20	0.50	0.16	0.00
$F_p1.8$	5a	5b	14a	14b	22a	22b	$F_p1.5$	5a	5b	14a	14b	22a	22b
5a	0.00						5a	0.00					
5b	0.02	0.00					5b	0.03	0.00				
14a	0.70	0.69	0.00				14a	1.16	1.11	0.00			
14b	0.03	0.05	0.77	0.00			14b	0.29	0.25	0.85	0.00		
22a	0.74	0.74	0.15	0.80	0.00		22a	1.00	0.95	0.01	0.73	0.00	
22b	1.09	1.09	0.55	1.16	0.37	0.00	22b	***1.51***	1.46	0.55	1.24	0.48	0.00
D_{hyst}	5a	5b	14a	14b	22a	22b	N_e	5a	5b	14a	14b	22a	22b
5a	0.00						5a	0.00					
5b	0.20	0.00					5b	0.01	0.00				
14a	***1.74***	***1.81***	0.00				14a	***1.81***	***2.47***	0.00			
14b	0.92	1.05	0.82	0.00			14b	1.19	1.48	0.47	0.00		
22a	***1.53***	***1.62***	0.04	0.74	0.00		22a	***1.61***	***2.03***	0.01	0.40	0.00	
22b	***2.35***	***2.39***	0.81	***1.53***	0.68	0.00	22b	***1.81***	***2.50***	0.02	0.46	0.01	0.00

Table IV. 2β rejection cases summary for EPP and EPH SDOF.

D_{kin}	$T = 0.1$	$T = 0.6$	$T = 1.5$	$T = 4.0$	D_{cyc}	$T = 0.1$	$T = 0.6$	$T = 1.5$	$T = 4.0$
EPP DL3	0	0	1	0	EPP DL3	0	0	1	0
EPP DL6	0	2	0	0	EPP DL6	0	0	2	3
EPH DL3	0	0	0	0	EPH DL3	0	0	0	0
EPH DL6	0	0	0	0	EPH DL6	0	0	0	0
D_{hyst}	$T = 0.1$	$T = 0.6$	$T = 1.5$	$T = 4.0$	N_e	$T = 0.1$	$T = 0.6$	$T = 1.5$	$T = 4.0$
EPP DL3	4	3	0	0	EPP DL3	8	3	3	2
EPP DL6	7	2	0	0	EPP DL6	8	8	0	0
EPH DL3	4	2	1	1	EPH DL3	8	6	3	2
EPH DL6	7	6	1	0	EPH DL6	7	8	6	1

same happens for the equivalent number of cycles where the rejection fractions are 0.38 (2β) and 0.53 (1.5β), respectively. In all cases where hypothesis test rejections were detected, the ratio of the responses always shows a larger demand for the larger I_D.

The hypothesis test results for the MC are summarized in Table VI. The conclusions are the same as for the nonevolutionary backbones. Looking at the magnitude of the ratios (i.e. in the N_e case) it can be observed, assuming comparable dispersion, that the MC backbone

Table V. 1.5β rejection cases summary for EPP and EPH SDOF.

D_{kin}	$T=0.1$	$T=0.6$	$T=1.5$	$T=4.0$	D_{cyc}	$T=0.1$	$T=0.6$	$T=1.5$	$T=4.0$
EPP DL3	0	0	0	0	EPP DL3	0	0	0	2
EPP DL6	1	3	2	1	EPP DL6	0	2	3	3
EPH DL3	0	0	1	0	EPH DL3	0	0	0	0
EPH DL6	0	1	0	0	EPH DL6	0	1	0	0
D_{hyst}	$T=0.1$	$T=0.6$	$T=1.5$	$T=4.0$	N_e	$T=0.1$	$T=0.6$	$T=1.5$	$T=4.0$
EPP DL3	8	7	6	3	EPP DL3	8	6	5	4
EPP DL6	8	6	6	1	EPP DL6	8	9	2	1
EPH DL3	8	4	5	4	EPH DL3	10	8	5	5
EPH DL6	8	5	6	0	EPH DL6	9	11	7	4

Table VI. Hypothesis test results $T=0.6$ s—MC SDOF, DL3.

