10CUEE CONFERENCE PROCEEDINGS
10th International Conference on Urban Earthquake Engineering
March 1-2, 2013, Tokyo Institute of Technology, Tokyo, Japan

INFLUENCE OF GROUND MOTION SPECTRAL SHAPE AND DURATION ON SEISMIC COLLAPSE RISK

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Abstract: The seismic collapse risk of a structure is largely influenced by the intensity and other characteristics of the earthquake ground motions. This study addresses the influence of the shape of the ground motion spectra and the ground motion duration on the structural collapse capacity, as determined by nonlinear response history analysis. The conditional spectrum is proposed as a more realistic characterization of spectral shape, compared to the commonly used uniform hazard spectrum. Ground motion duration is another important characteristic, which is quantified in terms of significant duration. The effects of spectral shape and duration on the estimated collapse capacity of a 5-story steel moment frame are demonstrated. Spectrally equivalent long and short duration record sets are employed to isolate the effects of duration. Preliminary findings indicate that cyclic strength and stiffness deterioration of components and accumulation of drift due to ratcheting can significantly reduce structural collapse capacity under long duration shaking.

1. INTRODUCTION

Calculation of the probability of structural collapse is an integral part of performance-based earthquake engineering. The intensity of ground excitation that causes structural collapse is a random variable, which is often defined by a lognormal cumulative distribution function called the collapse fragility curve – relating ground motion intensity to the probability of collapse. The collapse capacity is a common metric to evaluate the life-safety of buildings and an important component in loss assessment.

The process of estimating the collapse capacity of a structure first involves the creation of a nonlinear numerical model of the structure. Since collapse occurs after the structure has undergone large inelastic deformations, modeling the behavior of structural components at these large inelastic deformations is essential to obtain an accurate estimate of the collapse capacity. This behavior includes the cyclic and in-cycle deterioration of component strength and stiffness (see discussion of cyclic and in-cycle deterioration in FEMA Report 440, 2005).

The next step involves the selection of ground motions at different intensity levels where the characteristics of the chosen ground motions at each intensity level, such as response spectral shape (which acts as a surrogate for frequency content), duration and pulse-like characteristics closely match the characteristics of the ground motions that can be expected at the building site (NIST 2011). Choosing ground motions without ensuring this match in characteristics can lead to erroneous estimates of collapse capacity. This particular study addresses the effects of two of these characteristics: response spectral shape and duration. It is assumed that the expected values of ground motion characteristics for a particular site can be obtained either from seismic hazard curves or from seismic hazard deaggregation.

When different sets of ground motions are chosen at each intensity level, the analysis is called a Multiple Stripe Analysis (Jalayer 2003). On the other hand, where the same set of ground motions is scaled to different intensity levels, the analysis is called an Incremental Dynamic Analysis or IDA (Vamvatsikos and Cornell 2002, 2004). Multiple Stripe Analysis is considered to be more realistic and accurate than IDA since the expected spectral shape and other ground motion characteristics are likely to vary depending on the intensity level. This is in contrast to the linear scaling in the basic IDA procedure, which only addresses the change in ground motion intensity.

Nonlinear dynamic analysis is then conducted using the selected ground motion sets at each intensity level. During each analysis run, the structure is assumed to have collapsed if an unbounded increase in deformations is observed, or if the deformations exceed a rational pre-defined threshold (Haselton and Deierlein 2007). Residual deformations and other damage measures may be considered as an added layer of refinement in the performance assessment. The probability of collapse at each intensity level is then computed as the fraction of ground motions at the intensity level that causes collapse. The collapse fragility curve is then obtained by fitting a lognormal cumulative distribution function through these data points. Naturally, the number of ground motions used at each intensity level influences the accuracy of this estimate.

In this study, the reasons why response spectral shape and duration must be taken into account in ground motion selection are discussed. Finally, the effects of these two parameters on the collapse capacity of a 5-story steel special moment frame are demonstrated.

2. EFFECT OF SPECTRAL SHAPE

While a ground motion's intensity (represented here by $S_a(T_1, 5\%)$, the pseudo spectral acceleration at the 1st mode period and 5% of critical damping) alone is a strong predictor of structural response, it is well known that a structure will respond differently to two different ground motions even if they are scaled to have the same intensity. The reason for this is twofold. First, any multi-degree-of-freedom structure has many modes of vibration with different periods. Therefore, the response of such a structure is related not only to the response spectral ordinate of the ground motion at the fundamental mode period, but also to the ordinates at lower periods corresponding to the higher modes. Secondly, the spectral ordinate at any period is computed assuming linear elastic response, whereas the actual nonlinear response would usually lead to an effective elongation of the natural periods.

