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RESEARCH ARTICLE

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Sensitivity analysis of the seismic demands of RC moment resisting frames to different aspects of ground motions

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Summary

A weight vector representing the relative importance of various characteristics of ground motions (GMs) and a conditioning intensity measure (IM) are required to be able to use the generalized conditional IM framework for the purpose of GM selection. An inappropriate weight vector may result in the biased distributions of some important characteristics of GMs and, consequently, the bias in the structural responses. This article aims to provide the analyst with the understanding of which properties of GMs are important in capturing the accurate structural responses, to specifically assign a suitable weight to them and to select an appropriate conditioning IM as well. To this end, 4 reinforced concrete buildings, located at the site in which the seismic hazard is dominated by shallow crustal earthquakes, are considered. The findings reveal that the appropriate weight vectors depend on the characteristics of the employed structural systems. In addition, the role played by each IM in capturing the true structural responses changes over different earthquake intensity levels implying that different weight vectors are required over different earthquake levels. Furthermore, this study shows that, even in case of shorter-duration GMs from shallow events, GM duration should be incorporated in GM selection as it has effects on the peak-based structural responses in the earthquake levels beyond the level of 2%-in-50-years. Specifically, the findings reveal that in case of shallow events, unlike large magnitude earthquakes, the shorter the duration of GM the more rapid release of energy and, consequently, the larger the peak-based structural responses.

KEYWORDS

cloud analysis, generalized conditional intensity measure (GCIM), ground motion duration, ground motion selection, intensity measure (IM)

1 | INTRODUCTION

To estimate the seismic performance of structures considering variability in the seismic input [ie, earthquake ground motions (GMs)] and the uncertainty in structural modeling, performance-based earthquake engineering (PBEE) has been introduced as a powerful tool in recent decades. A key consideration in PBEE is the appropriate selection of GMs consistent with the seismic hazard of the interest site. Of the many research studies that have been performed on GM selection, the generalized conditional intensity measure (GCIM)[1] has been introduced as the most suitable method and as a major breakthrough in this field. For GM selection, the GCIM approach has the ability to include all those intensity measures (IMs) identified as effective

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in predicting the seismic response of interest. To this end, the GCIM framework needs a conditioning IM, which is well correlated with the structural responses, to compute the conditional distributions of other important features of GMs. Additionally, as extensively discussed by Bradley,[2] in the selection process, a normalized weight vector identifying the relative importance of different IMs is applied. The weight vector indicates the importance of different aspects of a GM so that it has a crucial influence on the characteristics of the selected GMs. Thus, an inappropriate weight vector may result in the biased distribution of some important IMs[1] and, consequently, a bias in the predicted structural responses. In practice, it is impossible to select a set of as-recorded GMs having the characteristics statistically matched with the GCIM distribution.[1] To overcome this limitation, 2 solutions have been proposed by Bradley.[1] One solution is reducing the number of required GMs for performing dynamic analysis. The other solution is neglecting the difference between some characteristics of the selected set of GMs and the expected characteristics at the interest site. However, the first solution, using the fewer number of GMs, may cause larger uncertainty in the predicted structural response that is not desired by PBEE.[1] In the second solution, those characteristics that the seismic response of interest is independent of them can be neglected.

Regarding the second solution and the GCIM approach, there are several questions, including whether it is required to focus on all IMs for GM selection, which characteristics of GMs are important for different engineering demand parameters (EDPs), and how sensitive the seismic demands of interest are to different aspects of GMs. In this regard, the effect of different GMs' features on different EDPs has been extensively researched in a wide variety of ways.[3-12] As an example, Shome et al[5] have shown that maximum interstory drift ratio (MIDR) in a 5-story building strongly depends on the spectral acceleration (SA) of the applied GMs. Ebrahimian et al[4] have recently examined the appropriateness of a large number of IMs for predicting the peak-based structural responses in terms of efficiency and sufficiency. There are also many studies[5-12] focusing on the influence of GM duration on the structural responses considering shorter- and longer-duration GMs from shallow and subduction earthquakes, respectively. Those focusing on shorter-duration shallow events[5-10] have mostly found that the impact of GM duration depends on the selected seismic response. For instance, they have observed that the dissipated energy of the structure moderately depends on the duration of the applied GMs, while the maximum structural deformation does not show any dependency on GM duration. On the other hand, in a comparison between predominantly longer-duration subduction earthquakes and shorter-duration shallow earthquakes, Chandramohan et al[11] and Barbosa et al[12] have claimed that GM duration influences the drift-based response measures depending on the consideration of strength and stiffness deterioration as well as the geometric nonlinearity in structural modeling. A question remains regarding GMs from shallow events is whether GM duration matters on the peak-based structural responses for the structural models exhibiting strength and stiffness degradation and appropriately accounting for the destabilizing action of the gravity loads. If so, whether the correlation between the peak-based structural responses and GM duration is the same as that reported for subduction events. More importantly, whether the effect of GM duration and even other features of GMs on the structural responses is a function of the intensity of applied GM. As mentioned earlier, several research studies (eg, Ebrahimian et al[4]) have tried to quantify the impact of all-important aspects of GMs on the structural responses. However, there is not a study previously evaluated that shows the effect of all IMs of GMs that may be important in predicting the true peak- and energy-based structural responses over different IM levels (ie, distinguishing between GMs from different earthquake IM levels). In this regard, a sensitivity analysis is required to recognize to what extent the structural responses are sensitive to different IMs over different intensity levels. This can finally lead to assigning appropriate weight vectors and choosing a suitable conditioning IM for GM selection based on the GCIM framework.

