TOWARDS IMPROVED GROUND MOTION INTENSITY MEASURES FOR ESTIMATING THE COLLAPSE OF STRUCTURES

Eduardo Miranda and Héctor Dávalos

John A. Blume Earthquake Engineering Center
Dept. of Civil and Environmental Engineering
Stanford University, Stanford

Abstract

Identifying a measure of ground motion intensity that is well correlated with strongly nonlinear response is desirable not only for reducing the required number of response history analyses but also for establishing criteria for selecting ground motion time histories for conducting such analyses. The most commonly used ground motion intensity is the response spectral ordinate of a 5% damped system with a period equal to the fundamental period of the structure being analyzed. In this study we explore and evaluate alternate measure of ground motion intensity with emphasis with those that are well correlated with strongly nonlinear response of multi-degree-of-freedom system and for estimating the probability of collapse of a structure. Preliminary results indicate that using the average of spectral ordinate over a relative wide range of periods including both periods shorter and longer than the fundamental period of vibration leads to significant reductions in the record-to-record variability of ground motion intensities triggering collapse. Other alternatives measure of intensity but based on time domain features of acceleration times histories are also being explored.

Introduction

Currently the large majority of structures located in seismic regions are designed using a linear elastic analysis using either an equivalent static analysis or using a modal response spectrum analysis both of which do not require the use of ground motion acceleration time histories. However, there are several situations where the use of response history analyses becomes necessary or it is mandatory according to current codes. One example is in the calculation of floor response spectrum in which one must compute floor acceleration time histories by conducting response history analyses to then compute response spectra of the computed acceleration response. Floor spectra are then used for the design of secondary systems such as equipment and other nonstructural components attached to structures. In fact, some of the early applications of relatively routinely use of response history analyses was for the design of secondary systems in nuclear power plants in the late 70's and early 80's. Other early use of response history analyses was for the design of seismically isolated structures or for structures incorporating energy dissipation devices for which design procedures for more than 20 years have typically required the use of nonlinear response history analyses. More recently, with the advent of Performance Based Earthquake Engineering, PBEE, nonlinear response history analyses are being used more often (e.g, for the evaluation of existing structures or for the design of tall buildings) and are expected to become even more common in the near future. In particular,

several recent consensus-based documents have highlighted the shortcomings of linear elastic analyses and of nonlinear static analyses and the benefits of using nonlinear response history analyses (FEMA 2005, 2009a, 2009b; NIST 2010). Nonlinear response history analyses are considered the most reliable analytical tool to estimate the seismic performance of a structure.

Unlike equivalent static analyses or modal response spectrum analyses conducting response history analyses requires the selection and scaling of recorded ground motions, the generation of artificial ground motions, or the modification of recorded ground motions to match target spectra. The selection and/or modification of recorded earthquake ground motions as well as the generation of artificial ground motions is closely tied to the parameter or parameters that are used to characterize the level of intensity of a particular ground motion. Moreover, the number of ground motions that are required to conduct the assessment of the seismic performance of a structure is also closely related to the parameter(s) used for characterizing the intensity of a ground motion. In particular, the use of ground motion intensity measures that are well correlated with highly nonlinear response are desirable as a higher correlation leads to a smaller record-to-record variability of the seismic response and therefore to reduced number of ground motions can be used greatly reducing the computational effort involved in the performance assessment.

The main goals of the currently ongoing investigation are: (1) The development of improved intensity measures that are well correlated with strong nonlinear behavior and collapse of structures; (2) Evaluation of improved ground motion intensity measures with emphasis on the level of reduction of record-to-record variability and robustness with respect to intensity measures used today; (3) Development of recommendations for selection and scaling of ground motions based on improved intensity measures.

Shortcomings of Some Ground Motion Intensity Measures

While current code recommend selecting appropriate ground motions from events having magnitudes, fault distance, and source mechanisms that are consistent with those that control the maximum considered earthquake, research by Prof. Cornell and his students (Bazzurro et al. 1998; Shome et al., 1998) has pointed out that such approach requires a very large number of ground motions in order to provide adequate results because of the significant record-to-record variability in the structural response when records are selected based on magnitude and distance bins. Since conventional probabilistic seismic hazard analysis makes use of the five percent damped spectral acceleration at the fundamental period of the structure, $Sa(T_1)$ as a measure of ground motion intensity they proposed scaling all ground motions records to the same spectral ordinate and then computing a measure of response (e.g., mean peak interstory drift demand, probability of exceeding a certain interstory drift or probability of collapse) conditioned on a certain level of spectral acceleration. They noted that this method offered a reduction in record-to-record variability and therefore reduced the required number of ground motions to achieve a certain level of error in the estimate of the response. When using three different sets of records Shome and Cornell (1999) noted that scaling records to $Sa(T_1)$ lead to an average reduction of 40% in the dispersion of peak interstory drift ratios of the structures they analyzed.

