Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 388

LOSS ESTIMATION OF MULTI-MODE DOMINATED STRUCTURES FOR A SCENARIO OF EARTHQUAKE EVENT

Nilesh Shome[1] and Nicolas Luco[2]

ABSTRACT

In recent years performance-based earthquake engineering (PBEE) has become popular among engineers for designing new structures or retrofitting old structures. In this paper, we focus on the issues of estimation of different engineering demand parameters (EDP) including loss of structures for the use in PBEE. Recently ATC-58 project has started developing a guideline for the application of PBEE concept to the real life problem of designing and retrofitting of structures. Among many other objectives, the guideline envisions estimating different EDPs for a given scenario of event (scenario-based assessment). In this paper, we will focus on estimating median EDPs only for multi-mode dominated structures. In general, estimation of EDPs for a scenario is carried out by scaling a set of accelerograms representative of the scenario event. The scaling of records is carried out to different intensities of ground motion at the most important structural period, which is typically the first-mode period (T_1). Additionally the records are selected such that response spectrum of the scaled record matches the mean spectrum conditioned on M, R, $S_a(T_1)$, known as conditional mean spectrum (CMS). When structures are multi-mode dominated, it is postulated by the engineers that the selection of first-mode period for estimating CMS may not be the best choice for the calculation of EDPs. In this paper, we have estimated EDPs based on the CMS at the first-mode period (T_1), at the second-mode period (T_2) and at twice the first-mode period ($2*T_1$). We have considered a modern 20-story RC frame structure to demonstrate the EDP results for these three cases for a scenario earthquake event in Los Angeles. Based on the results from these cases, we demonstrate the importance of consideration of an appropriate period (or nullify that) for the estimation of EDPs for multi-period dominated structures for a scenario of earthquake event.

Introduction

In recent years performance-based earthquake engineering (PBEE) has become popular among engineers for designing new structures or retrofitting old structures. In the PBEE framework, one has to estimate loss of structures (in dollar), down-time, and death of occupants (known as 3D of PBEE) as envisioned by Pacific Earthquake Engineering Research (PEER) Center. In this paper, we would focus only on the issues of estimating unbiased median values of loss and other important

[1]Director, Model Development, Risk Management Solutions, 7015 Gateway Blvd. Newark, CA 94560
[2]Research Structural Engineer, Geologic Hazards Team, U.S. Geological Survey, PO Box 25046, Denver, CO 80225

engineering demand parameters (EDP) for multi-mode dominated structures. Recently ATC-58 project is developing a guideline for the application of PBEE concept to the real life problem of design and retrofitting of structures. This guideline envisions estimating losses for a given intensity of ground motion (described in ATC-58 as “intensity-based assessment”) and estimating loss over a time period (“time-based assessment”) in addition to estimating loss for a given scenario of event (“scenario-based assessment”).

In this paper, we will focus only on the scenario-based assessment for easy understanding of the main issue addressed in this paper, which is estimation of different important EDPs for multi-mode dominated structures. Here, we will be estimating different EDPs of a modern 20-story RC-frame for a scenario earthquake event. The scenario event is M_w= 7.5 earthquake occurring on a strike-slip fault at a distance of 10km from the building site for the NEHRP Soil-D site condition (V_{s30} = 400m/s). In general estimation of different EDPs for a scenario is carried out by scaling a set of accelerograms (by a scalar factor) from a bin of magnitude (M) and distance (R) recorded at sites for a specific soil condition as defined by the scenario. The scaling of records is typically carried out to the spectral accelerations at the first-mode period (T_1) , which is typically the most important period of structures (Shome, et al. 1998). This approach of scaling records for a given scenario is improved by selecting the scaled records that match the mean spectrum conditioned on M, R, $S_a(T)$ as shown for example by Haselton and Baker 2006). The mean spectrum is known as the conditional mean spectrum (CMS) (Baker and Cornell 2006). When a structure is multi-mode dominated, it is presumed that the selection of first-mode period for estimating CMS may not be the best choice for estimating the median EDPs of the structure.