D_{kin}	5a	5b	14a	14b	22a	22b	D_{cyc}	5a	5b	14a	14b	22a	22b
5a	0.00						5a	0.00					
5b	1.10	0.00					5b	1.10	0.00				
14a	0.89	0.05	0.00				14a	0.89	0.05	0.00			
14b	0.20	1.16	0.97	0.00			14b	0.20	1.16	0.97	0.00		
22a	0.19	0.78	0.67	0.35	0.00		22a	0.19	0.78	0.67	0.35	0.00	
22b	0.47	0.59	0.51	0.61	0.23	0.00	22b	0.47	0.59	0.51	0.61	0.23	0.00
D_{hyst}	5a	5b	14a	14b	22a	22b	N_e	5a	5b	14a	14b	22a	22b
5a	0.00						5a	0.00					
5b	0.00	0.00					5b	1.04	0.00				
14a	***2.43***	***2.22***	0.00				14a	***2.73***	***4.64***	0.00			
14b	1.08	1.00	1.26	0.00			14b	***2.03***	***3.74***	1.11	0.00		
22a	***2.36***	***2.20***	0.20	1.33	0.00		22a	***3.20***	***4.59***	1.41	***2.02***	0.00	
22b	***2.55***	***2.39***	0.48	***1.56***	0.26	0.00	22b	***3.29***	***4.72***	***1.53***	***2.14***	0.07	0.00

is more sensitive to duration since larger I_D sets are more demanding than in the EPP. All these findings will be confirmed by IDA and fragility curves.

3.2. IDA curves

Hypothesis tests have been intended as preliminary tool for analysing statistical influence of duration on different demand measures. To observe effects of I_D on the demand's trend IDA curves are computed. In Figure 4 demands in the $0\,[g]$–$1\,[g]$ Sa range are reported for the $T=0.6$ s SDOF with EPP backbone (DL6). For the purpose of IDA, sets with the same I_D are merged in one set (i.e. $I_D5\text{a} \cup I_D5\text{b} \equiv I_D5$) increasing to 20 records each.

The relative distance of demand curves built with record sets featuring different I_D gives a picture of how it affects demand at given Sa. Demand medians in Figure 4 confirm the hypothesis test results. IDA shows how I_D influence is undetectable in displacement ductility ratio and cyclic ductility where curves overlap each other and no domination of larger duration may be detected (i.e. set with I_D5 gives a larger demand in D_{cyc} than I_D14 and I_D22).