Due to the aforementioned reasons, spectral ordinates at periods lower and higher than the fundamental period of a structure influence its dynamic response. This effect of the spectral ordinates at all periods other than the fundamental period is referred to as the spectral shape effect. Statistical studies indicate that if two ground motions have the same $S_a(T_1, 5\%)$, and ground motion #1 has higher spectral ordinates at all other periods than ground motion #2, then ground motion #1 is more likely to result in a lower collapse capacity than ground motion #2 (Baker and Cornell 2008; Haselton et al. 2011).

This effect of spectral shape has large implications on the ground motion selection procedure, or more specifically, the response spectrum that should be used as a target for ground motion selection at each intensity level. As noted previously, the target response spectrum should be representative of the response spectra of ground motions that are expected to be observed at the site. One commonly used target response spectrum is the uniform hazard spectrum, UHS, whose ordinate at each period T is the $S_a(T, 5\%)$ value that has a specified probability of being exceeded each year, defined by the hazard level (hazard levels and spectral intensities being related by the traditional seismic hazard curve). These ordinates are obtained from Probabilistic Seismic Hazard Analysis, $PSHA$ (Kramer 1996; McGuire 2004) conducted at each individual period. As indicated in previous studies, such as Baker and Cornell (2006), traditional $PSHA$ ignores the joint probability of exceedance of a number of spectral ordinates at different periods. Therefore, once the $S_a(T_1, 5\%)$ corresponding to a certain probability of exceedance has been determined, it is conservatively assumed that expected ground motion spectral ordinates at other periods are exceeded with the same probability. Hence, it is conservative to use the UHS as the target response spectrum.

The conditional spectrum has been suggested as an alternative target response spectrum that overcomes the shortcomings of the UHS (Baker and Cornell 2006; Baker 2011; Lin et al. 2012). The conditional spectrum is defined by the conditional mean and standard deviation of the spectral ordinates at all other periods, given a spectral ordinate at a period known as the conditioning period. The conditioning period is often chosen as the 1st mode period of the structure, although other periods could be used. The conditional mean and standard deviation of spectral ordinates are obtained using seismic hazard deaggregation information and regression equations based on statistical observations of correlations between spectral ordinates (Baker and Jayaram 2008). Therefore, given a specified $S_a(T_1, 5\%)$, the conditional spectrum defines the mean and standard deviation of the expected spectral ordinates at all other periods. A procedure has been developed by Jayaram et al. (2011) to select a set of ground motions that match a target mean and standard deviation spectrum. While the conditional spectrum is not without its own challenges, such as the need to define a structure-dependent conditioning period, it provides a much more realistic representation of the seismic hazard than the UHS.

The UHS and conditional mean spectrum at the 2% in 50 year hazard level, for a site in San Francisco, are plotted in Figure 1. A set of 20 ground motions was selected from the PEER NGA West2 database (Ancheta et al. 2012) to match this UHS. Since the shape of the UHS does not change considerably at different intensity levels, this ground motion set was used to conduct an IDA. On the other hand, since the shape of the conditional spectrum changes considerably at different intensity levels, for the Multiple Stripe Analyses different sets of 20 ground motions were chosen to match the conditional spectra for 11 different intensity levels. As described later, collapse analyses using these three alternative ground motion sets were conducted: (1) an *IDA* using a single set matched to the 2% in 50 year UHS, (2) a Multiple Stripe Analysis using 11 different sets, each matched and scaled to the conditional spectra at 11 different intensities, and (3) an IDA using a single set of motions matched to the conditional spectrum at the 2% in 50 year hazard level.

3. EFFECT OF DURATION

After ground motion intensity and spectral shape have been accounted for, it is important to ensure that the durations of the selected set of ground motions match the expected ground motion duration at each intensity level (Bradley 2011). The expected durations could be obtained from seismic hazard deaggregation and a prediction model for duration. The reason duration is expected to influence the predicted collapse capacity is that structural components are known to deteriorate in strength and stiffness under cyclic loading. Therefore the longer the duration of shaking, the larger the number of deformation cycles each component is subjected to, which implies a larger deterioration in strength and stiffness. Moreover, once the

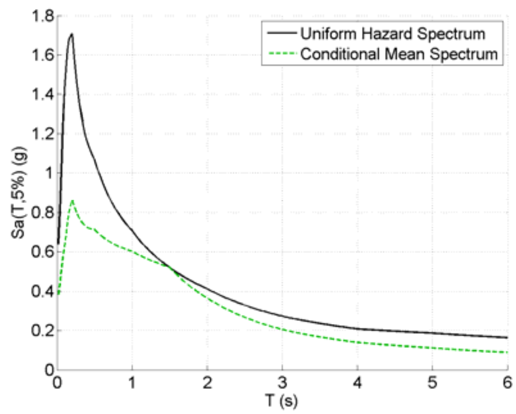


Figure 1: 2% in 50 year uniform hazard spectrum and conditional mean spectrum

structure has suffered inelastic deformations and deteriorated, long duration shaking further hastens sidesway collapse by ratcheting of deformations and drifts. Ratcheting is the phenomenon by which lateral inelastic deformations that occur early in a response history lead to amplified P-Δ moments that hasten subsequent sidesway collapse of the structure under later inelastic excursions in the same direction (Gupta and Krawinkler 2000).

