Scaling bias and record selection for fragility analysis

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SUMMARY
Lack of sufficient records for a given site and hazard level is a frequent challenge. Two typical methods are used to overcome these difficulties: modification of existing records or generation of synthetic ground motions. This paper considers the response of several simple nonlinear systems to amplitude scaled and synthetic ground motions suites to determine bias in the response obtained compared to unscaled records. The dependence of this bias ratio on properties of the nonlinear system (e.g., elastic period, yield strength, etc.) and the metric used to scale the ground motions (e.g., PGA, Arias intensity, epsilon, elastic spectral displacement, etc.) are investigated. Results show the amount of the bias is considerable and dependent on period, effect of higher modes of vibration, nonlinear characteristics of the structures, and metric used to scale the ground motions and can significantly affect the results of PBEE analysis.

Keywords: nonlinear dynamic analysis; synthetic ground motion; PBEE; maximum response

1. INTRODUCTION

Early attempts in developing seismic performance-based design have generalized conventional “load” and “resistance” terms with “demand” and “capacity” for design of structures. These attempts have been reflected in FEMA 273 (1997), FEMA 356 (2000) utilizing deterministic approach for structure performance assessment. A probabilistic approach to performance-based earthquake engineering (PBEE) emerged in FEMA 350 (2000) and evolved by incorporating inherent uncertainties in both demand and capacity. Types of material and workmanship, structural configuration, nonlinear behavior of joints and elements, nonstructural components, site characteristics and characteristics of ground motion are only some examples of uncertainties incorporated in PBEE (Yun et al., 2002). In addition, uncertainties associated with imperfection of knowledge for properly modeling the response of the structures to a variety of ground motions and change of assumed characteristics of the structure during the earthquakes should be considered. Quantifying earthquake demands is highly variable based on the site characteristics, hazard region, and existence of previously recorded ground motions. One of the drawbacks for extensive use of PBEE by engineers is scarcity of recorded ground motions that closely match the site characteristics and have the target intensity of interest. Different methods have been utilized to overcome this obstacle. Scaling the ground motions, using synthetic earthquakes or combination of both methods have been taken into account. A variety of scaling methods such as amplitude scaling, linear scaling for spectral acceleration for first period of structure Sa (T_1) (Shome et al., 1998), linear scaling of Sa over period range (Hancock, et al., 2008) and linear scaling using spectrum matching (Hancock et al., 2006) have been used previously.

In amplitude scaling of the ground motions, engineers seek a suit of ground motions with similar site characteristic as the structure site. Consequently each record can be scaled to multiple target intensities to preserve the proportionate distribution of the intensity measure of interest. However, scaling of ground motions created the concern of whether a record that has been scaled to target intensity has the same effect on the structure compared to a record that is naturally at the target intensity. Previous studies show that scaling of ground motions can cause bias in response of nonlinear structures. Shome et al. (1998) addressed the illegitimacy of scaling more directly whereas Sewell (1989), Iervolino and Cornell (2005) and Baker (2005) indirectly addressed the bias induced by scaling. According to Luco and Bazzurro (2004) these studies had little impact on engineering practice because the conclusions are limited by statistical concepts and findings. In more recent studies, Luco and Bazzurro (2004; 2007) investigated the bias associated with scaling in the median nonlinear structural drift response for a target Sa, and conclude records with the same value of Sa (T_1) structure should be considered in selection of records to avoid bias in the median response.

Huang et al. (2011) used four different scaling procedures including geometric-mean scaling, spectrum matching, Sa (T_1) scaling, and distribution-scaling to quantify bias induced in the spectral shape and median Sa, as well as dispersion in nonlinear responses of the structures. Epsilon ε has significant correlation with Sa (Baker and Cornell, 2005) and was considered a predicting parameter for legitimacy of scaling for each individual record based on Sa. The study by Huang et al. (2011) was limited by the scaling based on Sa, and the conclusions are limited to first-mode-dominated buildings with minor to moderate inelastic deformation. Despite the attempts that have been performed previously, no comprehensive study can be found in the literature that considers a variety of methods of scaling, SDOF and MDOF system parameters, and addresses the fundamental reasons corresponding to scaling-induced bias for response of nonlinear systems. The lack of such a study is rooted in the complexity and variability in the nature of ground motions, nonlinear systems, and their interaction.