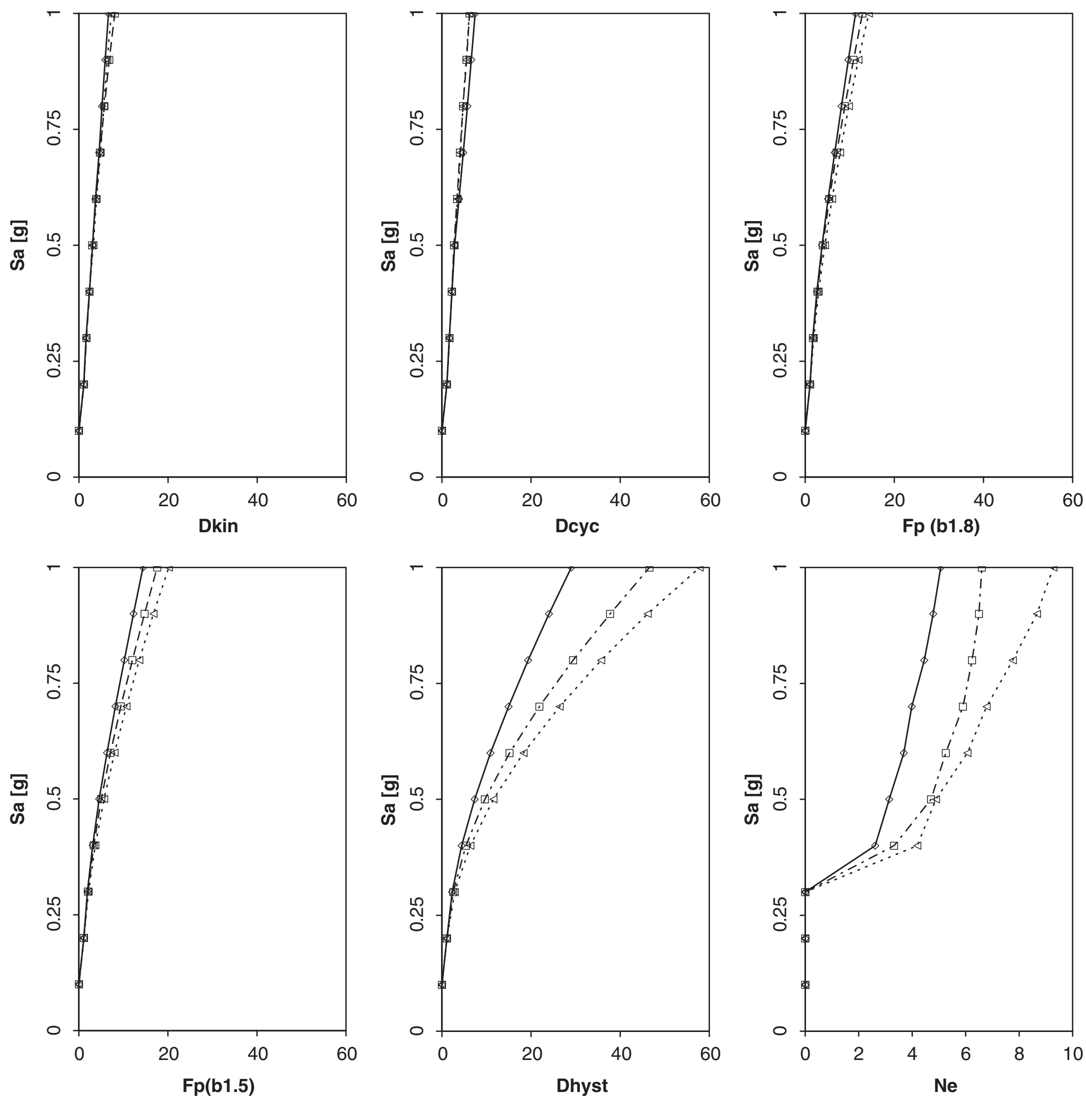

Figure 4. IDA curves for $T = 0.6$ s—EPP SDOF, DL6 (-◇-, I_D5; -□-, I_D13; -△-, I_D20).

IDA is also helpful in evaluating the influence of duration on the plastic fatigue, which the hypothesis test is not able to capture. F_p with $b = 1.8$ shows a slight influence of I_D; the demand curves are ranked in crescent sense of duration. F_p with $b = 1.5$, as expected, is more sensitive to duration giving more importance to the dissipated energy during the hysteretic behaviour of the structure. In this case, curves still respect the crescent sense of I_D and are more separated than for $b = 1.8$ case. Hysteretic ductility IDA suggests the larger influence of duration on this demand measure by a larger discrepancy among curves. The same observations hold for equivalent number of cycles.

Since plots refer to the same abscissa (Sa) range it is also possible to conclude that demand due to I_D increases progressively from D_{kin} to F_{p} $(b=1.8)$ and from F_{p} $(b=1.5)$ to D_{hyst}. This same trend was observed, without exceptions, in all other study cases which are not reported here.

3.3. *Fragility curves*

IDA pictures the median demand trend as a function of spectral acceleration. Effects of duration in terms of failure probability, is evaluated by fragility curves. Fragilities are estimated as described in Figure 3, considering scatter of IDA around its median and a capacity threshold; the latter is 5 times monotonic ductility. Figure 5 represents fragilities retrieved from