In this study, we will estimate EDPs based on the CMS at the first-mode period (T_1), at the second-mode period (T_2) and at twice the first-mode period ($2*T_1$). We have considered a modern 20-story RC frame structure to estimate the losses and other EDPs for the three cases of CMS for the scenario of earthquake event in Los Angeles. Based on the results from these three cases, we show the importance of consideration of period of spectral acceleration for the estimation of EDPs for multi-period dominated structures for a scenario of earthquake event.

Use of Conditional Mean Spectrum (CMS) in ATC-58 Performance Assessments

Use of the CMS in selecting ground motion records for nonlinear response history analysis (e.g., Baker and Cornell 2006) has been incorporated into the ATC-58 50% Draft Guidelines (2009). A brief summary of how the CMS used in the “intensity-based”, “scenario-based”, and “time-based” performance assessments of these Draft Guidelines is described briefly below. Since we have considered here a two-dimensional building model, we summarize how the CMS is used in this case rather than in selecting pairs of horizontal ground motion records for three-dimensional analysis, which is also considered in the Draft Guidelines.

Intensity-Based Assessment

The objective of an intensity-based assessment is to quantify the performance of a building for a given response spectrum, e.g., a CMS. As outlined on page 5-14 of the Draft Guidelines, the CMS is used to select 11 or more ground motion records whose spectra are similar to the shape of the given spectrum, and also to define the spectral acceleration (at a period of T_1 in our case of a two-dimensional building model) to which the records are amplitude scaled. Along the same lines, we take the following steps in our example intensity-based assessments:

1. Construct a CMS for a given spectral acceleration (at T_1, T_2, or 2*T_1) and associated earthquake magnitude and site-to-source distance, per Appendix E of the Draft Guidelines.
2. Collect a set of ground motion records whose earthquake magnitude and site-to-source distance are similar, to the extent possible, to those specified by the scenario.
3. Scale the amplitudes of each collected record such that its spectral acceleration (at T_1, T_2, or 2*T_1) is equal to that of the CMS constructed in Step 1. To "scale" means to multiply the amplitude, typically in terms of ground acceleration, of a record by a single constant factor.
4. Select from the scaled records those whose spectra are similar in shape to the CMS constructed in Step 1.

Using the records selected according the steps above for nonlinear response history analysis and averaging the natural logarithms of the resulting response parameters (e.g., story drifts and peak floor accelerations) and loss parameters (e.g., damage ratio) yields the median response/loss for the given CMS. This can also be thought of as the median response/loss for the given spectral acceleration (at T_1, T_2, or 2*T_1) and associated earthquake magnitude and site-to-source distance. We will be following a similar approach by using 28 records instead of suggested 11 records (for more robust estimation) to validate the calculation that we have followed in this paper for the estimation of median EDPs.

Scenario-Based Assessment

The objective of a scenario-based assessment is to quantify the performance of a building for a given earthquake magnitude (M) and site-to-source distance (R). As outlined in Appendix Section E.8 of the Draft Guidelines, a CMS for each of 11 spectral accelerations (at T_1 for a two-dimensional building model) that characterize the probabilistic distribution of spectral accelerations for the given M and R can be used to select a corresponding ground motions record whose spectrum is similar to its shape. Each CMS also provides the spectral acceleration (at T_1) to which each record is amplitude scaled. Along the same lines, we take the following steps in our example scenario-based assessments below:

1. Construct a CMS for each of *n* equally-probable spectral accelerations (at T_1, T_2, or 2*T_1) for the given M and R, where *n* is either 11 to emulate the procedure in the Draft Guidelines or 1000 in our examples below.
2. The steps 2, 3 and 4 are the same as in the previous sub-section, but only one record per CMS is considered. More than one record per CMS could be selected, but in our example scenario-based assessments below we demonstrate that this is unnecessary. We have followed the same approach described in the previous section to estimate the median EDPs. Note that this is conceptually and numerically different than the median response/loss for a given spectral acceleration (at T_1, T_2, or 2*T_1) and associated earthquake magnitude and site-to-source distance that would yield by an intensity-based assessment.