While $Sa(T_1)$ provides an exact measure of intensity of the peak deformation of an elastic single-degree-of-freedom (SDOF) system, its efficiency to estimate seismic behavior of structures rapidly diminishes with increasing level of nonlinearity and it leads to large record-to-record variability when used to estimate large nonlinear deformations in multi-degree-of-freedom (MDOF) structures. Figure 1 shows the spectral acceleration $Sa(T_1)$ by which 274 earthquake ground motions need to be scaled to in order to produce the collapse of a post-Northridge 4-story steel moment resisting steel building (Eads et al., 2013). The ground motions were recorded in earthquakes with moment magnitudes between 6.9 and 7.6 and Joyner-Boore distance (horizontal distance between the site and the projection of the fault rupture onto the surface) between 0 and 27 km and on sites classified as NEHRP site classes C or D. It can be seen that the ground motions intensities, when characterized by $Sa(T_1)$, exhibit a very large record-to-record variability with some ground motions producing the collapse of the structure when the record is scaled to a spectral ordinate of 0.48g at T_1=1.33s while others need to be scaled to spectral ordinates as large as 3.27g to produce the collapse of the structure. Also shown in the figure is the median collapse intensity which for this structure is 1.03g, the 5 percentile (ground motion intensity at which only 5% of the ground motions produce collapse in the structure) and 95 percentile (ground motion intensity at which 95% of the ground motions produce collapse). In this case the intensity corresponding to the 95 percentile (2.11g) is 3.64 times larger than the intensity corresponding to the 5 percentile (0.58g) indicating a large variability of the ground motion intensity required to produce collapse one can take the ratio of the 95% intensity to the 5% intensity. The corresponding logarithmic standard deviation is 0.39 which is very large.
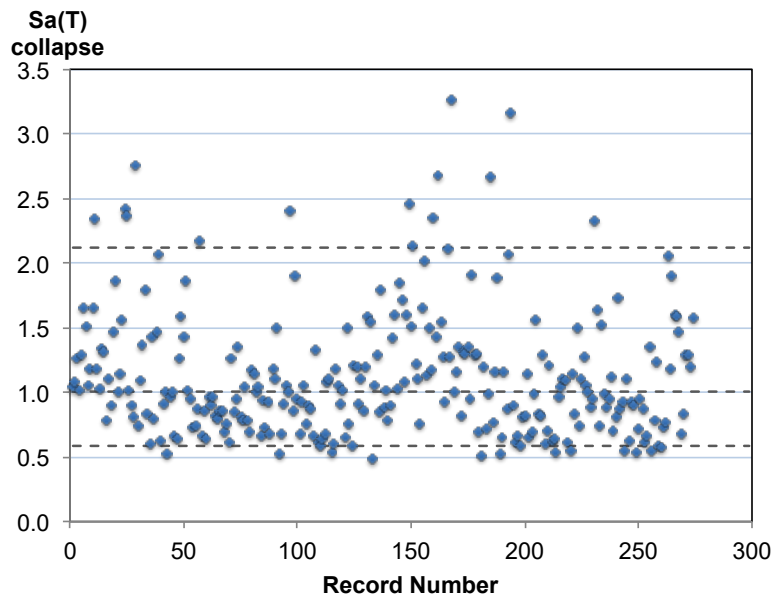

Figure 1. Scaled spectral accelerations at the fundamental period of vibration, $Sa(T_1)$, triggering the collapse of a post-Northridge 4-story steel moment resisting frame building (Eads et al., 2013).

Bazzuro and Cornell (2002) proposed a methodology for evaluating the site-specific seismic hazard of a structure by using a vector of ground motion intensity parameters instead of a

single scalar parameter. Their approach was referred generically as a vector IM. In their simplest case, they proposed a vector comprised of two spectral accelerations, $Sa(f_1)$ and $Sa(f_2)$ at two different oscillator frequencies f_1 and f_2 by using the median spectral ordinate at the two frequencies and correlation between the two spectral ordinates. They noted that this vector *IM* lead to somewhat smaller record-to-record variabilities and therefore better characterization of the seismic demands on the structure than when using $Sa(T_1)$ alone.
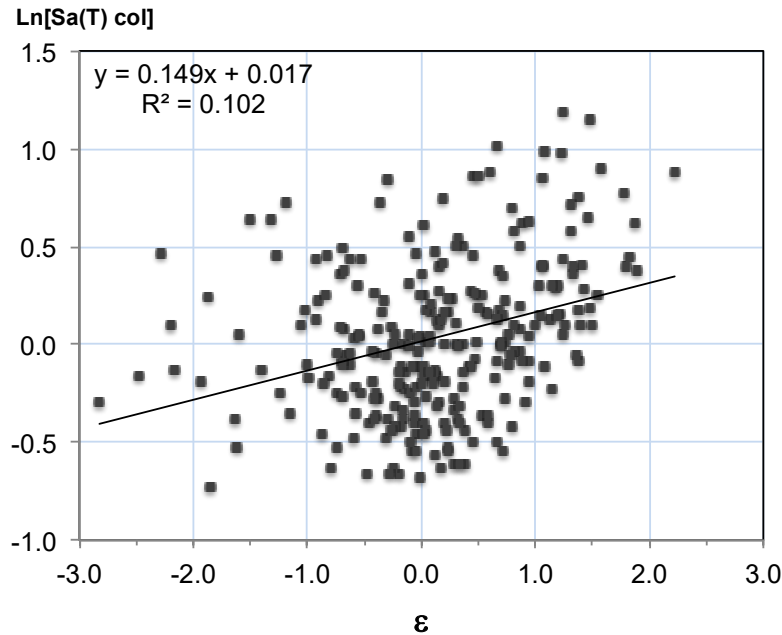

