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DAMAGE POTENTIAL OF NEAR-SOURCE GROUND MOTION RECORDS

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ABSTRACT

The assessment of structural response induced by earthquakes for both design and evaluation is often made using ground motion intensity measures, IMs, as predictors. The most widely used IM is the spectral acceleration, S_a, at the structure's fundamental period of vibration, T_1. Unless the response of the structure is first-mode dominated and not significantly beyond the onset of damage, the response variability for records with the same value of $S_a(T_1)$ is still considerable. We investigate whether we can identify "non-stationary" features of near-source, forward-directivity accelerograms that, in addition to S_a, improve structural response estimation. To simplify the search for useful signal characteristics beyond spectral values, the records are compatibilized to a common spectrum prior to use. We show that, for the considered structures, velocity pulse characteristics and record duration do not appreciably improve the accuracy of the response estimates beyond that achieved by using linear elastic spectral values alone. This study also demonstrates that accelerograms cannot be labeled as "aggressive" or "benign" without considering a particular structural vibration period and specific yield strength, F_y. Hence, record characteristics that do not account for T_1 and F_y are not likely to be "good" response predictors. For this reason, inelastic spectral displacement and the first significant elastic peak displacement of a single-degree-of-freedom (SDOF) oscillator of period T_1 are more effective structural response predictors.

Introduction

For structural engineers in seismic regions, the relationship between earthquake ground motion and structural response is of primary concern. Modern nonlinear dynamic analysis software allows engineers to more realistically estimate the structural response and damage resulting from a earthquake ground motion time history (i.e., an accelerogram). Although an accelerogram is the only characteristic of ground motion that is directly measured, it is more convenient to quantify the ground motion data by means of parameters derived from the accelerogram, such as peak ground acceleration (PGA) or elastic spectral quantities for acceleration, velocity, or displacement (S_a, S_v, and S_d, respectively). Parameters such as these are critical in estimating (or "predicting") the likelihood of specified levels of seismic response, of structural and non-structural damage, and ultimately of monetary loss for a given structure or for a portfolio of structures. To perform these risk assessment tasks efficiently and precisely, ground motion parameters that are strongly correlated with structural response are necessary.

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In the past few decades many researchers have linked the damage effectiveness of an earthquake time history to intensity measures such as PGA or, more recently, elastic spectral quantities. PGA is now widely regarded as a relatively poor indicator of most structural damage. Spectral quantities, instead, have been observed to be efficient predictors of structural performance for first-mode dominated structures subject to "ordinary" (i.e., not pulse-like) ground motions. For multi-mode dominated structures, a combination of S_a's at different frequencies can be used to achieve more predictive power (Bazzurro and Cornell, 2002). Particularly for pulse-like ground motions, inelastic spectral quantities have been demonstrated to be more efficient (Luco, 2002). Some researchers have considered time-domain rather than frequency-domain characteristics of earthquake records. Among others, Iwan *et al.* (1998), MacRae and Roeder (1999), and Alavi and Krawinkler (2001) have pointed out that time-domain features of near-source records, such as the amplitude and the period of the velocity pulse, considerably affect the building responses.

Given the remaining variability in the inelastic structural response for ground motions with the same elastic spectrum (which is quantified in this paper), the studies referred to above suggest that it may be more effective to include parameters of non-stationary time-domain "features" of the input ground motion in a pool of response predictors with frequency-domain-based quantities. We intend to test this hypothesis here. We address the response prediction of a multi-mode-dominated building of four different "strength" levels subject to near-source, forward-directivity, strike-orthogonal ground motion records.