Accurate evaluation of duration effects requires realistic nonlinear numerical models that incorporate in-cycle and cyclic deterioration of strength and stiffness (Ibarra et al. 2005; Lignos and Krawinkler 2011). As demonstrated below using a 5-story steel special moment frame, when included in the model, the combined effects of deterioration and ratcheting under long duration ground motions lead to significantly lower collapse capacities than short duration ground motions of similar intensity and spectral shape. The more ductile a structure and the faster the rate of deterioration, the larger the expected effect of duration of shaking (Ibarra and Krawinkler 2005).

Before the effect of ground motion duration on the predicted collapse capacity of a structure can be quantified, a suitable metric must first be chosen to measure the duration of strong shaking in an accelerogram. The observed correlation between ground motion duration and collapse capacity will largely depend on the chosen duration metric. A number of alternatives exist for defining the duration of an accelerogram (Bommer and Martinez-Pereira 1999). Among these, the following were identified as potential candidates:

- **Bracketed duration** is the time elapsed between the first and last excursions of the accelerogram above a certain acceleration threshold (commonly used thresholds are 0.05g and 0.10g).

- **Significant duration** is the time interval over which a specific percentage of the total energy represented by the integral $\int a^2 dt$ is accumulated, where a represents the ground acceleration. The commonly used ranges are 5% to 95% and 5% to 75% of the calculated energy.

- **Arias Intensity** $= \frac{\pi}{2g}\int_0^{t_{max}} a^2 dt$ is a measure of the energy contained in an accelerogram, where t_{max} represents the length of the accelerogram. Although not purely a metric of duration, Arias Intensity is considered here since it involves integration over time and is expected to be correlated to the duration of strong shaking.

- **Cumulative Absolute Velocity** $(CAV) = \int_0^{t_{max}} |a| dt$ is considered for the same reasons as the Arias Intensity above.

- $\boldsymbol{I_D} = \frac{\int_0^{t_{max}} a^2 dt}{PGA \times PGV}$ is a dimensionless duration metric proposed by Cosenza and Manfredi (1997), with PGA and PGV representing the peak ground acceleration and peak ground velocity respectively.

Each of the metrics defined above were evaluated against the following properties desired in a robust metric of ground motion duration for performance-based structural assessments:

- The duration metric should not be strongly correlated to commonly used intensity measures like pseudo spectral acceleration, since it is proposed that duration be considered *in addition* to intensity and spectral shape. As such, the duration metric should provide new information not quantified by those other measures.
- The duration metric should be unaffected by the process of scaling a ground motion since analysis procedures like IDA that involve ground motion scaling would then require the re-evaluation of ground motion duration at each new intensity level.
- The duration metric should not bias the spectral shape of the chosen ground motions. In other words, long duration ground motions selected on the basis of the duration metric should not have any peculiarities in their spectral shapes.

The comparison of all the selected duration metrics against these criteria is presented in Table 1. As shown, based on the qualitative assessment of the characteristics, significant duration appears to be the most robust measure for duration.

Table 1: Comparison of the selected duration metrics

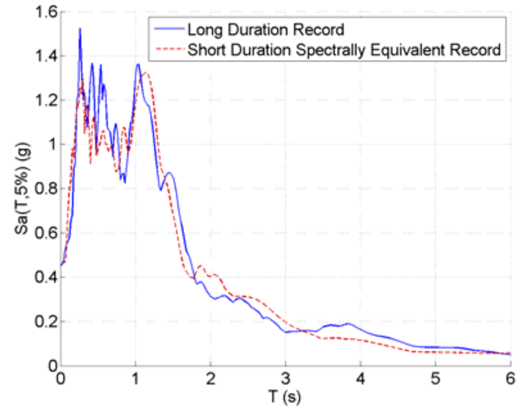
Desired Properties	**Bracketed duration**	**Significant duration**	**Arias Intensity**	**CAV**	$\boldsymbol{I_D}$
Not strongly correlated to common intensity measures	×	✓	×	×	✓
Unaffected by scaling	×	✓	×	×	✓
Does not bias spectral shape	✓	✓	✓	✓	×

To further evaluate the alternative duration metrics, $IDAs$ were conducted on several structures using a set of long and short duration ground motions, where the variation in predicted collapse capacity was plotted against each of the alternative ground motion metrics. It was observed that the 5-95% significant duration, referred to as t_{5-95}, best captured the expected decreasing trend in collapse capacity with duration. Based on this data and the comparison in Table 1, the 5-95% significant duration is considered as the best duration metric to screen ground motions for analysis (Foschaar et al. 2011).