Figure 2. Natural logarithm of $Sa(T_1)$ triggering the collapse of a 4-story SMRF building as a function of the ε of each record (Eads et al., 2013).

More recently, some investigators proposed using another vector *IM* that consists of the five percent damped spectral ordinate at the fundamental period of vibration of the structure $Sa(T_1)$ and the ground motion parameter ε (Baker and Cornell, 2006). The ground motion parameter ε is a measure of the difference between a record's spectral acceleration ordinate at a given period and the median predicted by a ground motion prediction equation (GMPE). They observed that ε could be used as a *proxy* to the spectral shape and when used together with $Sa(T_1)$ it could lead to an improved estimate of the seismic response of a structure. Furthermore, they noted that neglecting the spectral shape could introduce some bias in the results. In particular, they noted that as epsilon increased, that is, as the spectral ordinate at the fundamental period of the structure became larger with respect to the median value estimated by a ground motion attenuation equation the record was more benign, meaning it had to be scaled by a larger factor in order to induce a certain level of response or collapse of a structure. As an example, figure 2 shows a plot of the natural logarithm of the $Sa(T_1)$ by which 274 earthquake ground motions need to be scaled to in order to trigger the collapse of a post-Northridge 4-story steel moment resisting frame building (Eads et al., 2013).

Also shown in figure 2 is a linear fit regressed to the data. As illustrated in the figure, and as previously noted by Baker and Cornell, there is a tendency to increase the collapse intensity as

epsilon increases. They noted that many sites on the west coast of the United States in which design spectral ordinates correspond to values of ε larger than one there would be a tendency to underestimate the median collapse intensity, therefore producing over conservative results if spectral shape was not taken into account when selecting records. In order to avoid conservative results, they proposed a vector *IM* which considers the joint probability distribution of $Sa(T_1)$ and ε. Using this joint probability however, complicates significantly the performance evaluation of structures.

In order to approximately account for the spectral shape when evaluating structures Haselton et al. (2011) proposed a simplified procedure for correcting the collapse capacity of a structure when the spectral shape is not considered in the selection of the records by applying a correction factor whose amplitude is a function of ε. Their method uses a general ground-motion set, selected without regard to ε values, and then corrects the calculated structural response distribution to account for the mean ε expected for the specific site and hazard level. They mention that their method can be applied to all types of structural responses (e.g., interstory drifts and plastic rotations), but their paper focused on the estimation of the collapse capacity of a structure. The correction factor they recommend is based on the linear trend of the spectral shape ε and the natural logarithm of $Sa(T_1)$ from the results of eight reinforced concrete moment resisting frames with heights ranging from 2 to 20 stories. This procedure, which has now also been incorporated into the ATC-63 project and the FEMA P-695 document (FEMA, 2009), avoids having to consider the joint probability distribution of $Sa(T_1)$ and ε. Unfortunately, the procedure focuses on correcting the bias and not on increasing the correlation of the *IM* with collapse and/or in the reduction of the variability/dispersion. As a matter of fact, and contrary to popular belief, considering ε does very little in terms of reducing the record-to-record variability and therefore the vector *IM* consisting on $Sa(T_1)$ and ε remains *a relatively inefficient intensity measure*, meaning it does not leads to a significant reduction in dispersion and hence, although it may correct or partially correct the bias, it still requires a large number of response history analyses in order to estimate the response of the structure with an acceptable level of confidence. Figure 2 also shows the coefficient of determination (R^2) computed from the linear fit on the data which is only 0.1 indicating a relatively poor measure of fit and of correlation of the collapse intensity with ε. This low level of correlations indicates that only about 10% of the large variability in the intensities required to produce collapse is explained by the ε in each record.