Description of Earthquake Ground Motion Records

The 31 near-source ground motions considered are the same as those utilized in Paper No.1029 of these proceedings by Bazzurro and Luco (2006a) and described in detail in an appendix of (Luco, 2002). In brief, the records are strike-normal ground motion components recorded at rupture-to-site distances, R_{close}, shorter than or equal to 16km on stiff soil under forward directivity conditions. The records were generated by four different shallow crustal earthquakes in California with moment magnitude, M_w, between 6.5 and 6.9. Prior to using them as input to the structural analyses, the 31 records were modified in such a way that their spectra match a smooth target constituted by the median spectrum of the entire ensemble. The 31 original spectra and the target median spectrum are shown in Figure 1 of (Bazzurro and Luco, 2006a). The compatibilization was done using the time-domain, wavelet-based software RSPMATCH (Abrahamson, 1993). We must emphasize that we use spectrum-compatible records only to facilitate the search for time-domain characteristics of a signal to include in a suite of predictors along with elastic spectral quantities. Given that all of the records have the same elastic spectrum, the effectiveness of each additional predictor is immediately apparent without the need to resort to multiple regression analysis on both S_a's and the newly proposed predictors. Note that the spectrum compatibilization was done here in the time domain rather than in the frequency domain. The findings shown in this paper, however, have been confirmed by a larger-scope study (Bazzurro and Luco, 2006b) in which both a suite of real records and a suite of spectrum-compatible records matched in the frequency domain were also utilized.

Non-stationary Time-Domain Features

The non-stationary time-domain features considered as potential response predictors are the number of half-pulses, $n_{pulses/2}$, the pulse period, T_p, and the peak velocity, V_{peak}. In addition, we also consider the record duration, T_H, computed as the difference between the times corresponding to 95% and 5% of the total Arias intensity (Trifunac and Brady, 1975). Not all of the records (either original or spectrum-matched) show the distinct velocity pulse that one may expect in near-source, forward-directivity strike-normal components, and those that do can have an odd or even number of lobes. The records that do not show a clear pulse tend to have short T_p values and are assigned a value of $n_{pulses/2}$ equal to one. For the spectrum-matched records, the average value of $n_{pulses/2}$ is 1.4. The parameter V_{peak} varies from about 20 to over 70 cm/sec, with a median value of 53 cm/sec, while T_p ranges from approximately 1 to 5 sec, with a median value of 2.8 sec. T_H also varies considerably from record to record, from about 6 to 24 sec.

We estimate the values of V_{peak} and T_p in two different ways. In the first approach we simply read the maximum value of V_{peak} from the original velocity time history and estimate T_p by looking at the zero-crossings of the velocity pulse that bracket the peak value. The second approach does the same with a velocity time history derived from the original one by a signal processing technique known as the Empirical Mode Decomposition (EMD) (Huang *et al*., 1998). EMD decomposes the original signal into non-stationary nearly-orthogonal "modes" whose sum recovers the original signal, within a small tolerance. The first few modes remove the high-frequency waves that "ride" the long-period ones, thus revealing a clearer picture of the velocity pulse. The values of V_{peak} and T_p from the two methods are usually slightly different. The values of V_{peak} computed by the EMD-based procedure tend to be smaller than those from the original time history, while the values of T_p are equally likely to be either smaller or larger than those computed using the first method. The findings presented later, however, apply to either of the methods for computing the V_{peak} and T_p values. Here we will discuss in detail only those based on the use of the EMD method.

The LA9 SMRF Building and its Variants

The four building we considered are the SAC Steel Project 9-story Steel Moment-Resisting Frame (SMRF) (FEMA, 2000) designed for Los Angeles conditions (called here LA9), and three weaker “sister” buildings ($LA9_{1/2}$, $LA9_{1/4}$, and $LA9_{1/8}$) that have 50%, 25%, and 12.5% the lateral strength of LA9, respectively (i.e., strength reduction factor, *R*, equal to 2, 4, and 8, respectively). All four buildings have a fundamental period of vibration, T_1, equal to about 2.2 sec. The weaker versions of the LA9 building are obtained not by re-designing the structures but instead by scaling up all of the records considered by 2, 4, and 8 times and dividing the resulting responses by the same factors, respectively. This alternative is convenient and presumably provides similar (identical for SDOF structures) results to those that could be obtained by re-designing the LA9 building for progressively less severe seismic environments and keeping the records un-scaled. We recognize, however, that a realistic re-design of weaker structures would not likely preserve exactly the same stiffness, mass, and therefore the same T_1 of the LA9 building. Nevertheless, the sister buildings are useful for exploring the realm of more severe nonlinear responses. Finally, note that although LA9 was designed according to pre-Northridge practices, here the beam-column connections are modelled as ductile, as if they had been retrofitted to avoid fracture.