One of the challenges faced in the evaluation of duration in ground motion selection criteria has been the scarcity of long duration ground motions. Such long duration motions are expected to occur in sites where the hazard is dominated by large magnitude subduction zone earthquakes and certain soft soil conditions. The recent 2008 Wenchuan, 2010 Chile and 2011 Tohoku earthquakes have dramatically increased the available inventory of long duration motions. Nevertheless, finding recorded ground motions that both match a target response spectrum and provide a wide distribution of short to long durations remains a challenge.

To demonstrate the effect of ground motion duration on collapse capacity, a long duration record set was created containing ground motions recorded from the 1974 Lima - Peru, 1979 Imperial Valley - USA, 1985 Valparaiso - Chile, 2003 Hokkaido - Japan, 2008 Wenchuan - China, 2010 Maule - Chile, 2010 El Mayor Cucapah - USA and 2010 Tohoku - Japan earthquakes. About 3700 horizontal record pairs were acquired in total from all these events. These were baseline corrected and filtered based on the recommendations of Boore and Bommer (2005) and Boore (2005). To avoid using low intensity and short duration records, record pairs with a mean PGA of both components < 0.1g, mean PGV < 10cm/s or t_{5-95} < 45s were screened out. To prevent a single well-recorded event from dominating the selected record set, a maximum of only 25 record pairs were retained from each event. After the entire screening process, the resulting long duration record set contained 79 two-component record pairs.

A second set of short duration ground motions was selected with a spectral shape that matches that of the long duration record set. For each record in the long duration set, a corresponding short duration record was selected from the PEER NGA West2 database with t_{5-95} < 45s and a closely matching spectral shape. This corresponding set with matching spectral shapes was created so that any difference in the collapse capacities predicted by the two sets could be attributed to the difference in their durations. Figure 2 shows the comparison of the response spectra and time histories of one of the 158 pairs of long and short duration spectrally equivalent records. Figure 3 shows a comparison of the durations (t_{5-95}) of all the ground motions in each set. Both sets of ground motions were then used to conduct individual $IDAs$ on the model of a 5-story steel special moment frame.



(a)

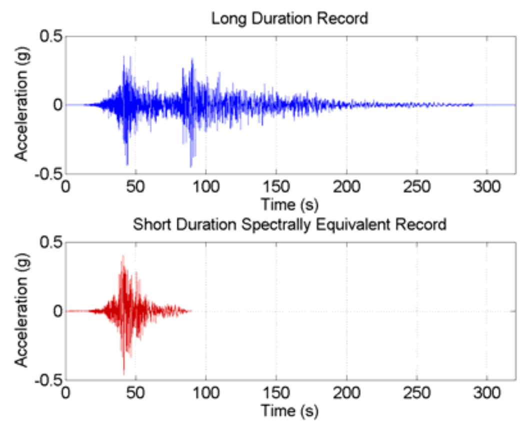


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Figure 2: Comparison of (a) response spectra and (b) time series of a long and short duration record pair

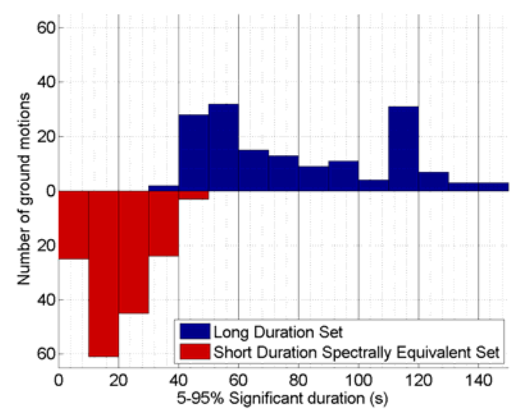


Figure 3: Comparison of the durations (t_{5-95}) of records in the long and short duration spectrally equivalent sets

4. ANALYSIS OF A 5-STORY STEEL SPECIAL MOMENT FRAME

The 2-dimensional numerical model of a 5-story steel special moment frame was created in OpenSees, the Open System for Earthquake Engineering Simulation (McKenna et al. 2006). A schematic of the elevation view of the frame is shown in Figure 4. The lumped plasticity approach was used to model material nonlinearity. The beams and columns were modeled using linear elastic elements. The hysteretic behavior of the panel zones was modeled using a tri-linear backbone curve. Zero-length plastic hinges were located at the two ends of each column and at each RBS cut. The hysteretic behavior of the plastic hinges was modeled using the Modified Ibarra-Medina-Krawinkler bilinear material model that includes a post-capping negative stiffness branch of the backbone curve to capture in-cycle deterioration, as well as an algorithm that cyclically deteriorates strength and stiffness based on the cumulative hysteretic energy dissipated (Ibarra et al. 2005). The contribution of the adjacent gravity system to the destabilizing P-Δ effect was modeled using a pin-ended leaning column. Rayleigh damping of 2.5% was assigned to the linear elastic elements of the frame.