To illustrate this important, and often overlooked, aspect of this recently proposed vector *IM*, consider the same four-story steel structure whose results of collapse intensities were previously presented in figures 1 and 2. We now apply a correction of each of the collapse capacities by applying the procedure proposed by Haselton et al. (2011) to account for the effect of ε by decreasing the intensity producing collapse for records with ε's larger than the mean epsilon in the record set and by increasing the intensity producing collapse for records with ε's smaller than the mean epsilon in the record set. Please note that instead of using a generic slope recommended in their paper that is based on their buildings, here we apply the slope that is specific to this structure and this set or records which was previously computed and shown in figure 2 corresponding to the best slope that can be used for this particular structure. The corrected natural logarithms of the collapse intensities as a function of ε are presented in figure 3. As expected, the bias (the slope of the linear trend) has now been fully eliminated, but notice that a large dispersion (variability around the linear fit) remains. To get further understanding on this

important result, the corrected collapse intensities for each record are plotted in figure 4 for each ground motion in the same manner as the uncorrected collapse intensities were plotted in figure 1. Again 5, 50 and 95 percentiles, corresponding to spectral ordinates equal to 0.58, 1.01 and 2.13, respectively, are also plotted in the figure with horizontal dashed lines. By comparing figures 1 and 4 it can be seen that, as previously mentioned, considering ε while it corrects the bias, it does not lead to a significant reduction in dispersion. As a matter of fact, for this structure the ratio of corrected collapse intensities corresponding to 95 percentile to 5 percentile actually has increased to 3.66 which is slightly larger than the ratio of the two percentiles prior to correction for epsilon which was 3.64. The corresponding logarithmic standard deviation does reduce after the correction is applied to consider the effect of ε, but the reduction is minimal, it only reduces from 0.39 to 0.37, which corresponds to only a reduction of approximately 5%.
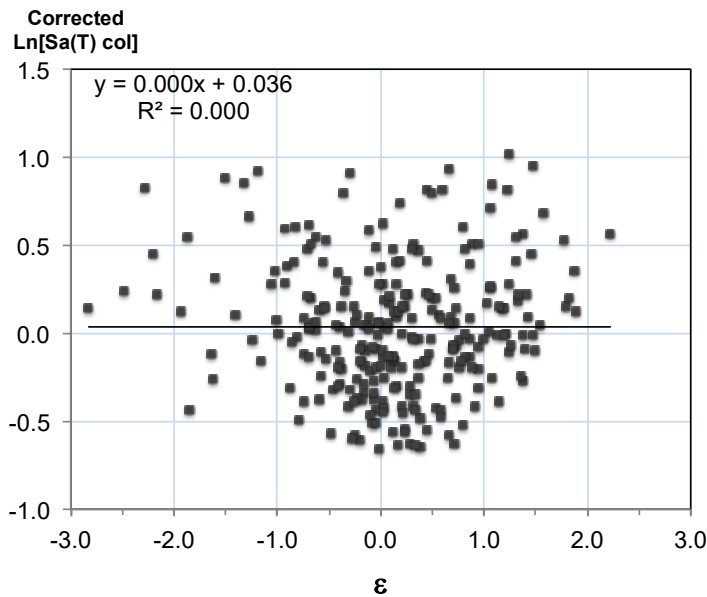

Figure 3. Natural logarithm of spectral accelerations that produce collapse in the four-story steel building after correction to take into account the ε of each record by using the procedure proposed by Haselton et al. (2011).

The reason why consideration of ε does not lead to a significant reduction in dispersion is because ε is not a direct measure of spectral shape but only a proxy to spectral shape as a single spectral ordinate relative to the intensity measured by an attenuation relation by itself cannot provide a measure of spectral shape. With exception of very extreme values, information on ε alone does not provide information on whether the spectral ordinate is in a peak or a valley just like providing the altitude on earth (height relative to sea level) cannot by itself provide an indication whether such point is in a peak or a valley. For example, one could be in a relatively low altitude such as 200 meters above sea level and still be in a peak. One could be in a high elevation such as 2,400 meters above sea level and still be in a valley. Similarly, saying that a spectral ordinate has a negative epsilon, such as -1 does not necessarily imply that such spectral ordinate corresponds to a spectral valley nor a spectral ordinate that has a positive epsilon, such as 1.0 or 1.5 necessarily imply that such spectral ordinate corresponds to a spectral peak.
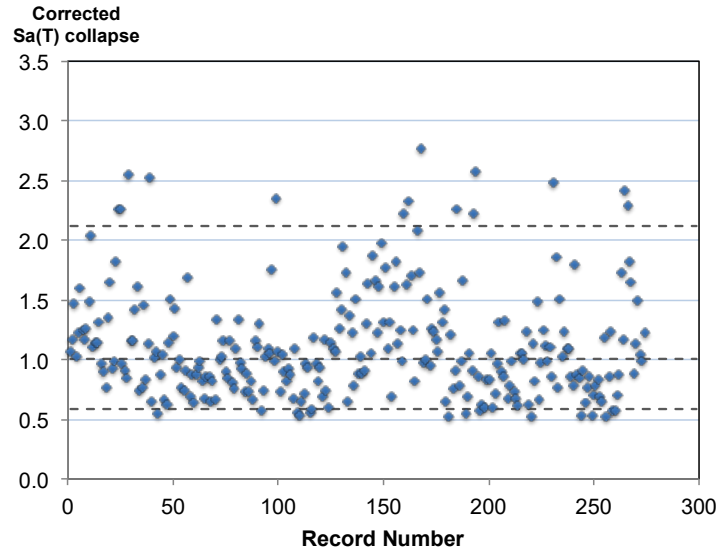
Figure 4. Spectral accelerations that produce collapse the collapse of the four-story steel building after correction by taking into account ε of each record.