Time-Based Assessment

The objective of a time-based assessment is to quantify the performance of a building over a given time span, e.g., 50 years. This type of assessment considers all the potential earthquake magnitude (M) and site-to-source distance (R) scenarios that could affect the building of interest. Thus, the use of CMS for time-based assessment is similar to that for scenario-based assessments. As outlined on page 5-18 of the Draft Guidelines, the only differences are that in time-based assessments: (i) conditional mean spectra for spectral accelerations from a seismic hazard curve are used instead of those for spectral accelerations that characterize the probability distribution for a given M and R; and (ii) for each CMS multiple ground motion records are selected instead of one.

Example time-based assessments are not included in this paper; they are left for future work. However, the conclusions reached in this paper for the use of conditional mean spectra in scenario-based assessments can be considered indicative of those that would be expected for time-based assessments, due to the aforementioned similarities between the two types of assessments.

Description of Structure and Engineering Demand Parameters (EDP)

We have considered a 20-story reinforced concrete moment frame building which conforms to the design requirements of modern special moment frames (RC-SMF). The design of the structure has been carried out following the guidelines in ASCE-7-02. The building has been designed as part of the Applied Technology Council Project ATC-63 (2007) and also considered for a research study in the Pacific Earthquake Engineering Research (PEER) Ground-Motion Selection and Modification (GMSM) program. The details of the model and design of the structure can be found in Haselton and Deierlein (2007). Modal analysis of the structure indicates that the first three modal periods of vibration are 2.63s, 0.85s, and 0.46s, and the mass participations at those modes are 78%, 13% and 4% respectively. The soil condition at the building site is NEHRP type D with an average shear-wave velocity in the first 30m (V_{s30}) of about 400 m/s. The building is designed for the maximum considered earthquake (MCE) defined for the highly seismic areas of California with an associated ground motion of 1.5g at short-period spectral accelerations (S_S) and of 0.9g at long-period accelerations (S_1). The nonlinear analyses have been carried out using OpenSEES program (2007). The results of the analyses performed in the PEER GMSM research program (2008) have been used here to estimate different engineering demand parameters (EDP) for the scenario event.

The EDPs considered in this study are the loss ratio (= loss/replacement cost) of the structure, probability of collapse (P_c), maximum of the peak story drift ratios among all the stories (SDR_{max}), and maximum of the peak floor accelerations among all the floors (PFA_{max}). The term "collapse" is used to describe the sidesway collapse, in which buildings become dynamically unstable due to rapid increase in the displacements leading to numerical instability in the solution algorithm. In addition, we will also look into the distribution of peak SDR and PFA along the height of the 20-story structure. A description of the fragility curves of different components of the building, and the loss calculation procedure followed in this paper can be found in the Shome and Bazzurro (2009).

Examples of Conditional Mean Spectrum (CMS) Approaches For a Given $S_a(T_1)$

In order to expedite the loss estimation of structures, we will adopt the approach of using the regression results fitted to the nonlinear time-history responses for a generalized case instead of carrying out nonlinear time-history analysis for large number of records for all the different cases that will be considered in this study. In this section, we will validate this approach of using fitted response results by comparing the results with those from direct nonlinear analysis of structures. To do this, we have first considered the mean spectrum of the scenario event conditioned on $S_a(T_1)$= 0.31g, which is about $+1\varepsilon$ ("epsilon") from mean intensity (representing about 2500-year ground motion in Los Angeles). Note that epsilon is the number of standard deviations by which the logarithmic spectral acceleration of any record differs from the mean logarithmic spectral acceleration predicted from an attenuation relationship. The conditional mean (geo-mean) spectrum (CMS) is shown in Fig. 1. It is observed that the CMS is higher than the median spectrum ($\varepsilon = 0$) at period T_1, but matches closely to the median spectrum at periods far from T_1 because of the low period-to-period S_a correlation. A detailed description of the calculation of CMS can be found in Baker and Cornell (2006). In this section, we will first calculate the median EDPs from the results of nonlinear time-history analysis (NLTHA) and compare these results with those from the fitted results to validate the approach in this paper. Note that median is defined here as the geometric mean.