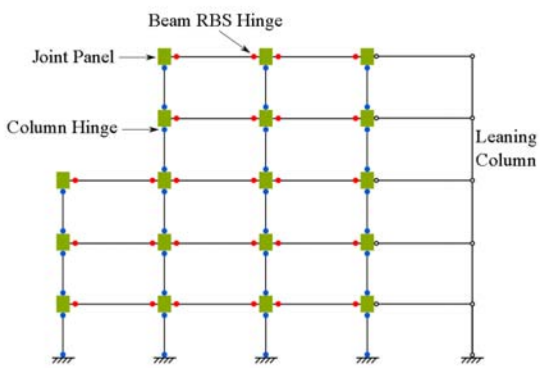


Figure 4: Schematic of the 5-story steel special moment frame model

The fundamental period of the structure was found to be 1.5s. The engineering demand parameter monitored during the nonlinear dynamic analyses was the peak story drift ratio (SDR), defined as the maximum lateral displacement of a story relative to the story below, expressed as a fraction of the corresponding story height, over all the stories and the entire duration of shaking. A peak SDR threshold of 10% was used to indicate structural collapse. The types of analyses performed, the record sets used in each analysis, as well as the collapse capacities computed as $S_a(1.5s, 5\%)$ are summarized in Table 2. The collapse fragility curves estimated from each of the five analyses are plotted in Figure 5.

Comparing the results of analyses #1 and #2, in the context of this example, targeting ground motions to the UHS instead of the conditional spectrum resulted in an under-estimation of the geometric mean collapse capacity by 22%. Comparing the

Table 2: Collapse fragility functions (quantified by geometric mean and lognormal standard deviation) for the example structure, predicted by the 5 analyses

Analysis number	Ground Motion set(s) used	Type of analysis performed	Geometric mean of predicted collapse capacity (g)	Lognormal standard deviation of predicted collapse capacity
1	2% in 50 year UHS matched set	Incremental Dynamic Analysis	0.87	0.30
2	2% in 50 year Conditional spectrum matched set	Incremental Dynamic Analysis	1.11	0.28
3	Conditional spectrum matched set at each intensity level	Multiple Stripe Analysis	1.43	0.40
4	Long duration set	Incremental Dynamic Analysis	0.53	0.42
5	Short duration spectrally equivalent set	Incremental Dynamic Analysis	0.90	0.38

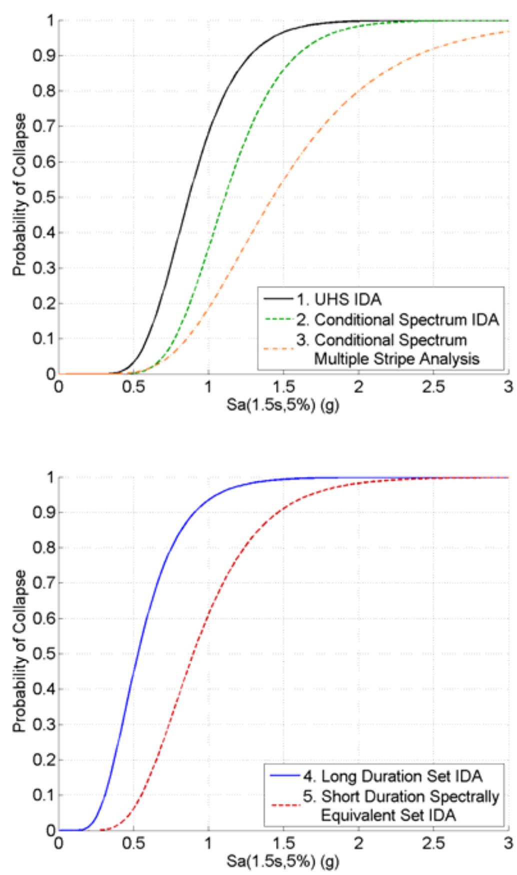


Figure 5: Collapse fragility curves predicted by the 5 analyses

results of analyses #2 and #3, it can be inferred that in the context of this example, conducting IDA instead of Multiple Stripe Analysis resulted in an additional difference of 22% in the geometric mean collapse capacity. Finally, conducting IDA using the UHS instead of the conditional spectrum Multiple Stripe analysis (#1 versus #3) led to an under-estimation of the geometric mean collapse capacity by 39%. These results are consistent with the observations made by Baker and Cornell (2006) that the UHS is a conservative choice for a target spectrum and that the changing spectral shape of the conditional spectrum at different intensity levels should be accounted for by the Multiple Stripe Analysis technique.