Synthetic earthquake ground motions have been used when appropriate recorded ground motions are not available. Many types of synthetic ground motion models have been developed in the past years and many are still under development. These models can be classified in three categories (Douglas and Aochi, 2008): 1) seismological models of site rupture mechanism and wave propagation, 2) parameterized stochastic models fitted to previously recorded ground motions, and 3) hybrid models employing a combination of first and second method elements. Seismological and hybrid models did not see widespread adoption in practice because they require extensive computation and thorough knowledge of the site characteristics, source, and wave path, which vary significantly by region (Rezaeian and Der Kiureghian, 2010). In this paper, ensembles of horizontal ground motion components with correlated parameters for specified earthquake and site characteristics were generated using the stochastic method proposed by Rezaeian and Der Kiureghian (2012). The ground acceleration process is described as the response of a linear filter with time varying parameters to white-noise excitation. The filter response is normalized by its standard deviation and is multiplied by a deterministic time-modulating function. While modulation of the process in time introduces temporal nonstationarity, variation of filter parameters provides spectral nonstationarity. The method generates orthogonal lateral components of ground motions by determination of the correlation between the parameters obtained from predictive equations developed for model parameters of each component.

The objective of this paper is to determine whether ground motion record amplitude scaling produces biased nonlinear structural response statistics. For this purpose a comprehensive study was performed using different types of nonlinear SDOF and MDOF systems and various well-known intensity measuring parameters for amplitude scaling. In addition to recorded ground motions, synthetically simulated ground motions were employed to identify a similar amplitude-scaling bias and to allow for generation of a larger catalog of high intensity records for comparison to unscaled ground motions. Using the synthetic ground motions also forms the basis of future efforts to identify the characteristics of ground motions that cause bias after amplitude scaling of records. The method used for synthetic record generation (Rezaeian and Der Kiureghian, 2012) provides distinct control over the temporal and spectral characteristics of the record. Different bins have been selected from real and synthetic suites of ground motions. Dependency of bias associated with scaling for different types of nonlinear systems, amount of scaling, and methods for selection of bins were studied. Fragility curves are one of the key tools in quantifying performance in PBEE. Consequently, dependency of fragility curves on bias induced by scaling was investigated. The results of this study can be used as a benchmark for more practical method for selection of records to eliminate bias for response nonlinear structures.

2 METHOD

In this section, the methodology for selection of recorded ground motions is introduced and a recent method for generation of synthetic ground motions based on Rezaeian and Der Kiureghian (2012) is described. The different types of nonlinear system utilized in this study are described, scaling by different parameter strategies was considered for this study and the bin selection and record-pairing algorithm for making pairs of bins for target intensity ratios are introduced. At the end of this section, the method for comparing the effect of the scaling of records on performance-based assessment of the structures is introduced. This method is illustrated with the variation of fragility curve parameters due to scaling of records.

2.1 Selection of recorded ground motions

For this study, several recorded earthquake were chosen from the PEER Ground Motion Database (2011). Records were selected from different sites based on parameters that represent engineering or seismological characteristics of each record, and M, R_{rup} and V_{s30} have been considered for selection of the records. M represents moment magnitude of the earthquake, R_{rup} represents the shortest distance from the recording location of the earthquake to the rupture area, and V_{s30} is the shear velocity of the top 30 meters of the site soil. For this study, earthquakes with moment magnitudes greater than 6 were selected to ensure larger magnitude events that are more likely to cause nonlinear response. Similarly, far field records with R_{rup} greater than 60 km were not considered. The shear wave velocity of the records selected was limited to the range of 180 m/s to 760 m/s to be consistent with USGS soil types C and D.

After considering these constraints on the selection of records from the database, a suite of 579 ground motions were selected. Each ground motion contains two orthogonal horizontal pairs (1158 records in total). Only horizontal components were selected and vertical components were not considered. No lower limit was placed on the site distance of the records, consequently records that exhibit near fault characteristics such as pulse and fling were also removed from the suite of records. After removing pulse like and fling-step records from the suite, 1132 ground motion time histories remained for this study. Fig 2.1 (a) and (b) shows the scatter plot for M versus R_{rup} and V_{s30} respectively.