As previously illustrated the vector *IM* comprised on $Sa(T_1)$ and ε although it eliminates the bias it does not lead to a significant reduction in record-to-record variability/dispersion hence requiring a relatively large number of ground motions to lead to adequate results. Furthermore, several studies have shown that ε is ineffective in accounting for spectral shape in the case of near-fault pulse-like ground motions (Baker and Cornell, 2006; Bojorquez and Iervolino, 2011). As a matter of fact, Haselton et al. (2011) when proposing their approximate method to consider the effect of ε explicitly wrote in their paper: "*the approach proposed in this paper should not be applied to near-fault motions with large forward-directivity velocity pulses*". This is very important because this type of ground motions is precisely the one that is more likely to produce the collapse of structures. It is then clear that there is a need for improved ground motion intensities.

Towards Improved Ground Motion Intensity Measures

As clearly demonstrated by Shome et al. (1998), having an intensity measure that is strongly correlated with strong nonlinear deformations and collapse of structures has enormous practical consequences for structural engineers. Namely, the level of record-to-record variability achieved in the level of structural response is related to the number of records that the engineer must use for obtaining a reliable estimate of the structural response. In particular, they noted the required number of ground motions required to estimate the structural response within a factor of X (e.g., ± 0.1) with 95% confidence would be given by

$$n = 4\left(\frac{\beta}{X}\right)^2 \tag{1}$$

where β is the level of dispersion in the response when using a certain intensity measure *IM* expressed as the logarithmic standard deviation. From this equation it can be seen that for the same level of desired accuracy the reduction in the necessary ground motions is proportional *to*

the square of the reduction in dispersion. For example, if an improved logarithmic standard deviation is used that leads to a 30% reduction in the level of dispersion, it then allows to obtain an estimate of the response with the same level of accuracy with only half the number of records. This is extremely important because there is a considerable computational effort involved in each nonlinear response history analysis and therefore of the amount of effort involved

Kennedy et al. (1984) noted that the dispersion in the nonlinear response was reduced when each of the ground motion records was scaled with respect to a spectral acceleration found by averaging spectral acceleration over range of periods varying from the fundamental period of the structure T_1 to an elongated equivalent period which depended on the level of nonlinearity in the structure. Shome et al (1998) used this approach with two structures with fundamental periods of vibration of 1.05s and 4.0s and observed reductions of 30% in the dispersion in lateral deformations. The same approach has more recently being used by Bojorquez and Iervolino (2011) who proposed using an improved intensity measure consisting on an average spectral acceleration averaged between the fundamental period of the structure and an elongated period T_N. Bojorquez and Iervolino (2011) proposed using an elongated period $T_N = 2T_1$. They showed that this intensity measure provided a more efficient *IM* than using $Sa(T_1)$ or the vector *IM* comprised on $Sa(T_1)$ and ε.

Here we use a similar, but new and improved intensity measure in which the averaged spectral acceleration takes into account both spectral ordinates that correspond to periods that are smaller than the fundamental period of the structure as well as spectral ordinates corresponding to periods that are longer than the fundamental period of vibration of the structure. Preliminary results suggest that this new improved intensity measure which provides information of the spectral intensity over a much wider range of frequencies leads to smaller dispersions than the one used by Bojorquez and Iervolino. A sample of results are shown in figure 5 which shows average spectral accelerations averaged over a range of period from one fifth of the fundamental period of vibration of the structure (i.e., $0.2T_1$) to three times the fundamental period of vibration of the structure (i.e., $3.0T_1$) that produces collapse of the four-story steel MRF structure previously discussed when subjected to 100 recorded ground motions recorded in earthquakes with moment magnitudes between 6.9 and 7.6 and Joyner-Boore distances (horizontal distance between the site and the projection of the fault rupture onto the surface) between 0 and 27 km and on sites classified as NEHRP site classes C or D. We use information of spectral ordinates of periods much shorter than the fundamental period (up to five times shorter) and spectral ordinates with periods of to three times the fundamental period of vibration, resulting in a period range that is 90% wider (almost twice as wide) than the one previously used by Bojorquez and Iervolino.