The results of analyses #4 and #5 indicate that with spectral shape being controlled for, the use of long duration ground motions reduced the geometric mean collapse capacity by 41%. Figure 6 shows a scatter plot of the collapse capacities predicted by each long and short duration spectrally equivalent record pair. The fact that nearly all the points lie above the 1:1 line indicates that on most occasions, within each record pair, the longer duration record predicts a lower collapse capacity. As shown in Figure 7, the decrease in collapse capacity as a function of ground motion duration (t_{5-95}) is clearly evident.

Figure 8 shows the IDA curves of the two record sets. The IDA curves indicate that the short duration ground motions on average reach a peak SDR of 7.2% before causing collapse. In contrast, the long duration ground motions reach a peak SDR of only 4.3% before collapse. This is believed to suggest that when large inelastic deformations begin to occur in the structure, aided by the resulting deterioration in strength and stiffness, a long duration ground motion is more likely to lead to structural collapse by ratcheting.

Finally, it can be argued that in the absence of a comprehensive description of the site hazard, the result of analysis #3 is expected to be most accurate since it best accounts for the effect of spectral shape. It does however neglect the effect of duration, which is expected to play a secondary role. An analysis that accounts for both spectral shape and duration is expected to produce the most accurate estimate of collapse capacity, but this would require further work to create the necessary framework to select appropriate ground motions that account for spectral shape as well as duration.

5. CONCLUSION

In any performance-based assessment, the chosen ground motions create the link between hazard analysis and demand analysis. Therefore it is critical to ensure that all the characteristics of the chosen ground motions are consistent with the site hazard to produce an accurate estimate of the demands. The effects of ground motion spectral shape and duration are particularly important for evaluating collapse under extreme (rare) ground motions. The 5-story steel special moment frame example illustrates these effects of ground motion spectral shape and duration.

With regard to spectral shape, it was argued and demonstrated that the conditional spectrum is a more accurate choice for a target spectrum than the UHS, which is

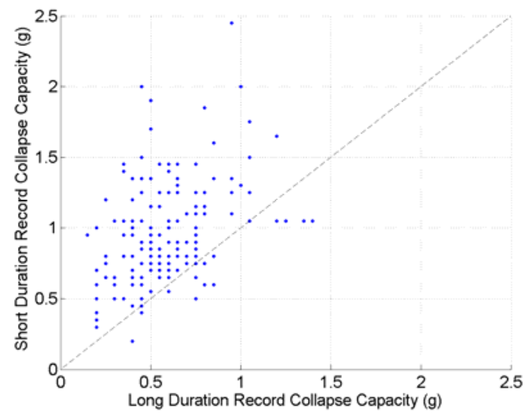
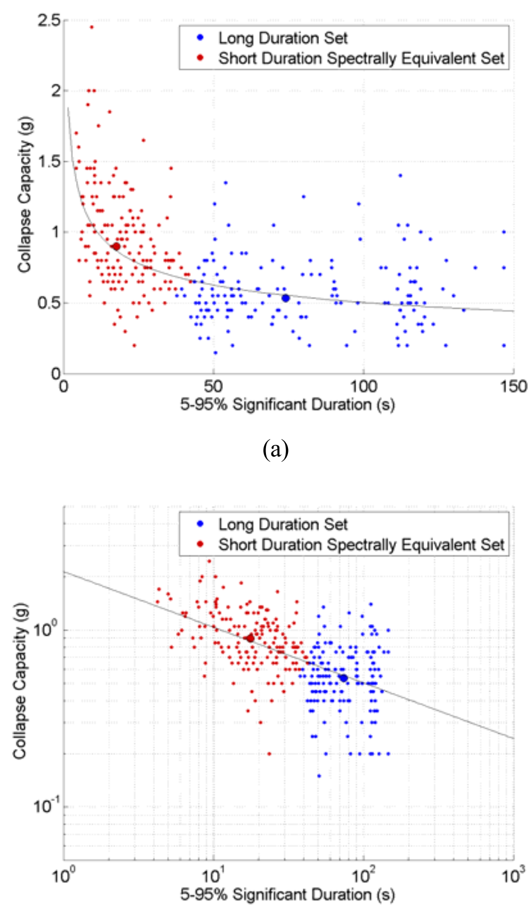


Figure 6: Scatter plot of collapse capacities predicted by long and short duration spectrally equivalent record pairs



(a)