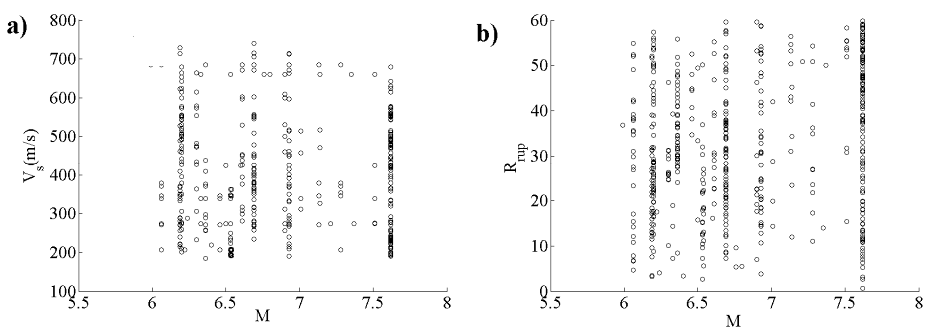

Figure 2.1 (a) Distribution of moment M versus R_{rup} and (b) Distribution of moment M versus V_{s30} for selected records

2.2 Generation of synthetic ground motions

In this paper, synthetic ground motions are used as a comparison with as-recorded ground motions. The same methods were applied to the originally recorded earthquakes as well as synthetically simulated ground motions for finding scale-induced bias. A method recently proposed by Rezaeian and Der Kiureghian (2012) was utilized for generating the synthetic ground motions in this study. Earthquake site characteristic are used as the input parameters for simulating an ensemble of records.

M, V_{s30}, R_{rup}, and fault type are the only required input parameters (Rezaeian and Der Kiureghian, 2012). Key spectral and temporal parameters were statistically calculated from site related parameters by employment of predictive equations obtained from regression analysis performed on data extracted from a subset of NGA strong motion database records. No extensive information or intensive computation is needed for simulation of synthetic earthquakes by this method. Consequently a total number of 566 pairs (total number of 1132 record) of ground motions were generated using the same site characteristics for as-recorded earthquakes selected in section 2.3. Inspection of the intensity parameters of each individual record led to removal of 4 records due to their large value for Arias Intensity (IA > 40 m/s). Table 2.2 shows intensity measuring parameters for as-recorded and synthetically generated records. In table 2.2, β is the ratio of mean value for intensity of synthetic earthquakes and real earthquakes and ξ is the ratio of their standard deviation values. Table 2.2 shows earthquakes obtained from simulation have smaller intensity variables and also have more energy content in large frequencies. The only exception here is the ratio of mean values of Arias Intensities that is more than one.

Table 2.2 Comparison between intensity parameters of real earthquakes and synthetic earthquakes

	PGA	PGV	IA	CAV	T=0.1 s	SD T=0.5 s	SD T=1 s	SD T=2 s	SD T=5 s
β	0.9326	0.4893	1.2527	0.5583	1.3445	0.6602	0.4714	0.4274	0.4619
ξ	1.115	0.6156	0.8615	0.5352	1.7101	0.9241	0.6551	0.4471	0.4913

2.3 Selection of nonlinear systems

For this study three different nonlinear systems were considered, and the characteristics of each system are described here. The first system is a simple nonlinear system that exhibits elastic-perfectly plastic response in a single dynamic degree of freedom. Characteristics of this nonlinear system are presented using pre-yielding stiffness and yielding strength of the system. Pre-yielding stiffness also determines the initial period of the oscillator (T). Yielding strength is the only parameter that differentiates this system from linear systems. The model unloads and reloads along the same initial stiffness. The yielding strength of the nonlinear system was chosen F_y=0.2 N to ensure the system will enter the nonlinear state for most of the records. The value F_y=0.2 N can guarantee yielding for 89.4% of SDOF systems with periods between 0.1 sec to 3 sec subjected to selected earthquakes. Fig 2.2 (a) shows the mean and mean ±σ response spectrum of SDOF linear system for the suite of real ground motions selected in section 2.1. Fig 2.2 (b) shows the percentage of as-recorded ground motions that cause yielding for a SDOF system with F_y =0.2 N. Bilinear SDOF systems with stiffness hardening ratios equal to 0.01 and 0.2 were used to capture the dependency of the results on this ratio. The yielding strength of the bilinear SDOF system considered was the same value as those for the elastic-perfectly plastic SDOF system.