Analysis of the Structural Responses

It is widely known that a ground motion record may have higher than average energy content at some periods and be more deficient than average at others. Hence, basic engineering principles suggest that a record may be highly damaging for some structures and less severe for others of different periods. This is why a ground motion parameter that accounts for T_1 of a structure (e.g., S_a at T_1) is a more powerful response predictor than one that does not (e.g., PGA). What is less obvious is the extent to which a record that is either very damaging or very benign for a structure of a given T_1 maintains its effectiveness in creating damage to *all* structures of the same period but of different strengths. In other words, *are there any non-stationary features of a signal that particularly affect the response of all structures at a given period*?

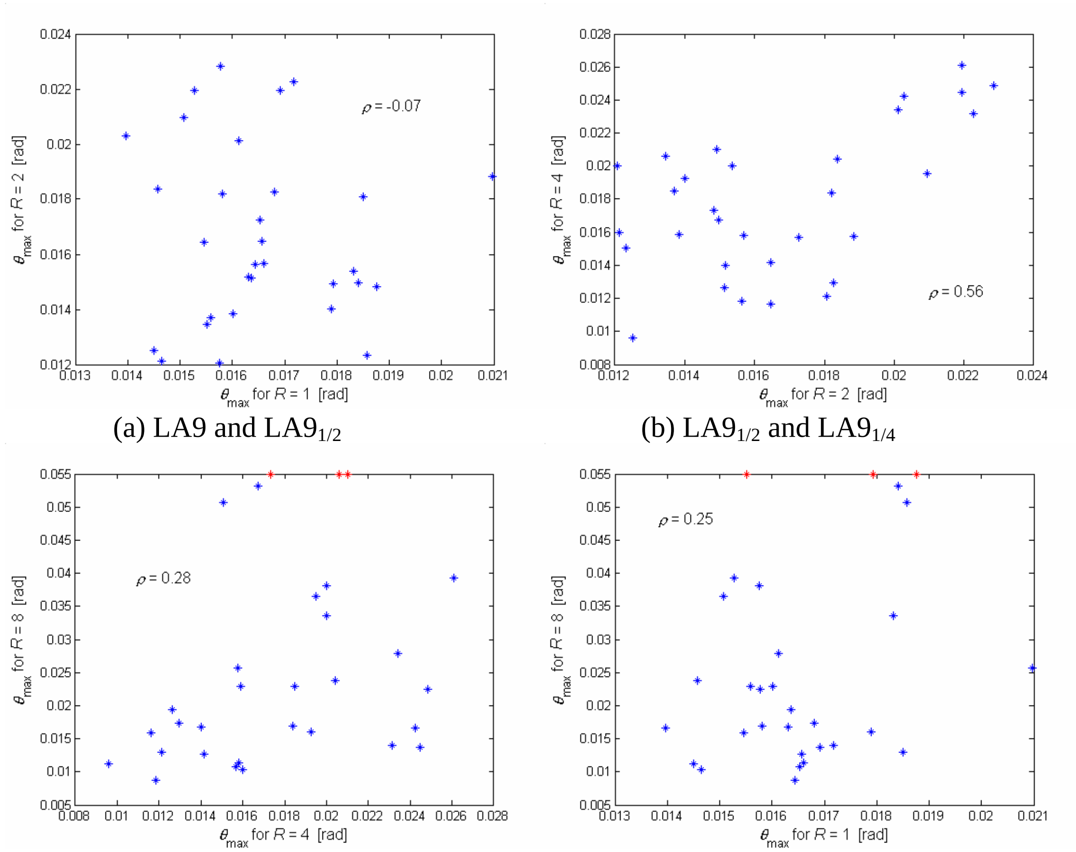
If the answer is affirmative, and if such features of a signal can be predicted in terms of the basic random variables M_w (magnitude) and R_{close} (distance) used in Probabilistic Seismic Hazard Analysis (PSHA), then the parameters of these features can be utilized as response predictors in the same fashion that PGA and S_a are used today. This would require only developing new attenuation equations, a conceptually straightforward task. If the answer is negative, however, and a record's damaging ability depends not only on the period of a structure but also, say, on its "strength," then one can conclude that there is nothing intrinsic in a ground motion time history that makes it particularly damaging or benign for all structures with the same T_1. In this case, for a ground motion parameter to be an effective response predictor it should also account for the structure's strength.