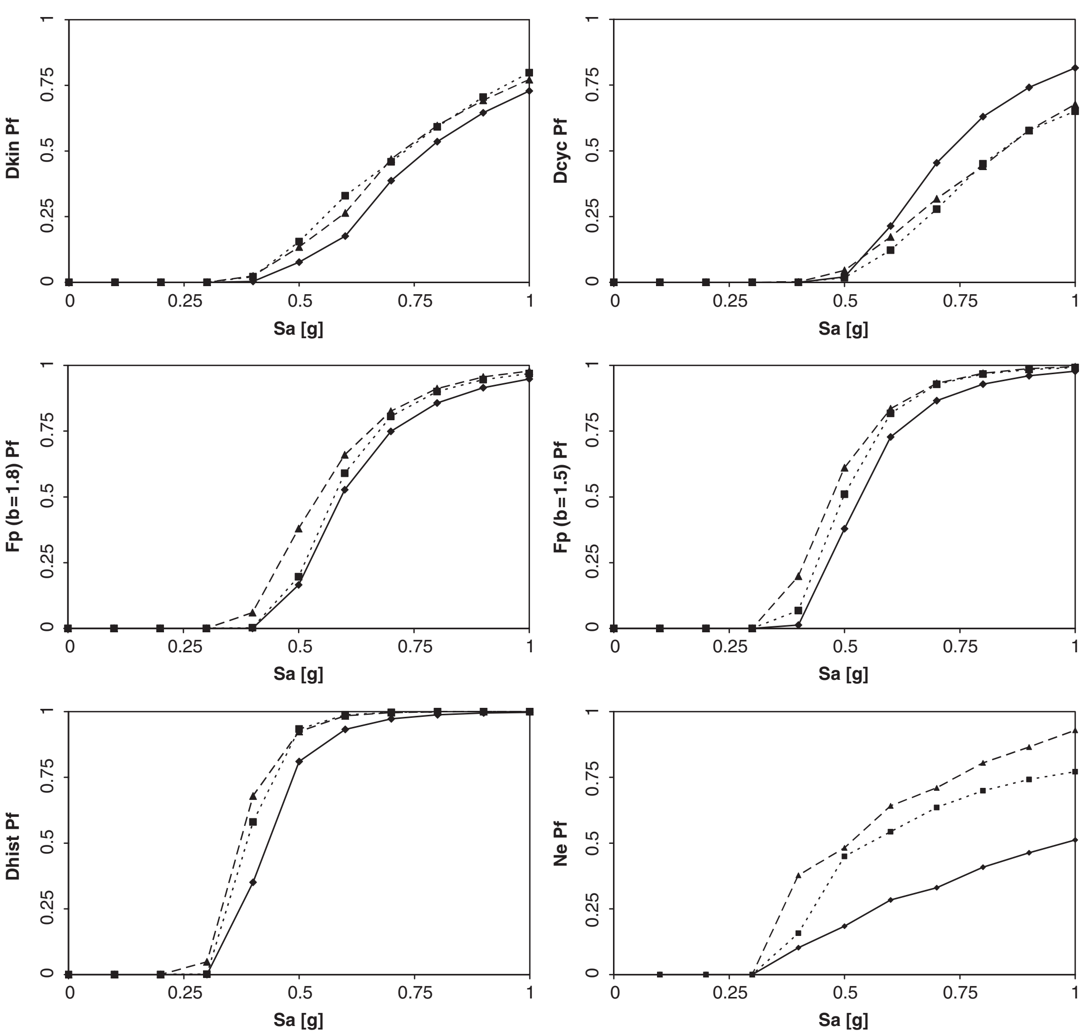

Figure 5. Fragility for $T = 0.6$ s—EPP SDOF, DL6 (-◇-, I_D5; -□-, I_D14; -△-, I_D22).

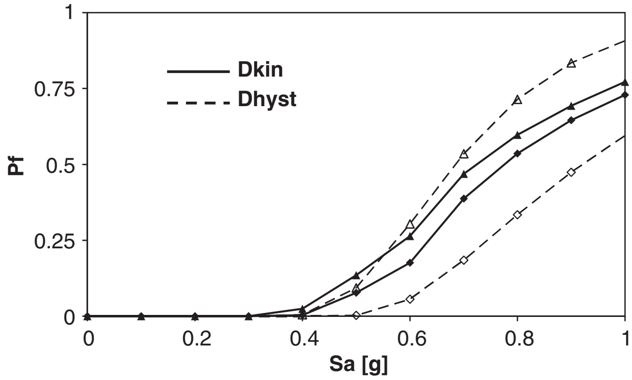

Figure 6. Fragility comparison for D_{kin} and D_{hyst} with different capacity (-◇-, I_D5; -△-, I_D22).

curves in Figure 4. (Fragility curves are not perfectly smooth because the number of Sa levels investigated in the [0,1] [g] interval is 10.)