For consideration of more complex nonlinear systems and comparisons between responses with SDOF nonlinear systems, a third type of nonlinear system was introduced. A reinforced concrete frame with nonlinear properties for both reinforcing steel and concrete was modeled as a two-dimensional MDOF dynamic system. Record components were applied to the frame in the lateral direction. The MDOF system consists of a pin-supported frame with two columns and one beam. The frame was not intended to directly represent an as-built case, but a MDOF extension to the previous two systems that incorporates more complex nonlinearities in the cross section. The frame is symmetric and the properties of the vertical members are identical. Horizontal and vertical lumped masses were assigned to the top nodes of the frame (top node of each column). The flexural stiffness of the beam was assumed to be large (20 times) relative to elastic column stiffness to simulate the rigid diagram movement for upper nodes of the frame. The height of the column was assumed to be 7.3 m and the width of the frame span was 10.9 m. The joint connection between the elements was assumed to be rigid.

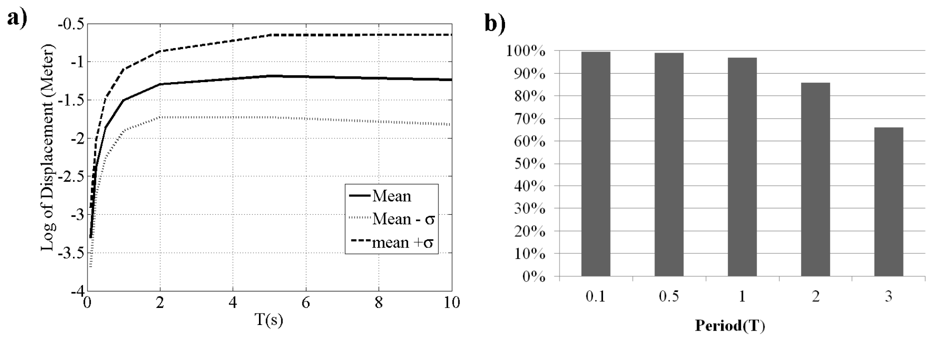

Figure 2.2 (a) Mean and mean $\pm\sigma$ response spectrum. (b) Percentage of yielding observed for SDOF system with F_y=0.2 N.

OpenSees software was used for modeling and nonlinear dynamic analysis of the structure. Fig 2.3 (a) shows the schematic view for the frame. In Fig 2.3 (a) black circles on the top of the columns are lumped masses. The outer radius of the column is 60 cm. and column cover concrete width is 3 cm. For the column, the core was discretized into 128 patches with 8 radial fibers and 16 tangential fibers. The cover was also discretized into 32 patches with 2 radial and 16 tangential fibers. Small values for column longitudinal-steel reinforcement ratio (0.2%) and compressive stress of concrete were chosen to guarantee inelastic response for most of the ground motion records applied. Properties of unconfined concrete such as unconfined concrete compressive strength, strain at maximum strength, ultimate stress and strain at ultimate stress were assumed to be 140 kg/cm^2, -0.003, 14 kg/cm^2, and -0.025, respectively. For confined concrete, the maximum stress of confined concrete, strain at maximum stress, stress at crushing stress and strain at crushing stress assumed to be 180 kg/cm^2 , -0.003, 90 kg/cm^2 and -0.025, respectively. The yielding stress of steel, initial elastic modulus and pre-to post-yielding tangent stiffness were assumed to be 4200 kg/cm^2 , 200 GPa, and 0.01, respectively. Fig 2.3 (b) shows pushover analysis result for the frame. The horizontal axis is lateral displacement of the top node of the column and the vertical axis is the summation of lateral forces applied equally to top nodes of the columns. The mass of the structure has been modified to acquire pre-yielding period of the frame equal to one second based on the pre-yielding stiffness obtained from pushover analysis.