Table 1. Nonlinear dynamic drift results for the SAC LA9 building and its three weaker sister buildings. The $LA9_{1/2}$, $LA9_{1/4}$, and $LA9_{1/8}$ building models have approximately 1/2, 1/4, and 1/8 the lateral strength of LA9. The median and COV for $LA9_{1/8}$ are "counted statistics," due to the collapses.

	LA9	$LA9_{1/2}$	$LA9_{1/4}$	$LA9_{1/8}$
Min	0.014	0.012	0.010	0.009
Median	0.016	0.016	0.017	0.019
Max	0.021	0.023	0.026	"collapse"
COV	0.090	0.190	0.260	0.540
% Collapses	0/31	0/31	0/31	3/31

In order to investigate this question the 31 spectrum-matched records were run through the LA9, $LA9_{1/2}$, $LA9_{1/4}$, and $LA9_{1/8}$ building models. We gauged the response by the largest peak (over time) of inter-story drift ratio (drift normalized by story height), denoted θ_{max}, at any one of the 9 stories. Table 1 shows the median calculated as the geometric mean of θ_{max}, and the standard deviation of the natural logarithms of θ_{max}, which is numerically close to the coefficient of variation (COV). Note that 3 out of the 31 records caused "collapse" of the $LA9_{1/8}$ building, which here means that equilibrium could not be reached and numerical instability developed before the analysis could complete. The θ_{max} results are plotted as paired samples in Figure 1. In particular, we have paired results that are almost linear (for LA9) to those that are severely nonlinear (for $LA9_{1/8}$), and other combinations in between. The trend, when it exists, is usually positive but extremely mild. More rigorously, the correlation coefficient, ρ, ranges from -0.07 for the LA9 vs. $LA9_{1/2}$ comparison, to 0.56 for the $LA9_{1/2}$ vs. $LA9_{1/4}$ case. This mild correlation implies that a record that causes a larger than average response in a "strong" building (e.g., LA9) of vibration period T_1 (here 2.2 sec) may very well be more benign than average for a weaker building with the same fundamental period (e.g., $LA9_{1/4}$). This statement is even more interesting if we remember that these results are generated by records that share the same elastic response spectrum (i.e., they cause the same maximum elastic response in SDOF systems at all periods) for structures that, aside from the yield strength, are identical.

These findings are more general than shown by the example above. The same mild correlation was also found when a) real rather than spectrum-matched records were used (in this case conditional on S_a at $T_{1=}$2.2s rather than the entire spectrum); b) spectrum-matched records were run through SDOF systems rather than these four multi-degree-of-freedom structures; and c) when energy-based parameters (such as, for example, input energy) were used in place of a peak response parameter such as θ_{max} (Bazzurro and Luco, 2006b).



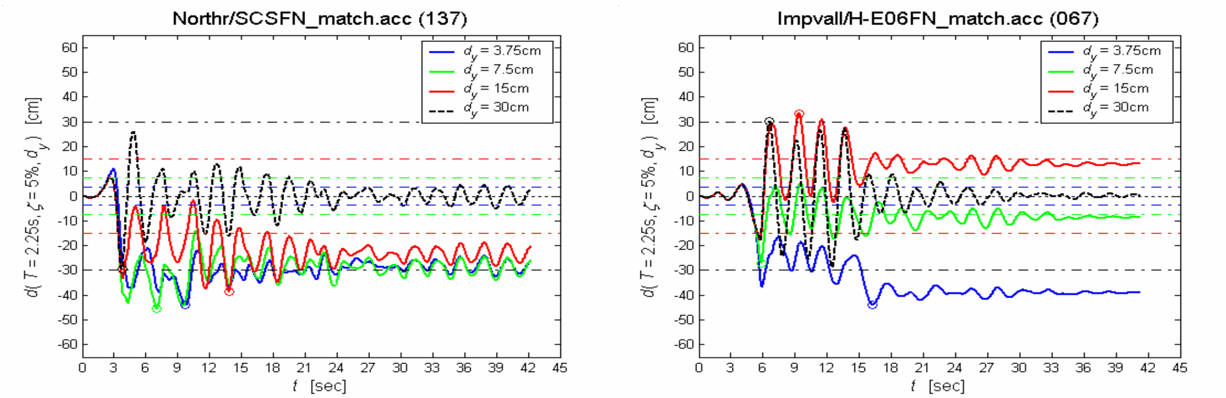
(a) LA9 and LA9$_{1/2}$ (b) LA9$_{1/2}$ and LA9$_{1/4}$