Similarly to figures 1 and 4, the 5, 50 and 95 percentiles, which correspond to average spectral ordinates of 0.52, 0.71 and 1.86, respectively, are also plotted in the figure with horizontal dashed lines. By comparing the record-to-record variability in figures 1 and 4 with those in figure 5 it can be readily seen that, a significant reduction in dispersion is produced when using the proposed *IM*. In this case the ratio of the collapse intensities corresponding to 95 percentile to 5 percentile actually is now 1.86 while this ratio was 3.64 for the case in which $Sa(T_1)$ alone was used as an IM or 3.64 when the vector *IM* comprised on $Sa(T_1)$ and ε was used.
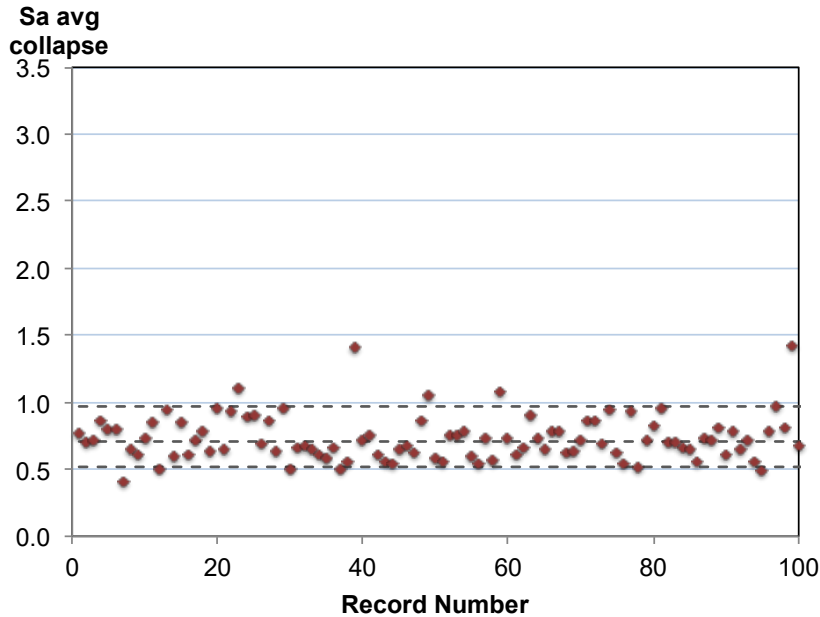
Figure 5. Spectral accelerations averaged over a range of periods from $0.2T_1$ to $3.0T_1$, by which 100 earthquake recorded ground motions need to be scaled to in order to produce the collapse of a post-Northridge 4-story steel moment resisting frame building analyzed by Eads et al. (2013).

The corresponding logarithmic standard deviation for the proposed *IM* is 0.22 which is 44% smaller and 41% smaller the case in which $Sa(T_1)$ alone was used and when the vector *IM* comprised on $Sa(T_1)$ and ε was used, respectively. These reductions in dispersion can translate to being able to use approximately only 31% to 35% of the number of records that would be required when using currently recommended *IM*s, in other words with approximately one third of the computational effort and still be able to achieve a similar level of confidence in the results.

In order to investigate the reason(s) behind the significant reduction in record-to-record variability of ground motion intensities producing the collapse of the structure we plotted the natural logarithm of the spectral intensity triggering the collapse of each record as a function of the ratio of the conventional IM (spectral ordinate at the fundamental period of vibration of the structure) to the average of spectral ordinates of each record averaged over a range of periods from $0.2T_1$ to $3.0T_1$. This ratio is given by

$$SaRatio = \frac{Sa(T_1)}{Sa_{avg}(T_1 \cdot [a, b])}$$ (2)

Figure 6 shows the spectral ordinate of 100 ground motions triggering collapse plotted as a function of *SaRatio*, . It can be seen that there is a clear and strong tendency for the collapse-triggering spectral ordinates to increase as *SaRatio* increases, meaning that as $Sa(T1)$ increases relative to the average of spectral ordinates in the range of $0.2T_1$ to $3T_1$) the record becomes more benign and requires a considerably larger intensity to produce collapse in the structure. Also shown in the figure is the equation of the regressed linear trend between *SaRatio* and the natural

logarithm of the spectral ordinate, as well as the coefficient of determination, R^2. Comparing the coefficient of determination previously shown in figure 2 with that shown in figure 6 it can be seen that *SaRatio* provides a coefficient of determination that it is more than six times higher than that of ε. In other words whereas only 10% of the large variability in spectral ordinates of ground motions triggering collapse is due to changes in the ε of each of the records, 62% of the variability is related to changes in *SaRatio*.