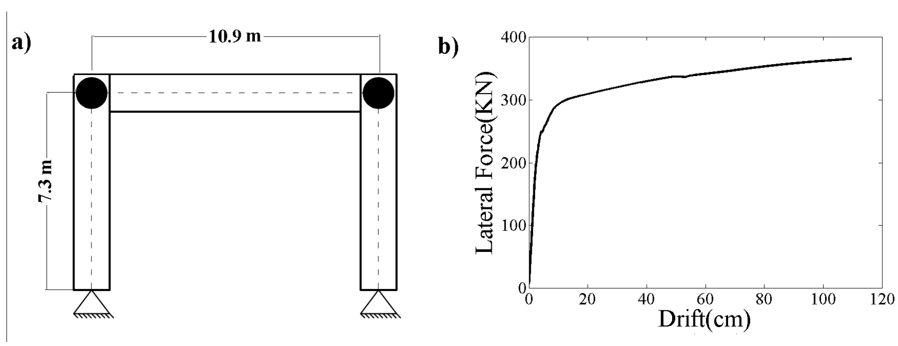

Figure 2.3 (a) Schematic dimensions for the frame (b) pushover analysis results.

2.4 General method for identification of bias in scaling

In this section, the method used for identifying bias in the response of the nonlinear systems is discussed. For the ground motions selected from the PEER Ground Motion Database, some parameters were calculated as an indicator for the intensity of each individual record. These parameters, I_j where j=1,2,…5 are peak ground acceleration (PGA), peak ground velocity (PGV), cumulative absolute velocity (CAV), Arias intensity (IA), and elastic spectral displacement with 5% equivalent viscous damping (SD), respectively. All these are well-known parameters for measurement of the intensity of ground motions. For the j^{th} intensity parameter, two bins of records were selected for each scale factor. The i^{th} record at bin one was selected such that if the amplitude is scaled by the target scale factor of interest, its I_j parameter matches the, I_j parameter of i^{th} record in bin two. As an example, if binning with respect to IA and a target scale factor of two, the IA of the i^{th} record in bin 2 is two times greater than IA of the the i^{th} record in bin 1. Therefore bin one contains records that should be scaled by the target scale factor to match the intensity of records in bin two. The only exception for this procedure is binning based on SD values. For selection of the records for each bin based on SD, the variation of the elastic response of the structure with change in period of the system should be taken into the account.

Bin selection was repeated for scale factors of 0.1 … 10 for each different type of nonlinear system. The nonlinear systems were selected with elastic periods corresponding to 0.1 … 5. Maximum response of the systems to selected ground motions was captured. The scale induced bias from bin one is measured with respect to response of the unscaled records from bin two that are naturally at the target intensity of interest. Bias is defined as follow:

$$Bias = \frac{\boldsymbol{mean\ of\ drift\ response\ to\ scaled\ records}}{\boldsymbol{mean\ of\ drift\ response\ to\ unscaled\ records}(\ \boldsymbol{that\ are\ naturally\ at\ target\ intensity})} \qquad (2.1)$$

When the bias value calculated from Eqn. 2.1 is more than one, the bias can be defined as positive bias. When the bias value is less than one it can be called negative bias, and when it's equal to one results can be called unbiased.

A fragility curve describes the probability of exceeding a limit state as a function of ground motion intensity parameter. To investigate the effects of scaling on the PBEE analysis, fragility curves of the structure were calculated for scaled bin one and unscaled bin two. Structural capacity was assumed to be in terms of maximum displacement (or drift) and log-normally distributed. For the complete damage state for a structure, the mean value and coefficient of variation of the capacity were assumed to be $7\times\delta_y$ (δ_y represents yielding displacement) and 0.4, respectively (Choi et al., 2004). The log-normal distribution parameters were obtained from the mean and coefficient of variation, and the probability of failure was computed based on the maximum displacement associated with each ground motion. Fragility curves were obtained by fitting a CDF (cumulative probability distribution function) on the damage data using the least squares error method presented by Porter et al. (2007).