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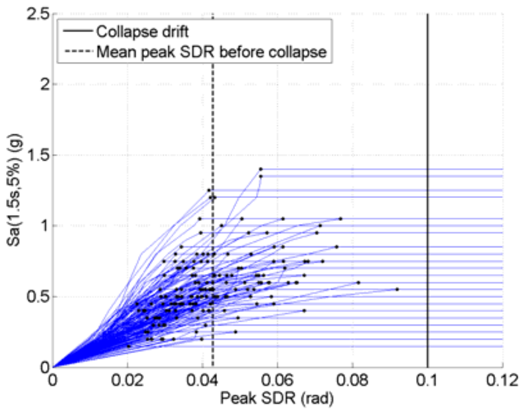
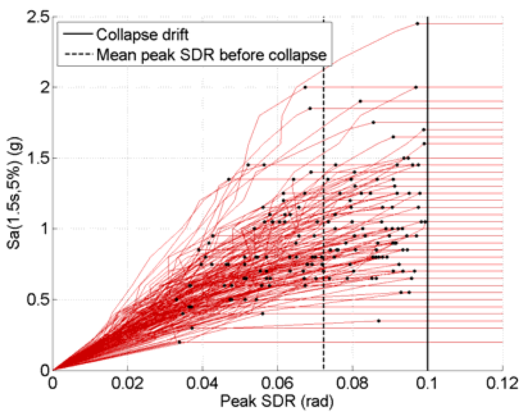
Figure 7: Collapse capacity versus duration on (a) linear plot (b) log-log plot (larger circles correspond to the geometric mean collapse capacity and geometric mean duration of all records in each set)



(a)



(b)

Figure 8: IDA curves of (a) long duration and (b) spectrally equivalent short duration sets

conservative in nature. With regard to duration, the 5-95% significant duration ($\boldsymbol{t_{5-95}}$) was identified as the duration metric best suited for use within the performance-based framework, where the collapse capacity is conditioned on ground motion intensity. It was also shown that the effect of ground motion duration on predicted collapse capacity could be quantified using spectrally equivalent record sets whose ground motions varied only in duration, represented by t_{5-95}. It should also be emphasized that the detection of ground motion duration effects requires the use of a realistic numerical model that accurately captures component deterioration. It is recognized that a number of previous studies on the effect of ground motion duration on structural damage have produced mixed and inconclusive results (Hancock and Bommer 2006). The reasons for this are believed to be (1) the use of structural models that did not incorporate deterioration, (2) the study of mildly nonlinear rather than collapsing systems, and (3) the use of inefficient duration metrics.

Consideration of both spectral shape and duration requires understanding of the seismic hazard at the site of interest so that ground motions for analysis can be selected to have spectral shapes and durations consistent with those expected at the site. Notably, spectral shape and duration values of ground motions are expected to differ for low-intensity and high-intensity ground motions, even for the same site. Therefore where possible, a different set of ground motions should be chosen at each intensity level to accurately account for these differences. This implies that Multiple Stripe Analysis, rather than IDA, is needed for collapse capacity estimation.

Acknowledgements:

This work was supported by the State of California through the Transportation Systems Research Program of the Pacific Earthquake Engineering Research Center (PEER). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the funding agency.

The authors would like to thank the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) for the use of their computing facilities and the prompt help provided, when required.

The Instituto Geofisico del Perú, Departamento de Geofisica, Universidad de Chile, and the National Research Institute for Earth Science and Disaster Prevention (NIED), Japan are also acknowledged for providing the ground motions used in this study.

Finally, the authors would like to thank Wenhao Chen for providing the 5-story structural model used in the example.

References:

Ancheta, T. D., Bozorgnia, Y., Chiou, B., Stewart, J. P., Boore, D. M., Graves, R., Abrahamson, N. A., Campbell, K. W., Idriss, I. M., Youngs, R. R., and Atkinson, G. M. (2012). "PEER NGA-West2 Database : A Database of Ground Motions Recorded in Shallow Crustal Earthquakes in Active Tectonic." *15th World Conference on Earthquake Engineering*, Lisbon, Portugal.

Baker, J. W. (2011). "Conditional Mean Spectrum: Tool for Ground-Motion Selection." *Journal of Structural Engineering*, 137(3), 322–331.

Baker, J. W., and Cornell, C. A. (2006). "Spectral shape, epsilon and record selection." *Earthquake Engineering & Structural Dynamics*, 35(9), 1077–1095.

Baker, J. W., and Cornell, C. A. (2008). "Vector-valued Intensity Measures Incorporating Spectral Shape For Prediction of Structural Response." *Journal of Earthquake Engineering*, Taylor & Francis, 12(4), 534–554.

Baker, J. W., and Jayaram, N. (2008). "Correlation of Spectral Acceleration Values from NGA Ground Motion Models." *Earthquake Spectra*, 24(1), 299–317.