Unlike ε which is only a proxy to spectral shape and not a very good one, *SaRatio* is a direct quantitative measure of how much higher or lower is the spectral ordinate at a period equal to the fundamental period of vibration relative to an average spectral ordinates averaged over periods shorter and longer than the fundamental period of vibration. Values higher than one indicate that the spectral ordinate at the fundamental period of vibration of the structure is larger than the average spectral ordinate while values smaller than one indicate that the spectral ordinate at the fundamental period of vibration is lower than the average acceleration. Results shown in figure 6 indicate a records whose spectrum has a peak at the fundamental period of vibration would most likely results in *SaRatio* larger than one and be a more benign record. Similarly, a record with a spectral valley at a period of vibration equal to that of the fundamental period of vibration would tend to have small values of *SaRatio* and be a more damaging record for the structure, meaning it would require to be scaled to a lower level of intensity in order to produce the collapse of a structure. Since *SaRatio* provides, a more direct indication of how high the spectral ordinate is relative to spectral ordinates at periods to the left and to the right of the fundamental period, then it provides a significantly better measure of ground motion intensity.
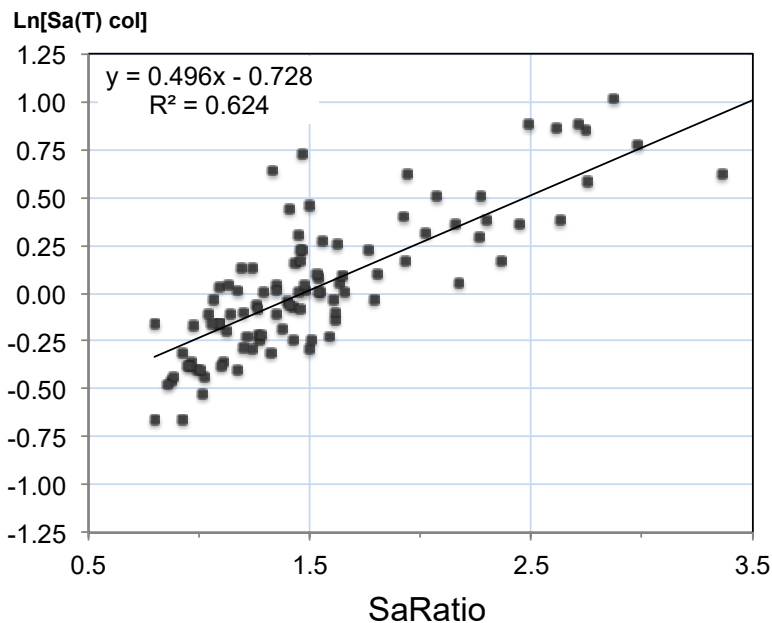

Figure 6. Spectral accelerations of ground motions producing collapse as a function of the *SaRatio* of each record.

But while information of ε is not contained in $Sa(T_1)$ and Baker and Cornell (2006) proposed the use of a vector IM, Sa_{avg} is the definition the ratio of $Sa(T_1)$ and $SaRatio$ and therefore contain more and better information for describing the intensity of a ground motion. It can be used as a scalar IM just like the conventional Sa(T1). Although results presented in figures 5 and 6 are extremely promising, it is necessary to carefully evaluate the proposed IM with: (a) a larger number of ground motions; (b) for different ground motions sets to evaluate if the same IM is applicable and equally efficient for other types of ground motions (e.g., near-fault pulse-type ground motions); (c) for different structures with fundamental periods in other spectral regions; (d) explore the optimum period range in which spectral ordinates should be averaged. Furthermore, it is important to also evaluate other alternative improved IMs. As part of this ongoing investigation, at present time we are evaluating two alternative IMs based in time domain features of acceleration time histories.

Summary and Conclusions

Using the spectral ordinate at the fundamental period of vibration of a structure as a ground motion intensity measure has the advantage that it corresponds to the way in which seismologists and geotechnical engineers have described the intensity of a ground motion and a large and important body of research has been devoted to developing equations to estimate spectral ordinates as a function of the magnitude, distance, focal mechanism and site conditions. However, most structures cannot adequately be modeled as single-degree-of-freedom systems and therefore information or the intensity of the ground motion at other periods/frequencies is neglected. Furthermore, current design provisions allow strong nonlinearities to occur in the structure in the event of strong earthquake ground motions and motions that are well correlated with large responses in linear SDOFs are not necessarily the same as those producing large responses in nonlinear SDOF systems, therefore improved intensity measures are needed to establish the criteria by which ground motions are selected and scaled for conducting nonlinear response history analyses.

The use of a vector IM consisting of the spectral ordinate at the fundamental period of vibration and ε was evaluated and was found to provide better results for reducing possible biases in the response, however, the record-to-record variability remains approximately the same as that when using $Sa(T_1)$ alone and therefore the required number of ground motions and the computational effort is not reduced. This is because, with the exceptions of very extreme values, ε does not provide a good measure of spectral shape as it does not contain any information about spectral ordinates at other periods of vibrations.