"Direct" Calculation of EDPs

In this case, we have selected 28 records that match closely to the shape of the CMS. The response spectrum of the 28 records is shown in Fig. 2. These records are first scaled to $S_a(T_1)$= 0.31g and carried out nonlinear analyses to estimate the median (geometric mean) of different EDPs. The results are shown in Table 1. The details of the records and a description of the analysis results can be found in the GMSM report (2009). The loss results (not reported in the GMSM report) are calculated from the results of drifts and accelerations following the calculation procedure given in Shome and Bazzurro (2009). Since the time history analyses for any of the records do not lead to numerical instability, i.e., do not collapse, we are assuming that $P_c = 0$ for the scenario represented by the Fig. 1.

Calculation of EDPs from Fitted Results

In this case, the EDPs are calculated from the fitted results for the CMS shown in Fig. 1. A description of the NLTHA results can be found in the GMSM report (2009) and the regression models can be found in Shome and Bazzurro (2009). In this paper, we will be estimating median EDPs from the fitted results to address the issues of calculating accurate EDP for multi-mode dominated structures. The median EDPs for the CMS from the fitted response results are shown in the first column of Table 2. It is observed that although the median EDPs are quite close to those estimated before, the differences in the results are statistically significant (compare the median loss ratio results in Tables 1 and 2). The results in the GMSM report (2008) (referred as "point of comparison") are also shown in the second column of Table 2 and these results are quite similar to those estimated from the approach proposed in this paper. We have already seen in Fig. 2 that the average response spectrum of the selected records is close to the target CMS, but the individual response spectrum of these records are not exactly the same. It is expected that this difference in the records is causing the difference in the response results. Fig. 3 shows the variation of SDR and PFA along the height of the structure for the 28 records to illustrate the variability in response even for these closely matched records. The figure also shows the difference between the median results and the median estimated from the fitted function. Since the response of the structure is quite sensitive to the variation of the response spectrum, it would be difficult to close the differences in the results unless we match the target spectrum exactly.

Table 1. Results of the median EDPs from records that match closely the scenario CMS.

Parameter	Median (Geo-mean)	Counted Median
Max Story Drift Ratio (SDR_{max})	1.4%	1.4%
Max Peak Floor Accl (PFA_{max})	1.5g	1.5g
Prob. of Collapse (P_C)	0.0	0.0
Loss Ratio	16%	17%

Table 2. Results of the median EDPs from different methods of calculations.

Parameter	Fitted Results (this study)	PEER GMSM
Max Story Drift Ratio (SDR_{max})	1.7%	1.7%
Max Peak Floor Accl (PFA_{max})	1.5g	1.5g
Prob. of Collapse (P_C)	0.01	0.01
Loss Ratio	20%	—

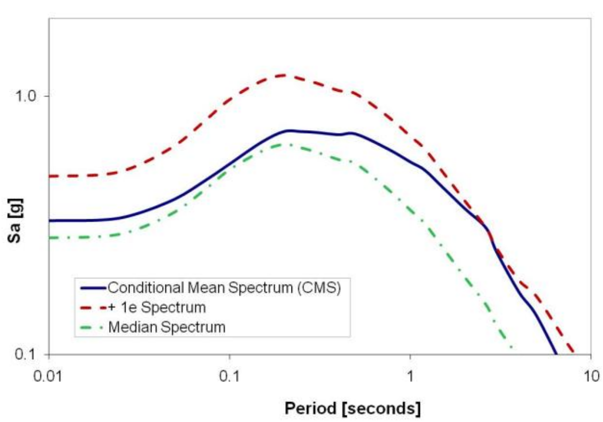


Figure 1. Mean (geo-mean) spectrum conditioned on M_w = 7.5, R=10km, Vs30 = 400m/s and $S_a(T_1=2.63s)$ = 0.31g, which is about +1ε intensity at T_1. The red dashed line shows the "+1ε" spectral acceleration values at