3 RESULTS

3.1 SDOF bias ratio based on records from PEER database

The bias ratio corresponding to each scale factor and each SDOF system were computed using Eqn. 2.1. Fig 3.1 (a) to Fig 3.1 (f) shows the bias for the SDOF systems induced by scaling based on binning for the recorded ground motions. In Fig 3.1 (a) to Fig 3.1 (f), the horizontal axis is the target scale factor, which can be defined as the ratio of intensity of bin two compared to unscaled bin one. The vertical axis is the bias ratio defined by the Eqn. 2.1. At scale factor one, the bias ratio is assumed to be unity, or the no bias case. The different lines on these figures indicate bias for SDOF periods but the same yielding strength. Fig 3.1 (a) shows the bias introduced for binning biased on PGA. The general trend for Fig 3.1 (a) shows a significant bias for all structural periods. The system with the period T=5 sec have largest bias ratio value compared to other systems for scale factors more than one. This implies that a softer system with the greater period shows more bias to scaling when the records are scaled based on their PGA intensity. Fig 3.1 (b) shows bias ratio versus scale factor of SDOF systems binned based on IA. Scaling based on IA induces more bias for SDOF systems while the dispersion of the results for different periods is not as significant as PGA scaling. Fig 3.1 (c) and Fig 3.1 (d) describe the bias ratio values for different scale factors and binning based on PGV and CAV. These graphs show that binning based on CAV and PGV leads to smaller bias for the different

SDOF nonlinear systems and different scale factors. The only exception is T=5 sec for scale factor 0.1. Except for the system with long period, when the range of scale factors varies between two to ten, the bias ratio for most of the systems can be considered equal to one especially when compared to the bias obtained from binning by PGA and IA in Fig 3.1 (a) and Fig 3.1 (b) . Fig 3.1 (e) shows the bias associated with SD. Between all the intensity parameters considered in this study, SD is the only variable that incorporates both intensity of the record and characteristics of the structure. Fig 3.1 (e) shows that systems with smaller periods tends to have more bias for different scale factors, while for softer systems the bias ratio is close to unity. Results for binning based on SD also show smaller bias compared to binning based on IA and PGA.

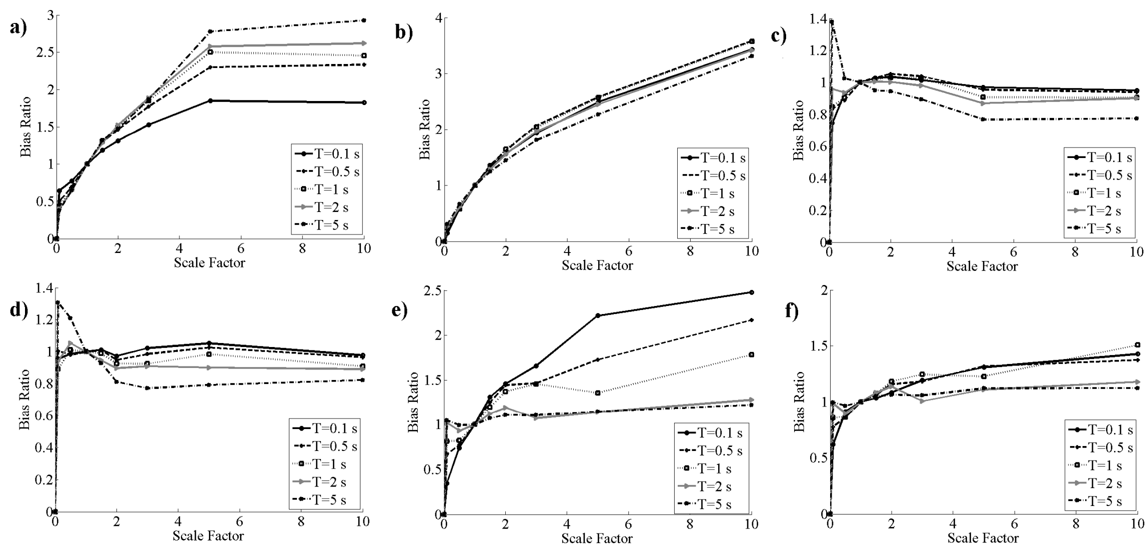

Figure 3.1 (a) to (e); bias values for as-recorded ground motions and elasto-plastic system based on PGA, IA, PGV, CAV and SD respectively. (f); for binning based on SD and bilinear system with hardening ratio equal to 20%.