The large record-to-record I_D variability in the I_D22 set (see Figure 2) leads to a smaller distance in fragilities of I_D22 and I_D14, but raking in the crescent sense of duration is always respected. Fragilities are useful in improving significance and accuracy of conclusions if I_D5 and I_D22 curves are compared. As in hypothesis tests and IDA: it is not possible to recognize any I_D effect in displacement and cyclic ductility where, for a given Sa (abscissa), failure probability for different I_D are close, and, most importantly, fragility curves cross each other not respecting any particular order. Looking at plastic fatigue and hysteretic ductility or equivalent numbers of cycles, failure probability is crescent with I_D at each given Sa. Moreover, going toward energy-based demand quantities, the curves become progressively steeper meaning an increasing difference in failure probability among different duration sets.

For example, for plastic fatigue ($b = 1.5$) at Sa $= 0.4$ [g] the corresponding failure probability is about 0.15 for the I_D5 set and it is 0.4 for the I_D22 set yielding to a ratio (of the latter divided by the former) of 1.5. At the same Sa level this ratio in the hysteretic ductility is about 2 and about 4 in the equivalent number of cycles.

Overall, even though relative distance among curves is also dependent on capacity threshold and sensitivity of demand upon Sa, fragility curves indicate an easier collapse for those sets with larger duration by increasing in slope. This effect is undetectable for displacement and cyclic ductility, moderate for plastic fatigue with large b, strong for low b and hysteretic ductility.

Now may be called into question how capacity threshold affects the conclusions resulting from fragility analysis. Figure 6 shows the comparison of displacement ductility ratio and hysteretic ductility curves, for the SDOF just discussed, when the D_{hyst} capacity is increased by a factor of 5 while the capacity for D_{kin} is kept the same as in Figure 5. (The I_D14 curve has been removed to keep the graph clear.) It is possible to observe how the influence of I_D on the failure probability is independent of the capacity level. In fact, the failure probability for the I_D22 set is larger than I_D5 in the D_{hyst} (dashed); such discrepancy is very small for D_{kin} (solid).

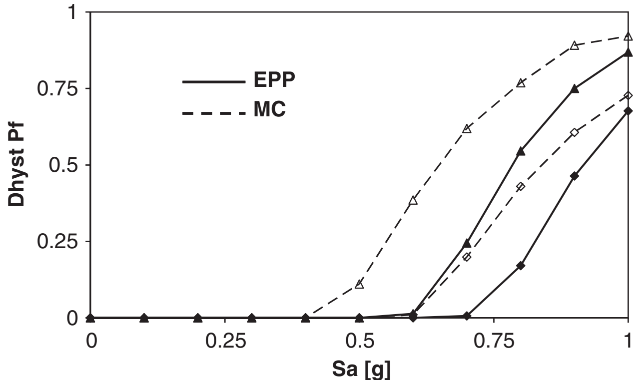

Figure 7. D_{hyst} fragility comparison for EPP and MC backbones (◇, I_D5; △, I_D22).

Figure 7 gives information about different sensitivity of nonevolutionary and evolutionary backbones to duration (I_D). Hysteretic ductility fragility curves for EPP and MC backbones are compared ($T = 0.6$s—DL3). For the given capacity value (6 monotonic ductility) the influence of duration is larger for the evolutionary backbone rather than for the nonevolutionary. For example, at Sa $= 0.65$ [g] failure probabilities for I_D22 divided by I_D5 yield a ratio of 2 for the EPP while it is about 3.5 for the MC indicating more influence of duration on the latter than on the former.

4. CONCLUSIONS

This study evaluated, on a statistical basis, how ground motion duration, herein primarily expressed in terms of I_D, affects nonlinear seismic response of selected SDOF systems. Duration has been found to be insignificant to displacement ductility demand assessment, regardless of oscillation period and backbone (nonevolutionary and evolutionary), while it considerably affects other demand parameters such as hysteretic ductility and equivalent number of cycles. Ultimately the results lead to the conclusion that the answer to the question '*does duration matter*?' depends on the considered demand measure. According to hypothesis tests, the assumption that duration influences nonlinear seismic analysis has to be rejected for displacement-based demand indices and has to be accepted for energy-based as hysteretic ductility in all the investigated cases. IDA curves confirm hypothesis tests resulting in a broad range of spectral accelerations and prove the dependence of plastic fatigue on duration as function of the 'b' value. Fragility analyses call into question record-to-record variability and structural capacity; these curves indicate no influence of duration on failure probability for displacement ductility ratio and cyclic ductility since curves cross each other. Failure probability discrepancy between large and small I_D sets progressively increases from plastic fatigue (large b) to equivalent number of cycles suggesting, again, a significant duration influence. Fragility analysis is also able to show how conclusions hold independently of the capacity and how nonevolutionary backbones are less sensitive to duration than evolutionary.