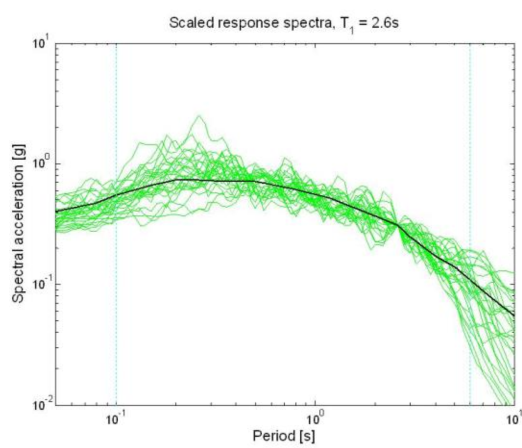
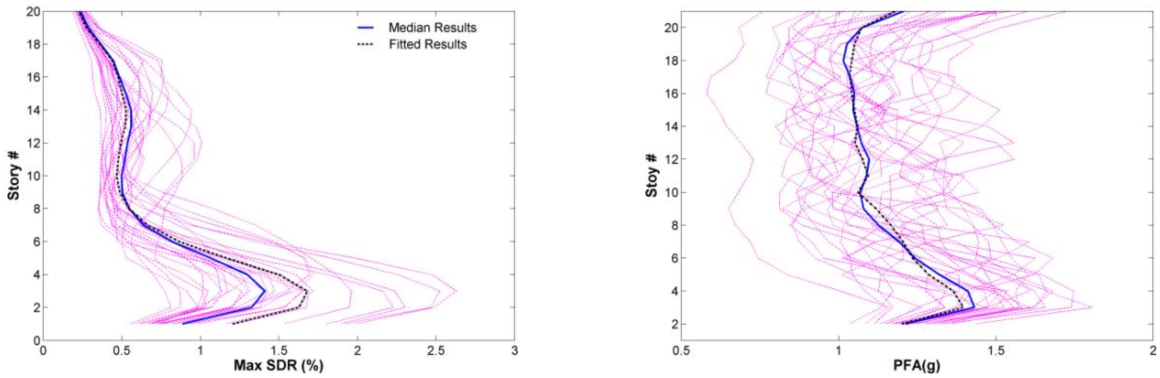


Figure 2. Comparison of the response spectrum of the 28 records (shown by green lines) and the CMS for M_w = 7.5, R=10km, V_{s30} = 400m/s and $S_a(T_1=2.63s)$ = 0.3g (black line).

different periods, the green dash-dotted line
shows the median spectrum (ε=0).



(a) (b)

Figure 3. Variation of nonlinear response results for the 28 records shown in Fig. 1. The median results are shown by the solid blue line and the median estimated from the fitted response results are shown by the black dotted line

Median EDPs for The Scenario Event Based on $S_a(T_1)$

In the previous section, we have estimated the EDPs for the mean spectrum conditioned on a specific $S_a(T_1)$ for the scenario event, which is a magnitude 7.5 earthquake at a distance 10km on a strike-slip fault, at a site with 30m shear wave velocity of 400m/s. In this section, we will repeat the calculation of EDPs from the fitted response results as described in the previous section for 1000 equal probable samples of $S_a(T_1)$ to estimate the median EDPs for the scenario event based on $S_a(T_1)$. The ground-motion intensities for the calculation of EDPs are the mean spectrum for the scenario event conditioned on the samples of $S_a(T_1)$ and the response spectrum of the 1000 CMS is shown in Fig. 4. The median (geometric mean) EDPs based on these CMS are shown in the Table 3 (column of $S_a(T_1)$). The variation along the height as well as the distribution of peak SDR and PFA of the structure are shown in Fig. 5. The figure demonstrates the shift of maximum SDR from upper stories at low intensities to the lower stories at high intensities. Since the PFAs are dependent primarily on the high frequency component of the ground motion and Fig. 4 shows that the mean of the high frequency components of the ground motion do not change significantly conditioned on S_a at T_1, the PFA at different stories remains close to the median values. Note that the EDPs required for the calculation of loss ratio are not deterministic for a given intensity of ground motion. We have estimated the variability of the EDPs by regression analysis and we have considered this variability in the simulations to improve the estimation of the median EDPs. In this study, we have considered explicitly the effect of the shape of spectrum associated with different periods conditioned on S_a at T_1 for the estimation of different EDPs. The influence of duration, if any, has also been considered implicitly in the process by selecting large number of records representing the scenario. Since we have considered only the conditional *mean* spectrum to estimate the EDPs, the variability as shown in the Fig. 5 is on the low side compared to the true variability of those EDPs. As discussed before, the accurate estimation of the variability of the EDPs is not within the scope of this study.