(c) LA9$_{1/4}$ and LA9$_{1/8}$ (d) LA9 and LA9$_{1/8}$

Figure 1. Drift results for the four different LA9 sister buildings, plotted as paired samples. The quantity ρ is the correlation coefficient. The three asterisks on the top margin of the graphs in panels (c) and (d) represent the three collapse cases reported in Table 1.

In summary, records appear to be damaging or benign only in relation to a structure with a particular period of vibration *and a particular strength*. No time-domain feature, at least for this record set and these structures, seems to make an accelerogram either aggessive or "gentle," *per-se,* for all structures with the same vibration period but different strengths. As suggested earlier, an immediate consequence of this finding is that for a response predictor to be effective (when considered along with spectral values), it should account for the structure's strength, not just its fundamental vibration period.

To gain insights into the reasons for the somewhat unexpected lack of strong correlation described in the preceding subsection, we repeated the same nonlinear dynamic analyses for an elastic-perfectly-plastic SDOF oscillator with the same T_1 = 2.2 sec as the four sister buildings and with F_y estimated from a static pushover curve for LA9. Again, we considered four different yield strength levels, F_y, $F_y^{R=2}$, $F_y^{R=4}$, and $F_y^{R=8}$, where the latter three are obtained by dividing F_y by a strength reduction factor of 2, 4, and 8, respectively. The corresponding values of yield displacements in the four cases are d_y=30cm, $d_y^{R=2}$=15cm, $d_y^{R=4}$=7.5cm, and $d_y^{R=8}$=3.75cm. We singled out two records: Record 1 creates severe post-elastic responses consistently at the three yield strength levels $F_y^{R=2}$, $F_y^{R=4}$, and $F_y^{R=8}$, whereas Record 2 is fairly severe at the $F_y^{R=2}$ and $F_y^{R=8}$ levels, but rather benign at the $F_y^{R=4}$ level. Figure 2 shows the two sets of SDOF displacement time traces. The horizontal dotted-dashed lines mark the d_y in the four cases, while the open circles represent the peak displacement over time, namely S_d^I. The black line, which shows the elastic response obtained for the F_y case, has its maximum absolute value equal to d_y = 30cm, as expected, and oscillates around the zero-displacement line. The other three responses all enter the post-elastic regime before the record is over. All four time traces coincide until the pertinent yield displacement (i.e., $d_y^{R=2}$, $d_y^{R=4}$, or $d_y^{R=8}$) is exceeded, and after that time the traces depart from one another. The amount of separation seems to be dependent on how far beyond the yield displacement the first significant peak is.



(a) Record 1 (b) Record 2

Figure 2. Time histories of the SDOF displacements generated by two records for yield displacements d_y=30cm, $d_y^{R=2}$=15cm, $d_y^{R=4}$=7.5cm, and $d_y^{R=8}$=3.75cm. The open circles represent the peak values over time.