APPENDIX A

I_D Set	Event	Station	Record	t_D (s)	t_n (s)	I_D
5a	Mammoth Lakes 1980/05/25 16:49	54099 Convict Creek	MAMMOTH/J-CVK180	8	4	5.5
5a	Kocaeli, Turkey 1999/08/17	Botas	KOCAELI/BTS000	29	11	6.6
5a	Coyote Lake 1979/08/06 17:05	1492 SJB Overpass, Bent 3 g.l.	COYOTELK/SJ3067	8	5	6.6
5a	Mt. Lewis 1986/03/31 11:55	57191 Halls Valley	MTLEWIS/HVR000	10	4	5.5
5a	Trinidad offshore 1983/08/24 13:36	1498 Rio Dell Overpass, E Ground	TRINIDAD/RDE000	7	5	6.6
5a	Westmorland 1981/04/26 12:09	5051 Parachute Test Site	WESTMORL/PTS225	15	9	4.4
5a	Taiwan SMART1(33) 1985/06/12	29 SMART1 M07	SMART1/33M07EW	10	5	6.6
5a	San Fernando 1971/02/09 14:00	994 Gormon—Oso Pump Plant	SFERN/OPP270	7	3	4.4
5a	Cape Mendocino 1992/04/25 18:06	89509 Eureka—Myrtle & West	CAPEMEND/EUR000	21	10	6.6
5a	Loma Prieta 1989/10/18 00:05	57066 Agnews State Hospital	LOMAP/AGW000	18	9	6.6
5b	Mammoth Lakes 1980/05/25 19:44	54099 Convict Creek	MAMMOTH/A-CVK180	5	3	6.6
5b	Coyote Lake 1979/08/06 17:05	1492 SJB Overpass, Bent 5 g.l.	COYOTELK/SJ5337	7	4	6.6
5b	Kocaeli, Turkey 1999/08/17	Botas	KOCAELI/BTS090	31	12	5.5
5b	Trinidad offshore 1983/08/24 13:36	1498 Rio Dell Overpass, W Ground	TRINIDAD/RDW000	6	4	6.6
5b	Morgan Hill 1984/04/24 21:15	56012 Los Banos	MORGAN/LBN180	18	9	5.5
5b	Duzce, Turkey 1999/11/12	Yarimca	DUZCE/YPT060	37	22	6.6
5b	Coalinga 1983/05/02 23:42	36457 Parkfield—Fault Zone 16	COALINGA/H-Z16000	11	6	6.6
5b	San Fernando 1971/02/09 14:00	994 Gormon—Oso Pump Plant	SFERN/OPP000	7	3	5.5
5b	Victoria, Mexico 1980/06/09 03:28	6621 Chihuahua	VICT/CHI102	15	7	5.5
5b	Whittier Narrows 1987/10/01 14:42	90079 Downey—Birchdale	WHITTIER/A-BIR180	3	2	5.5