Recently, ATC-58 (2009) has prescribed using only 11 equal probable samples (compared to 1000 samples used in this study) for the estimation of median EDPs. We have estimated the CMS conditioned on $S_a(T_1)$ at the 11 defined values of "epsilons" and estimated the median EDPs for these mean spectra. The results are shown in Table 3. The median values are almost identical to those estimated before from the 1000 samples of $S_a(T_1)$. Note that if one is interested in estimating the distribution of EDPs for a scenario event (which is important, for example, for estimating the probable maximum loss (PML) for the risk assessment of structures), the ATC-58 method will not be able to provide an accurate estimate of the distribution of the EDPs.

Table 3. Results of the median EDPs from different methods of calculations.

Parameter	$S_a(T_1)$	$S_a(T_2)$	$S_a(2{*}T_1$	***ATC-58***
Max Story Drift Ratio (SDR_{max})	0.8%	0.8%	0.8%	0.8%
Max Peak Floor Accl (PFA_{max})	1.5g	1.5g	1.5g	1.5g
Prob. of Collapse (P_C)	0.0	0.0	0.0	0.0
Loss Ratio	15%	14%	15%	15%

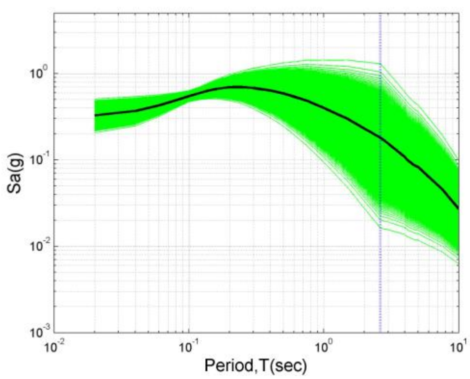


Figure 4: Mean spectrum for the scenario event conditioned on 1000 equal probable samples of $S_a(T_1)$.

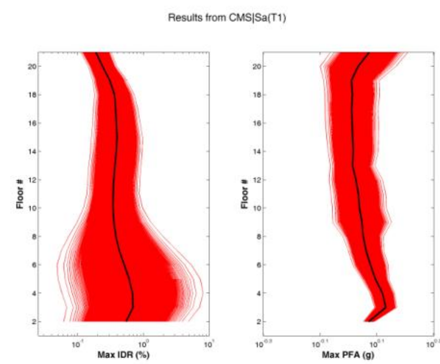
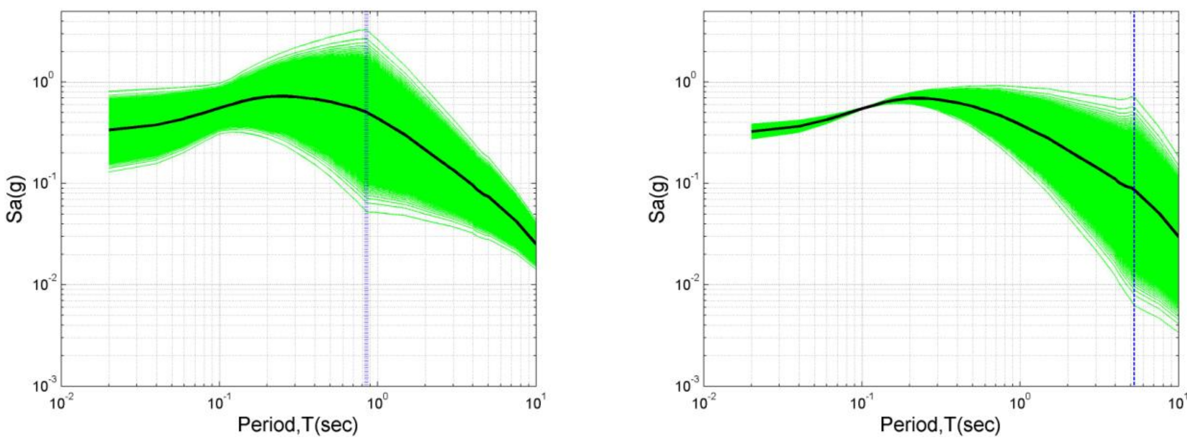