Panel (a) of Figure 2 shows that, in the three nonlinear cases, the first peak that considerably exceeds the yield levels is negative and occurs at about 4 sec. The displacement for the $F_y^{R=8}$ also exceeded $d_y^{R=8}$ before 3 sec, but not enough to cause a major departure from linearity. The excursion to the post-elastic regime at about 4 sec in all three $F_y^{R=2}$, $F_y^{R=4}$, and $F_y^{R=8}$ cases is so severe that the displacement cannot recover. Hence, this record is damaging for all the yield strengths. Panel (b) of Figure 2 shows a different picture. The first large excursion is again negative and occurs around 6 sec. For the $F_y^{R=8}$ case, the exceedance of $d_y^{R=8}$ is so significant that, again, the system drifts away to large negative displacements. For the $F_y^{R=4}$ case, however, the exceedance of $d_y^{R=4}$ is not severe enough to prevent the system from being pushed back by the next large ground motion peak in the opposite direction. After being re-centered, the displacement keeps oscillating around relatively small values. In the last $F_y^{R=2}$ case, the first exceedance of $d_y^{R=2}$ is minor, but the next ground motion peak pushes the SDOF system well beyond yield in the positive direction. In summary, this record is very "benign" at the $F_y^{R=4}$ level and fairly severe at the $F_y^{R=2}$ and $F_y^{R=8}$ levels.

This qualitative rationale as to why the maximum inelastic displacement can be either small or large is also applicable to the other ground motions and 9-story buildings considered here.

Figure 3 shows scatter plots of θ_{max} versus pulse period, T_p, peak velocity, V_{peak}, and number of half-pulses, $n_{pulses/2}$, and versus the ground motion duration, T_H. The results are plotted for the $LA9_{1/4}$ building. The results for the LA9, $LA9_{1/2}$, and $LA9_{1/8}$ models, omitted here for brevity, are similar to those shown and can be found in (Bazzurro and Luco, 2006b). Each asterisk represents the nonlinear dynamic analysis result for one of the 31 spectrum-matched records. An inspection of Figure 3 shows that the correlation between θ_{max} and T_p, V_{peak}, $n_{pulses/2}$, and T_H is too weak to be useful for prediction. Only for the $LA9_{1/4}$ building was a mild positive trend found with T_p, which implies that longer pulse periods, on average, generate larger responses in this case. This is to be expected, to the extent that the inelasticity that occurs during the ground shaking tends to elongate the effective structural vibration period to values close to the larger T_p's in this data set. Miranda and his co-workers (as reported in Comartin, 2002) and Alavi and Krawinkler (2001) have found similar results (for non spectrum-matched records). For the LA9, $LA9_{1/2}$, and $LA9_{1/8}$ buildings, however, there is almost no correlation between T_p and θ_{max}. Given that T_p does not reflect the strength level, it is not too surprising that the correlation of T_p with θ_{max} is non-negligible for only one of the strength levels. The very weak negative trend with V_{peak} is contrary to engineering intuition that would suggest a positive trend instead. Once again, however, it is important to keep in mind that all of the records used here have the same elastic spectrum. The lack of correlation with T_H is also counter-intuitive to some extent, but is in agreement with findings of previous studies (e.g., Sewell, 1993).