14a	Landers 1992/06/28 11:58	90058 Sunland—Mt Gleason Av	LANDERS/GLE260	37	21	13.2
14a	Northridge 1994/01/17 12:31	90068 Covina—S. Grand Ave.	NORTHR/GRA074	20	11	14.3
14a	Imperial Valley 1979/10/15 23:16	6610 Victoria	IMPVALL/H-VCT075	19	10	15.4
14a	Chi-Chi, Taiwan 1999/09/20	CHY050	CHICHI/CHY050-N	39	21	14.3
14a	Borrego Mtn 1968/04/09 02:30	475 Pasadena—Athenaeum	BORREGO/A-PAS270	32	19	13.2
14a	Coalinga 1983/05/02 23:42	36138 Parkfield—Fault Zone 12	COALINGA/H-PRK180	16	10	15.4
14a	N. Palm Springs 1986/07/08 09:20	23321 Hesperia	PALMSPR/HES002	17	10	14.3
14a	Morgan Hill 1984/04/24 21:15	1656 Hollister Diff Array #5	MORGAN/HD5255	21	11	14.3
14a	Trinidad, California 1980/11/08 10:27	1498 Rio Dell Overpass, E Ground	TRINIDAD/B-RDE000	12	7	15.4
14a	Friuli, Italy 1976/05/06 20:00	8004 Codroipo	FRIULI/A-COD000	19	11	14.3
14b	Landers 1992/06/28 11:58	90020 LA—W 15th St	LANDERS/W15180	36	20	13.2
14b	Northridge 1994/01/17 12:31	90070 Covina—W. Badillo	NORTHR/BAD270	15	9	14.3
14b	Imperial Valley 1979/10/15 23:16	5052 Plaster City	IMPVALL/H-PLS135	10	6	14.3
14b	Borrego Mtn 1968/04/09 02:30	475 Pasadena—Athenaeum	BORREGO/A-PAS180	38	21	14.3
14b	Coalinga 1983/05/02 23:42	36451 Parkfield—Cholame 6W	COALINGA/H-C06090	13	8	14.3
14b	N. Palm Springs 1986/07/08 09:20	754 Colton Interchange—Vault	PALMSPR/CLI082	10	6	14.3
14b	San Fernando 1971/02/09 14:00	12331 Hemet Fire Station	SFERN/H05135	16	9	15.4
14b	Taiwan SMART1(25) 1983/09/21	25 SMART1 C00	SMART1/25C00NS	15	8	13.2
14b	Taiwan SMART1(33) 1985/06/12	25 SMART1 C00	SMART1/33C00NS	12	6	14.3
14b	Whittier Narrows 1987/10/01 14:42	24526 Lancaster—Med Off FF	WHITTIER/A-LMD010	11	7	14.3
22a	Landers 1992/06/28 11:58	12025 Palm Springs Airport	LANDERS/PSA090	36	22	19.8
22a	Northridge 1994/01/17 12:31	90065 Glendora—N. Oakbank	NORTHR/OAK080	17	9	24.2
22a	Coalinga 1983/05/02 23:42	36412 Parkfield—Cholame 4AW	COALINGA/H-C4A000	13	8	20.9
22a	Duzce, Turkey 1999/11/12	Fatih	DUZCE/FAT270	44	21	24.2
22a	Kern County 1952/07/21 11:53	135 LA—Hollywood Stor FF	KERN/HOL090	31	19	20.9
22a	San Fernando 1971/02/09 14:00	272 Port Hueneme	SFERN/PHN270	48	24	20.9
22a	Kobe 1995/01/16 20:46	0 FUK	KOBE/FUK090	33	19	19.8
22a	Borrego 1942/10/21 16:22	117 El Centro Array #9	BORREGO/B-ELC090	30	16	23.1
22a	Chalfant Valley 1986/07/21 14:42	1661 McGee Creek Surface	CHALFANT/A-MCG360	12	7	24.2
22a	Whittier Narrows 1987/10/01 14:42	90044 Rancho Palos Verdes—Luconia	WHITTIER/A-LUC186	16	9	24.2
22b	Landers 1992/06/28 11:58	90061 Big Tujunga, Angeles Nat F	LANDERS/TUJ262	33	17	19.8
22b	Northridge 1994/01/17 12:31	90081 Carson—Water St.	NORTHR/WAT180	23	13	22
22b	Imperial Valley 1979/10/15 23:16	6605 Delta	IMPVALL/H-DLT262	51	26	24.2
22b	Duzce, Turkey 1999/11/12	Kocamustafapaba Tomb	DUZCE/KMP090	40	21	22
22b	Kern County 1952/07/21 11:53	135 LA—Hollywood Stor FF	KERN/HOL180	29	17	19.8
22b	El Alamo 1956/12/17 14:33	117 El Centro Array #9	ELALAMO/ELC180	37	19	24.2
22b	Borrego 1942/10/21 16:22	117 El Centro Array #9	BORREGO/B-ELC000	29	14	19.8
22b	Chalfant Valley 1986/07/21 14:42	1661 McGee Creek Surface	CHALFANT/A-MCG270	12	7	26.4
22b	Whittier Narrows 1987/10/01 14:42	90056 Newhall—W Pico Canyon	WHITTIER/A-WPI316	11	7	20.9
22b	Morgan Hill 1984/04/24 21:15	57066 Agnews State Hospital	MORGAN/AGW330	40	23	20.9