Figure 5. Variation of peak SDR and PFA along the height for the mean S_a conditioned on different intensities based on $S_a(T_1)$.

Median EDPs For The Scenario Event Based on Other Spectral Parameters

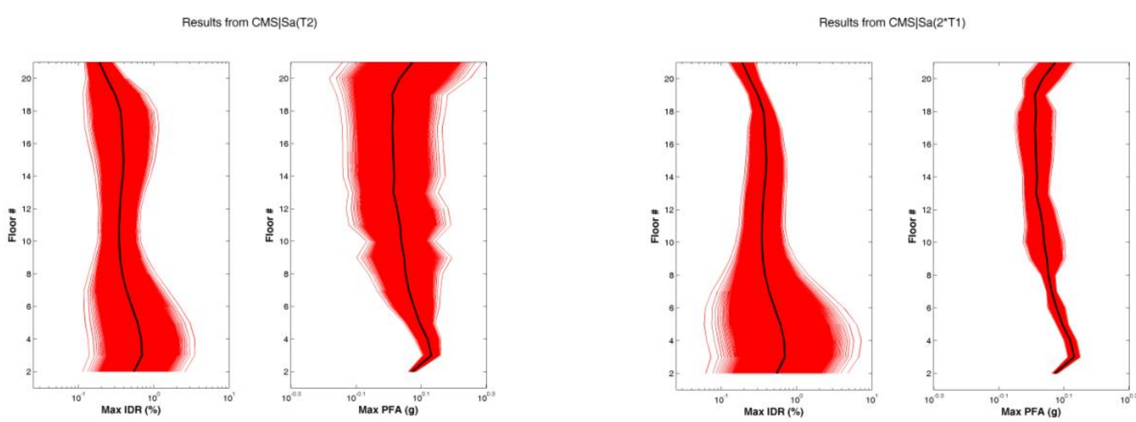
So far we have estimated the median EDPs based on CMS for $S_a(T_1)$. Since the 20-story building is a multi-mode dominated structure (first-mode mass participation is only 78%), it is suggested by the engineers that the ground-motion intensity should consider other spectral parameters in addition to $S_a(T_1)$ in order to improve the accuracy of the estimation of median EDPs. We will address this concern by comparing the results for the CMS based on $S_a(T_2{=}0.85s)$ and $S_a(2{*}T_1 = 5.3s)$ with those estimated before for $S_a(T_1)$.