To investigate the effect of post-yielding behavior of the oscillator on bias, the bilinear oscillator results are also presented. Bias ratio values for different scale factors and different pre-yielding period of a bilinear structure with 1% stiffness hardening ratio and binning based on SD is similar to Fig 3.1 (e). The reason is, 1% stiffness hardening ratio in the nonlinear system cannot create much difference in system characteristics compared to the elasto-plastic system. In Fig 3.1 (f), the results for a bilinear system with 20% stiffness hardening ratio are presented. Similar to bias values for elasto-plastic systems when binning based on SD, the bias values here are significant for small periods. However, for large periods, the bias ratio values are negligible. Comparison between Fig 3.1 (f) and Fig 3.1 (e) shows bias values for bilinear system with 20% stiffness hardening ratio is less than the elasto-plastic system. This observation can be explained by the characteristics of the oscillator such that the average period of a bilinear system is closer to linear system compared to elasto-plastic oscillator with the same period and yielding force, i.e., the response of a bilinear system can tend to a linear system as the stiffness hardening ratio tends to 100%.

3.2 SDOF bias ratio based on binning from synthetic earthquakes

The same method used for originally recorded ground motions was employed for selection of records and making bins one and bin two for measuring the bias. Results have been plotted in Fig 3.2 (a) to Fig 3.2 (f). Fig 3.2 (a) and Fig 3.2 (b) show the variation of bias values for synthetic earthquakes and binned based on PGA and IA respectively. The trend is similar to those for real ground motions presented in fig 3.1 (a) and 3.1(b) but bias values are smaller for synthetic ground motions. Fig 3.2 (c) and Fig 3.2 (d) show the bias for synthetic earthquakes and binning based on PGV and CAV respectively. For binning based on PGV, the bias is close to one for different scale factors and periods. Binning based on CAV results in almost the same properties as binning based on PGV. The difference is, for scale factor equal to 0.1, positive bias can be seen on the graph and for scale factor greater than one, a slight negative bias can be observed. Trends of bias values for binning based on CAV and PGV are similar to those for as-recorded earthquakes.

Bias values associated for elasto-plastic and bilinear systems with 20% stiffness hardening systems can be seen in Fig 3.2 (e) and Fig 3.2 (f). As it can be seen an increase of the stiffness hardening ratio for the SDOF system can decrease the bias values as the characteristics of nonlinear system tend to linear and system demonstrate less period elongation during the period of earthquake. Comparison between results from as-recorded and synthetic ground motions shows scaling originally recorded earthquakes make more bias compared to synthetic earthquakes. However bias clearly exists for scaling procedure for both types of as-recorded and synthetically generated ground motions.

The fact that bias can be observed in both types of ground motions shows bias is not only a feature of record characteristics, it is also a feature of nonlinear systems. Similar to as-recorded earthquakes, using PGV or CAV for record selection can result in less bias compared to the other types of intensity parameters studied. An increase in the stiffness hardening ratio for the SDOF system can decrease the bias values, as the characteristics of the nonlinear system tend toward a linear system and produce less period elongation of the system during the duration of strong ground motion.

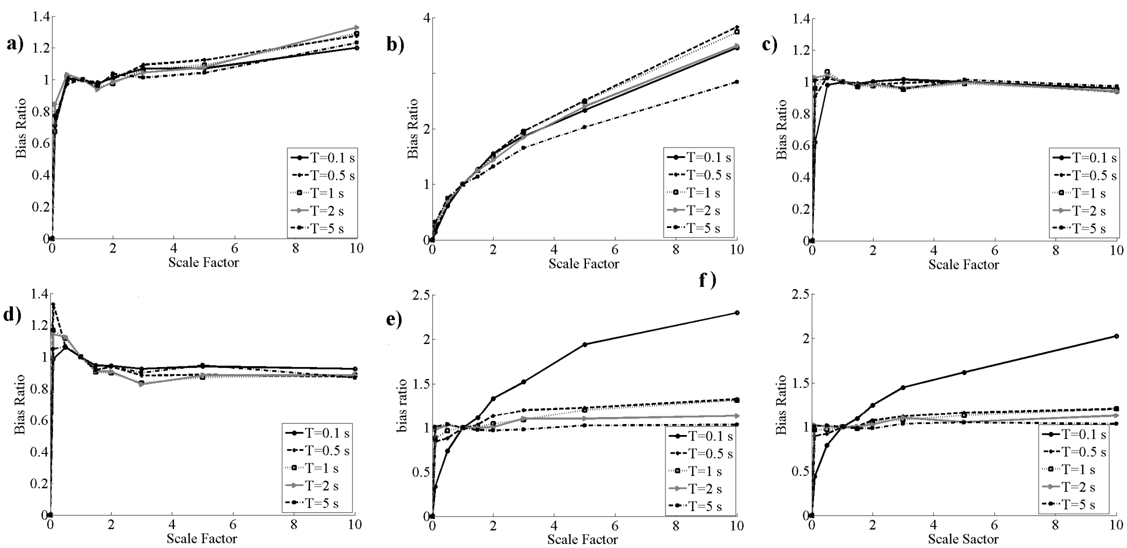

Figure 3.2 (a) to (e); bias values for synthetic ground motions and elasto-plastic system for binning based on PGA, IA, PGV, CAV and SD respectively. (f); for binning based on SD and bilinear system with hardening ratio equal to 20%.