An improved IM consisting of an average spectral ordinates which are averaged between period of $0.2T_1$ and $3T_1$ is being evaluated. This intensity measure is found to have a much stronger correlation with strong nonlinear response and therefore leads to significantly smaller record-to-record variability. The reason why this improved IM reduces record-to-record variability is because it contains far more information about the intensity of the ground motion. In particular, it was found the ratio of the spectral ordinate at the fundamental period of vibration of the system to Sa_{avg} is strongly correlated to the spectral ordinate of ground motions triggering the collapse of structures, therefore using Sa_{avg} which corresponds to the ratio of Sa(T1) and

SaRatio provides a better measure of ground motion intensity. The main advantages can be summarized as follows:

1. Has a significantly higher level of correlation with large inelastic deformation and with collapse intensities than currently recommended intensity measures such as $Sa(T_1)$ or the vector *IM* comprised on $Sa(T_1)$ and ε;

2. Requires only about a third of the number of ground motions with respect to current *IM*s to achieve the same level of desired accuracy in the estimated seismic response;

3. Similarly to $Sa(T_1)$ it is a scalar that it is easy to interpret and does not require joint probability distributions between $Sa(T_1)$ and ε or correlations between the spectral ordinates (or ε) at the fundamental period of vibration and those at other periods of vibration;

4. It is somewhat similar to scaling procedures currently used by practicing engineers as specified in chapter 16 of ASCE 7 in which each pair of motions is scaled such that in the period range from $0.2T_1$ to $1.5T_1$, the average of the SRSS spectra from all horizontal component pairs does not fall below the corresponding ordinate of the response spectrum used in the design;

5. It is equally applicable to all types of ground motions, including near fault pulse-like ground motions and therefore does not require the use of different procedures for different types of ground motion.

Acknowledgements

References

American Society of Civil Engineers ASCE (2010), ''Minimum design loads for buildings and other structures.'' ASCE 7-10, ASCE, Reston, Va.

Baker, J. W., & Cornell, C. A. (2006). *Vector-valued ground motion intensity measures for probabilistic seismic demand analysis*. Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley.

Bazzurro, P., Cornell, C. A., Shome, N., & Carballo, J. E. (1998). Three proposals for characterizing MDOF nonlinear seismic response. *Journal of Structural Engineering*, *124*(11), 1281-1289.

Bojorquez, E., & Iervolino, I. (2011). Spectral shape proxies and nonlinear structural response. *Soil Dynamics and Earthquake Engineering*, *31*(7), 996-1008.

Eads, L., Miranda, E., Krawinkler, H., & Lignos, D. G. (2012) Deaggregation of Collapse Risk. In *20th Analysis and Computation Specialty Conference* (pp. 521-531). ASCE.

Eads, L., Miranda, E., Krawinkler, H., & Lignos, D. G. (2013). An efficient method for estimating the collapse risk of structures in seismic regions. *Earthquake Engineering & Structural Dynamics*, *42*(1), 25-41.

FEMA 440 (2005), Improvement of nonlinear static seismic analysis procedures. Report FEMA 356, Federal emergency management agency, Washington DC, 2005.

FEMA, P. 440A (2009) Effects of strength and stiffness degradation on seismic response. *Federal Emergency Management Agency, Washington, DC*.

FEMA (2009). Quantification of Building Seismic Performance Factors (FEMA P695 Report), prepared by Applied Technology Council for the Federal Emergency Management Agency. Washington, D.C.: FEMA.

FEMA, P. 58 (2012). *Seismic performance assessment of buildings. Report P-58, Prepared by Applied Technology Council as ATC*, *58*, Federal Emergency Management Agency Washington, D.C.

Haselton, C. B., Baker, J. W., Liel, A. B., & Deierlein, G. G. (2009). Accounting for ground-motion spectral shape characteristics in structural collapse assessment through an adjustment for epsilon. *Journal of Structural Engineering*, *137*(3), 332-344.

Kennedy, R. P., Short, S. A., Merz, K. L., Tokarz, F. J., Idriss, I. M., Power, M. S., & Sadigh, K. (1984). *Engineering characterization of ground motion. Task I. Effects of characteristics of free-field motion on structural response* (No. NUREG/CR-3805). Structural Mechanics Associates, Inc., Newport Beach, CA (USA); Woodward-Clyde Consultants, Walnut Creek, CA (USA).

National Institute of Standards and Technology (NIST) (2010) Applicability of nonlinear multiple-degree-of-freedom modeling for design. Report NIST GCR 10-917-9, prepared by the NEHRP Consultants Joint Venture, Gaithersburg

Shome, N., Cornell, C. A., Bazzurro, P., & Carballo, J. E. (1998). Earthquakes, records, and nonlinear responses. *Earthquake Spectra*, *14*(3), 469-500.