The CMS of equal probable 1000 samples for $S_a(T_2)$ and $S_a(2{*}T_1)$ are shown in Figures 6. It is expected that the response results from CMS for $S_a(T_2)$ would show relatively higher influence from high-frequency components of ground motion, whereas those for $S_a(2{*}T_1)$ would show relatively higher influence of low-frequency components of ground motion. The median EDPs are calculated for the sample spectrums for each of the cases by following the exact same procedure as described in the previous section. The results as shown in Table 3 show that we are getting similar results from all the different approaches of computation of input ground-motion intensities for the multi-mode dominated structure. Fig. 7 shows the distribution of responses along the height of the structure. As expected, we observe relatively (compared to those in Fig. 5) higher variation of SDR at higher stories and PFA at all stories for $S_a(T_2)$-based intensities since these response parameters are dependent as well on the high-frequency component of ground motion. The variation of SDR at lower stories, on the other hand, is higher for the $S_a(2*T_1)$-based intensities since the responses at lower stories are dependent on the low-frequency component of the ground motion. We also observe in Fig. 7(b) that since the PFAs for all the stories are dependent on the high-frequency component of ground motion , these response parameters do not change much for all the different conditional mean spectra. So it can be concluded that we should be able to estimate accurately the median EDPs based on for $S_a(T_1)$ like the single-mode dominated low-rise buildings.



(a) $S_a(T_2)$ (b) $S_a(2*T_1)$

Figure 6. Median Response spectrum for the scenario event conditioned on 1000 equal probable samples of S_a.



(a) From $S_a(T_2)$-based intensities (b) From $S_a(2*T_1)$-based intensities

Figure 7. . Variation of story drifts and accelerations along the height of the structure for different mean spectra conditioned on S_a at different periods.

Summary and Conclusion

We have estimated median of different EDPs, which are important for evaluating the performance of a multi-mode dominated 20-story RC-frame structure. Although it was expected that the calculation of median EDPs of multi-mode dominated structures represented by the 20-story structure is dependent on the selection of S_a parameter, we have observed that the presumption was not true. The median EDPs based on conditional mean spectrum (CMS) for three different S_a parameters, which are $S_a(T_1)$, $S_a(T_2)$, and $S_a(2*T_1)$, are found to be very close to each other. We have estimated the EDPs by fitting the nonlinear response results for large number of records to multiple S_a parameters. If any other ground characteristic that is not captured by the ground motion intensities represented by S_a and the associated shape of response spectrum, and if those parameters have significant effect on the calculation of EDPs, the conclusion drawn in this paper would require further investigation.

Acknowledgements

We are grateful to Prof. Curt Haselton, and the other members of PEER GMSM group for providing the nonlinear time-history analysis results for the research study in this paper. We also want to thank Prof Jack Baker of Stanford University for all the helpful suggestions to our research.

References

ATC-58, 2009. Guidelines for Seismic Performance Assessment of Buildings (50% Draft). *Applied Technology Council*, Redwood City, CA.

ATC-63/FEMA P695, 2007. Quantification of building seismic performance factors. *Applied Technology Council*, CA/ Federal Emergency Management Agency, Washington, DC.

American Society of Civil Engineers (ASCE7-02), 2002. *Minimum Design Loads for Buildings and Other Structures*. Reston, VA.

Baker, J.W. and Cornell, C.A., 2006. Spectral shape, epsilon and record selection. *Earthquake Engineering & Structural Dynamics* 35(9), 1077–95.

Ground-Motion Selection and Modification (GMSM) Program, 2008. *Pacific Earthquake Engineering Research (PEER)*. University of California, Berkeley. http://peer.berkeley.edu/ gmsm/ (last accessed October 1, 2009).

GMSM, 2009. Evaluation of Ground Motion Selection and Modification Methods: Predicting Median Interstory Drift Response of Buildings. *PEER Report 2009/01*, Curt B. Haselton, Editor. Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley.

Haselton C. and Baker J.W., 2006. Ground motion intensity measures for collapse capacity prediction: Choice of optimal spectral period and effect of spectral shape. *8th National Conference on Earthquake Engineering*, San Francisco, California.

Haselton, C. and Deierlein, G., 2007. Assessing seismic collapse safety of modern reinforced concrete moment frame buildings. *Report No. 156*, The John A. Blume Earthquake Engineering Center, Stanford University.

Shome, N. and Bazzurro, P., 2009. Comparison of Vulnerability of a New High-Rise Concrete Moment Frame Structure using HAZUS and Nonlinear Dynamic Analysis. *10th International Conference on Structural Safety and Reliability*, Osaka, Japan.

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