3.3 Bias for MDOF system

Bias values have been calculated with the same bins that have been used for the SDOF systems with period equal to one. Only CAV and SD were considered for binning. Fig 3.3 shows the calculated bias values for the frame based on SD and CAV for as-recorded and synthetic ground motions. Comparison between results from frame analysis versus SDOF systems indicates bias values are sensitive to variation of nonlinear characteristics of structure. Similarities can be observed by comparing frame results and SDOF system results presented in Fig 3.1 and 3.2. Similar to SDOF systems, synthetic ground motions caused smaller bias values for scale factor more than one.

Another observation is the effect of higher modes of vibration for the frame system can change the trend of bias values. For example, the trend of bias for the frame based on CAV and synthetic ground motion is increasing while Fig 3.2 (d) shows a decreasing trend for bias of the SDOF system with period T=1 sec. Fig 3.3 (b) shows the effect of bias equal to 1.37 induced by scaling on the fragility curve of the frame. The vertical axis represents probability of failure (P_f) for the structure and the horizontal axis represents intensity of the records in terms of SD. Fig 3.3 (b) shows positive bias over-estimates the P_f of the structure and also changes the parameter estimates of the CDF.

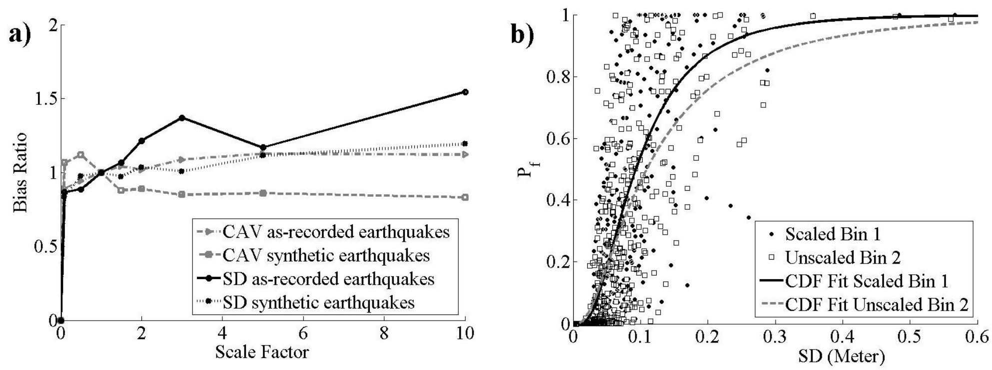

Figure 3.3 (a) bias values of frame for binning based on SD and CAV (b) Fragility curves for the frame associated to scaled and unscaled bins for bias value equal to 1.37.

3 CONCLUSIONS

Amplitude-scaling ground motions can induce considerable bias in nonlinear response of structures. Consequently, this bias can affect results for PBEE analysis, presented in terms of parameters of fragility curves in this paper. Positive and negative bias can be observed that can produce over estimation or under estimation of structure demand in PBEE analysis. Bias observed for scaling nonlinear systems are the result of nonlinear behavior of the structure as well as characteristics of earthquakes. Scaling of synthetic ground motions produces bias similar to as-recorded ground motions; however, the conclusions are limited to the method used for generating synthetic ground motions in this study. Bias can vary based on magnitude of scaling, period of structure, nonlinear behavior of the structure, and the metric used to scale the ground motions. Selection of earthquakes for scaling based on CAV and PGV can induce less bias compared to PGA, IA, and SD. Bias obtained from the MODF system are consistent with those for the SDOF systems; however, effects of higher modes of vibration can produce slight variations in magnitude of bias as well as trend of bias in relation to magnitude of scaling.

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