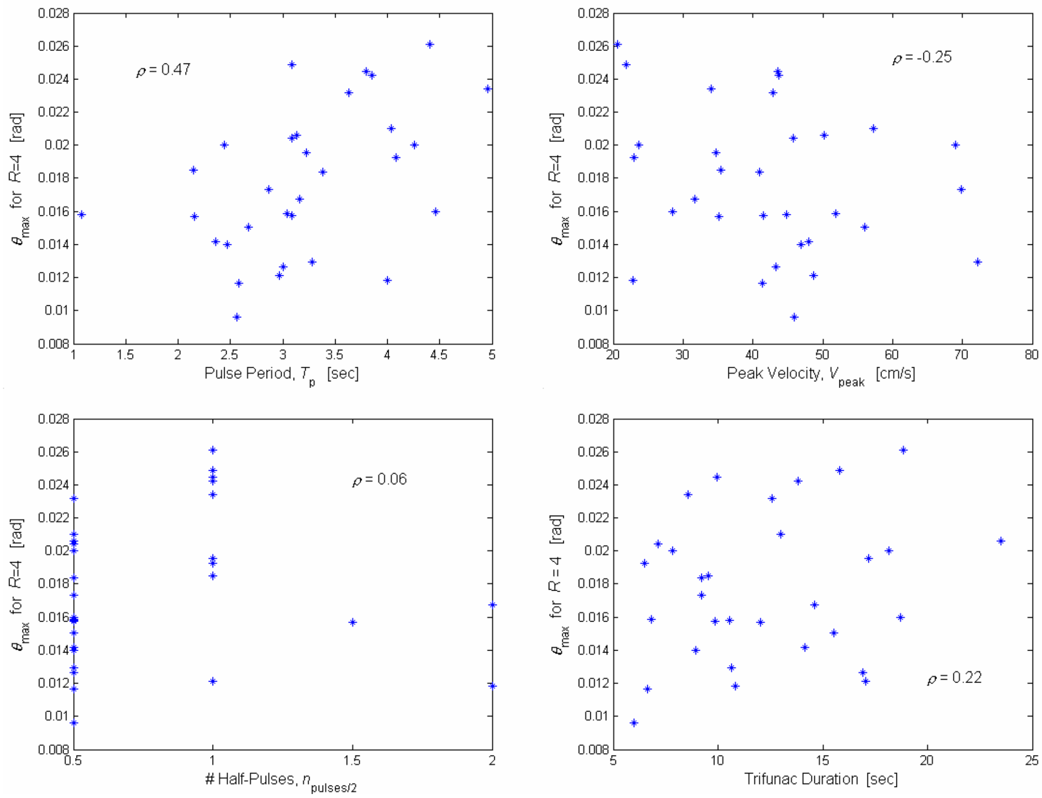


Figure 3. Scatter plots of θ_{max} versus T_p, V_{peak}, $n_{pulses/2}$, and T_H, obtained for the $LA9_{1/4}$ building. The quantity ρ is the correlation coefficient. Keep in mind that these results are for records that have identical elastic response spectra.

Table 2. Measure of the spectrum-matched record-to-record variability of θ_{max} for the LA9, LA9$_{1/2}$, LA9$_{1/4}$, and LA9$_{1/8}$ buildings that is left "unexplained" after a linear regression on the predictor(s) in the first column. The results for LA9$_{1/8}$ exclude the three earthquake records that caused collapse.

Predictor(s)	COV of θ_{max}			
	LA9	LA9$_{1/2}$	LA9$_{1/4}$	LA9$_{1/8}$
None (Spect. Comp.)	0.09	0.19	0.26	0.49
Trifunac Duration	0.09	0.19	0.26	0.49
T_p & V_{peak} (via EMD)	0.09	0.19	0.24	0.51

More formally, linear regression analyses of θ_{max} on the four candidate predictors T_p, V_{peak}, $n_{pulses/2}$, and T_H, considered both separately and in different combinations, are also performed. We are interested in monitoring the reduction in the record-to-record response variability "explained" by including one or more predictors in the regression model. The reduction in variability directly translates into a lower number of analyses needed to achieve a prescribed accuracy in the response estimates (see Eq.1 in Bazzurro and Luco, 2006a). The quantitative results for T_p and V_{peak} (together) and T_H (alone) are shown in Table 2, where the first row represents the initial benchmark, namely the variability explained by the response spectrum alone (via spectrum-matching). Nearly identical results (not shown here) are obtained from regressions on T_p, V_{peak}, and $n_{pulses/2}$, independently or all together. Clearly the extra variability explained by the additional predictors is negligible. This means that the characteristics of the velocity pulse (T_p, V_{peak}, $n_{pulses/2}$) and the duration of the record (T_H) do not add information for the prediction of θ_{max} that is not already carried by the spectral values. In other words, if the spectral values are already used for the prediction of θ_{max}, and here they implicitly are via spectrum-matching, then the knowledge of T_p, V_{peak}, $n_{pulses/2}$, and T_H does not seem to improve the prediction. Note that this conclusion is not in contrast with findings by Iwan *et al.* (1998), MacRae and Roeder (1999), and Alavi and Krawinkler (2001). These researchers used real records with un-matched response spectra. If spectral values are not used as predictors, the information carried by the pulse characteristics can be expected to become more valuable for response estimation.