Bommer, J. J., and Martinez-Pereira, A. (1999). "The Effective Duration of Earthquake Strong Motion." *Journal of Earthquake Engineering*, Taylor & Francis, 3(2), 127–172.

Boore, D. M. (2005). "On Pads and Filters: Processing Strong-Motion Data." *Bulletin of the Seismological Society of America*, Seismological Society of America, 95(2), 745–750.

Boore, D. M., and Bommer, J. J. (2005). "Processing of strong-motion accelerograms: needs, options and consequences." *Soil Dynamics and Earthquake Engineering*, 25(2), 93–115.

Bradley, B. A. (2011). "Correlation of Significant Duration with Amplitude and Cumulative Intensity Measures and Its Use in Ground Motion Selection." *Journal of Earthquake Engineering*, 15(6), 809–832.

Cosenza, E., and Manfredi, G. (1997). "The improvement of the seismic-resistant design for existing and new structures using damage criteria." *Seismic Design Methodologies for the Next*

Generation of Codes, H. Krawinkler and P. Fajfar, eds., Balkema, Rotterdam, 119–130.

FEMA (2005). *Improvement of nonlinear static seismic analysis procedures*, FEMA Report 440, Washington, D.C.

Foschaar, J. C., Baker, J. W., and Deierlein, G. G. (2011). "Preliminary Assessment of Ground Motion Duration Effects on Structural Collapse." *15th World Conference on Earthquake Engineering*, Lisbon, Portugal.

Gupta, A., and Krawinkler, H. (2000). "Dynamic P-delta effects for flexible inelastic steel structures." *Journal of Structural Engineering*, 126(1), 145–154.

Hancock, J., and Bommer, J. J. (2006). "A State-of-Knowledge Review of the Influence of Strong-Motion Duration on Structural Damage." *Earthquake Spectra*, 22(3), 827.

Haselton, C. B., Baker, J. W., Liel, A. B., and Deierlein, G. G. (2011). "Accounting for Ground-Motion Spectral Shape Characteristics in Structural Collapse Assessment through an Adjustment for Epsilon." *Journal of Structural Engineering*, American Society of Civil Engineers, 137(3), 332–344.

Haselton, C. B., and Deierlein, G. G. (2007). *Assessing seismic collapse safety of modern reinforced concrete moment frame buildings (PEER 2007/08)*. Pacific Earthquake Engineering Research Center, Berkeley, CA.

Ibarra, L. F., and Krawinkler, H. (2005). *Global Collapse of Frame Structures under Seismic Excitations (PEER 2005/06)*. Pacific Earthquake Engineering Research Center, Berkeley, CA.

Ibarra, L. F., Medina, R. A., and Krawinkler, H. (2005). "Hysteretic models that incorporate strength and stiffness deterioration." *Earthquake Engineering & Structural Dynamics*, 34(12), 1489–1511.

Jalayer, F. (2003). "Direct Probabilistic Seismic Analysis: Implementing Non-Linear Dynamic Assessments." Ph.D. Dissertation, Stanford University.

Jayaram, N., Lin, T., and Baker, J. W. (2011). "A Computationally Efficient Ground-Motion Selection Algorithm for Matching a Target Response Spectrum Mean and Variance." *Earthquake Spectra*, 27(3), 797–815.

Kramer, S. L. (1996). *Geotechnical earthquake engineering*. Prentice Hall, Upper Saddle River, NJ.

Lignos, D. G., and Krawinkler, H. (2011). "Deterioration Modeling of Steel Components in Support of Collapse Prediction of Steel Moment Frames under Earthquake Loading." *Journal of Structural Engineering*, 137(11), 1291–1302.

Lin, T., Harmsen, S. C., Baker, J. W., and Luco, N. (2012). "Conditional Spectrum Computation Incorporating Multiple Causal Earthquakes and Ground Motion Prediction Models." *To appear in Bulletin of the Seismological Society of America*, 103(2a).

McGuire, R. K. (2004). *Seismic hazard and risk analysis*. Earthquake Engineering Research Institute, Oakland, CA.

McKenna, F., Fenves, G. L., and Scott, M. H. (2006). "OpenSees: Open system for earthquake engineering simulation." *Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA., http://opensees. berkeley. edu*.

NIST. (2011). *Selecting and Scaling Earthquake Ground Motions for Performing Response-History Analyses (NIST GCR 11-917-15)*. National Institute of Standards and Technology, Gaithersburg, MD.

Vamvatsikos, D., and Cornell, C. A. (2002). "Incremental dynamic analysis." *Earthquake Engineering & Structural Dynamics*, 31(3), 491–514.

Vamvatsikos, D., and Cornell, C. A. (2004). "Applied Incremental Dynamic Analysis." *Earthquake Spectra*, 20(2), 523–553.