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REFERENCES

1. Sewell RT. Impacts of earthquake strong motion duration on inelastic structural response factors and on ground-motion damage potential. *Final Report*, Risk Engineering Inc., 1993.
2. Cosenza E, Manfredi G. Damage indices and damage measures. *Progress in Structural Engineering and Materials* 2000; **2**:50–59.
3. Vamvatsikos D, Cornell CA. Incremental dynamic analysis. *Earthquake Engineering and Structural Dynamics* 2002; **31**:491–514.
4. Bommer J, Magenes M, Hancock J, Penazzo P. The influence of strong-motion duration on the seismic response of masonry structures. *Bulletin of Earthquake Engineering* 2004; **2**:1–26.
5. Uang CM, Bertero VV. Evaluation of seismic energy in structures. *Earthquake Engineering and Structural Dynamics* 1990; **19**:77–90.
6. Malhotra PK. Cyclic-demand spectrum. *Earthquake Engineering and Structural Dynamics* 2002; **31**:1441–1457.
7. Kunnath SK, Chai YH. Cumulative damage-based inelastic cyclic demand spectrum. *Earthquake Engineering and Structural Dynamics* 2003; **33**:499–520.
8. Trifunac MD, Brady AG. A study on the duration of strong earthquake ground motion. *Bulletin of the Seismological Society of America* 1975; **65**:581–626.
9. Trifunac MD, Novikova EI. Duration of strong ground motion in terms of earthquake magnitude epicentral distance, site conditions and site geometry. *Earthquake Engineering and Structural Dynamics* 1994; **23**: 1023–1043.
10. Cosenza E, Manfredi G. The improvement of the seismic-resistant design for existing and new structures using damage criteria. In *Seismic Design Methodologies for the Next Generation of Codes*, Fajfar P, Krawinkler H (eds). Balkema: Rotterdam, 1997; 119–130.
11. Manfredi G. Evaluation of seismic energy demand. *Earthquake Engineering and Structural Dynamics* 2001; **30**:485–499.
12. Mahin SA, Bertero VV. An evaluation of inelastic seismic design spectra. *Journal of Structural Division* (ASCE) 1981; **107**:1777–1795.
13. Krawinkler H, Nassar AA. Seismic design based on ductility and cumulative damage demands and capacities. In *Nonlinear Seismic Analysis and Design of Reinforced Concrete Buildings*, Fajfar P, Krawinkler H (eds). Elsevier Applied Science: Oxford, 1992; 23–40.
14. Cosenza E, Manfredi G, Ramasco R. The use of damage functionals in earthquake engineering: a comparison between different methods. *Earthquake Engineering and Structural Dynamics* 1993; **22**:855–868.
15. Fajfar P, Vidic T. Consistent inelastic design spectra: hysteretic and input energy. *Earthquake Engineering and Structural Dynamics* 1994; **23**:523–532.
16. Farrow KT, Kurama YC. SDOF demand index relationships for performance-based seismic design. *Earthquake Spectra* 2003; **19**:799–838.
17. Cornell CA, Sewell RT. Non-linear behavior intensity measures in seismic hazard analysis. *Proceedings of the International Workshop on Seismic Zonation*, Guangzhou, China, December 1987.
18. Conte JP, Pandit H, Stewart JP, Wallace J. Ground motion intensity measures for performance-based earthquake engineering. *Proceedings of the Ninth International Conference on Applications of Statistics and Probability in Civil Engineering* (*ICASP9*), San Francisco, CA, U.S.A., 2003.
19. Shome N, Bazzurro P, Cornell CA, Carballo JE. Earthquakes, records, and nonlinear MDOF responses. *Earthquake Spectra* 1998; **14**:469–500.
20. Iervolino I, Cornell CA. Record selection for nonlinear seismic analysis of structures. *Earthquake Spectra* 2005; **21**(3):685–713.
21. Benjamin JR, Cornell CA. *Probability Statistics and Decision for Civil Engineers*. McGraw-Hill: New York, 1970.
22. Lanzano G. Effetti, sulla Risposta Sismica delle Strutture, della Durata del Terremoto. *B.S. Thesis*, Department of Structural Analysis and Design, University of Naples Federico II, Italy. Advisor: E. Cosenza, co-advisor: I. Iervolino, 2004 (in Italian).