Inelastic spectral displacement and first significant elastic peak displacement

Among the possible ground motion parameters that account for both T_1 and d_y we tested the predictive power of a) the inelastic spectral displacement, S_d^I, of the elastic-perfectly-plastic SDOF oscillator with the same T_1 as the corresponding 9-story building and a d_y based on its static pushover curve), and b) the first peak of the elastic displacement response of the SDOF system with period T_1 that is "significantly" higher than the yield strength d_y, denoted here as P_1^E. More specifically, P_1^E is the first peak of the elastic response that exceeds 1.2 x $d_y^{R=2}$ for LA9$_{1/2}$, 1.8 x $d_y^{R=4}$ for LA9$_{1/4}$, and 2.0 x $d_y^{R=8}$ for LA9$_{1/8}$. (These margins beyond d_y used to identify P_1^E were found to be fairly stable for other SDOF structures with different T_1.) The use of P_1^E was motivated by the considerations presented earlier when discussing Figure 2. The correlation (ρ) of θ_{max} with S_d^I and P_1^E are higher than those obtained for any of the combinations of T_p, V_{peak}, $n_{pulses/2}$, and T_H considered earlier. This is especially true for S_d^I, in which case ρ varies from 0.66 for LA9$_{1/2}$ to 0.78 for LA9$_{1/8}$. The formal regression analysis results of θ_{max} on

S_d^I and on P_1^E are shown in Table 3. The knowledge of either of these two parameters reduces the record-to-record variability of the responses for all the buildings, and especially for $LA9_{1/4}$ and $LA9_{1/8}$, although more so for S_d^I than for P_1^E. This translates into considerably fewer nonlinear runs needed to achieve comparable accuracy in the median response estimate (see numbers in parentheses in Table 3). See Bazzurro and Luco (2006b) for more details on the use of S_d^I and P_1^E.

Table 3. Measure of the record-to-record variability of θ_{max} left "unexplained" after a linear regression on the predictor(s) in the first column. The minimum number of records needed to estimate the median response with ±10% accuracy is in parenthesis.

Predictor	COV of $\theta_{\max}$		
	$LA9_{1/2}$	$LA9_{1/4}$	$LA9_{1/8}$
None (Spect. Comp.)	0.19 (4)	0.26 (7)	0.49 (24)
First (in time) Significant Peak Elastic Displacement	0.16 (3)	0.21 (4)	0.45 (20)
$S_d(T_1$=2.2s, ζ=5%, d_y=30cm/$R)$	0.15 (2)	0.20 (4)	0.30 (9)

Summary and Conclusions

This article presents findings on the use of time-domain ground motion characteristics in addition to customary elastic spectral values as predictors of nonlinear structural response. We have limited our study to four steel moment-resisting frames subjected to near-source accelerograms recorded under forward-directivity conditions. To simplify the statistical analyses, the ground-motion records are spectrum-matched to the median elastic spectrum of the suite prior to computing the structural response via nonlinear dynamic analysis. The structural response gauge is the maximum inter-story drift ratio. The validity of the findings presented here, however, is broader. They apply to ground motions spectrum-matched with other algorithms and to real ground motions, and also to response measures that are energy- rather than peak-based.

This study demonstrates that there is nothing clearly intrinsic in the time signal of a ground motion record that makes it either very damaging or very benign to all structures of different periods and strengths. There is only a mild correlation between the nonlinear response of a strong and of a weak structure with the same initial fundamental period of vibration subjected to the same record. The damage potential of a record is a more meaningful concept when addressed in conjunction with a given period *and strength* of the structure of interest. We showed that several time-domain characteristics of near-source records (i.e., the amplitude and the period of the velocity pulse, and the number of half-pulses) do not seem to carry *additional* response-prediction power not already provided by customary elastic spectral quantities. Similarly, the duration of the record was not found to be a useful additional predictor, at least for assessing the response of ductile buildings. The fact that these four ground motion parameters do not explicitly account for the period or strength of a structure seems to limit their predictive power. In contrast, the inelastic spectral displacement of an elastic-perfectly-plastic SDOF oscillator with about the same fundamental period and strength as the structure of interest, and the amplitude of the first "significant" peak of the *elastic* displacement response of the SDOF system, are more strongly correlated with the adopted response measure and lead to a significant reduction of the record-to-record response variability compared to the level achieved by using spectral values alone. This reduction translates into running fewer records to achieve the same level of accuracy in estimating the median response.

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