The main objective of the present study is to use cloud analysis[13] for performing sensitivity analysis for reinforced concrete (RC) moment-resisting frame buildings. The aim of the sensitivity analysis is to answer the aforementioned questions and provide the analyst with the appropriate weight vectors for GM selection based on the GCIM framework. To this end, first, the sensitivity of the structural responses to various IMs will be performed and the validity of the results will be examined. Second, whether the sensitivity of structural response to different IMs, particularly GM duration, changes over different intensity levels will be investigated through differentiating between low- and high-intensity GMs. Third, an illustrative example will be presented to demonstrate how structural responses are sensitive to different weight vectors. Fourth, several efficient and important vector-valued IMs including those single IMs recognized as important in predicting the structural responses will be proposed. Finally, a discussion on different approaches in which the results of vector-valued IMs can be implemented for GM selection will be provided.

2 | ENGINEERING DEMAND PARAMETERS

The evaluation of material damage is commonly implemented to estimate the overall damage to structures. It is well recognized that the damage to engineering materials due to an earthquake not only depends on the magnitude of material strain but also depends on the number and sequence of material strain, particularly in the plastic zones.[14] Among various metrics for measuring the structural damages, MIDR or the peak strain in the material has received more attention in the literature, which it just captures a partial picture from the damage to the engineering structures. Hence, for evaluating the damage to the structural systems subjected to a set of GMs, different response parameters representing different features of damage should be taken into account. In this study, 3 damage measures or EDPs comprising MIDR, maximum floor acceleration (MFA), and normalized hysteretic energy (NHE),[5] which are representatives of different aspects of damage in the structural building systems, are considered. The first 2 damage indices are used herein as indicators to evaluate the damage to structural and nonstructural elements, while the third one demonstrates the total hysteretic energy observed by structural components divided by twice the yield strain energy.

3 | THE DESIGN AND MODELING OF THE CONSIDERED STRUCTURES

The present study mainly focuses on the RC moment-resisting frame buildings. The structural models employed in this case study are 4 RC moment-resisting frames with 3, 6, 9, and 15 stories, which were designed as intermediate moment-resisting frames[15] on the basis of ACI318-05 provisions.[16] The structures cover a various range of stiffness and height such that the fundamental periods of the 3-, 6-, 9-, and 15-story frame buildings are 0.98, 1.43, 1.96, and 2.66 seconds, respectively. To model the buildings, the Open System for Earthquake Engineering Simulation[17] is implemented. In all cases, an interior frame is selected for modeling and analysis. In addition, in the structural models, both the geometric nonlinearity ($P-\Delta$effects) and material nonlinearity are taken into account. The material nonlinearity is included in the models using the lumped plasticity model such that plastic hinges are modeled at the ends of beams and columns with the zero-length springs. In addition, the linear elastic elements are used between plastic hinges. The Ibarra-Medina-Krawinkler peak-oriented model[18] considering both strength and stiffness deterioration is implemented to model the hysteretic behavior of the mentioned plastic hinges. To model the structural damping, Rayleigh damping is applied for all the models. Finally, pushover analysis is carried out to compute the yield displacement and ductility of structures. The yield interstory drift ratio for the 3-, 6-, 9-, and 15-story buildings are 12.2%, 10.3%, 9.8%, and 8.3%, respectively.

4 | GM DATABASE AND GM IMS

The main aim of the present study is to evaluate the impact of a large number of GMs characteristics on the response of structural systems located at sites with the seismic hazard dominated by shallow crustal earthquakes. Thus, in choosing a GM library, the geographical origin of GMs (ie, being associated with crustal origin or subduction zones) is taken into account. For this purpose, GM database is extracted from PEER NGA-West2 library[28] containing only shallow crustal earthquakes. Furthermore, from an engineering viewpoint, weak GMs are not important and they would not have a considerable impact on the structural systems. Therefore, those GMs with the geometric mean peak ground acceleration (PGA) smaller than 0.15 g or with the magnitude less than 4.5 are excluded from the database. Eventually, a suite of 745 pairs of GMs are picked up for performing nonlinear dynamic analyses. Only 6.5% of the final set of GMs have a magnitude less than 5.5. Also, the source-to-site distances for all of the selected GMs are less than 104 km. In addition, 90% of records have the source-to-site distances less than 50 km.

A large number of widely used IMs are implemented to evaluate their effects on the seismic response of RC moment-resisting frames. The applied IMs can be classified into 3 categories: peak-, frequency response-, and cumulative and duration-based IMs. The employed IMs associated with their definitions are presented in Table 1. It should be noted that to compute the pseudo spectral values (acceleration, velocity, and displacement), 5% damping is applied but is not used in the notation. For simplicity, the term of pseudo is not used hereafter.

When the sensitivity of the structural responses is the concern, as also suggested by Bradley et al,[3] those IMs with previously developed GM prediction equations (GMPEs) are preferred to use. This makes it possible to develop the distributions of IMs over multiple earthquake intensity levels and produce seismic hazard curves. For the most applied IMs, a robust GMPE is available in the literature. Furthermore, the GMPEs for SA at single period can be implemented to indirectly develop new GMPEs for the average SA. Finally, as will be discussed in more detail later, the definition of orientation-independent measures of IMs (GMRotI50 or 50th percentile rotation-independent geometric mean)[29] is chosen for the purpose of this research study.

TABLE 1 The definition of the applied IMs

Category	Name	Definition
Frequency response-based IMs	$Sa(T_i)$	SA at period of T_i. T_1, T_2, and T_3 are the first, second, and third modes of vibration, respectively. $1.5T_1$, $2T_1$, $3T_1$ are the lengthened periods considering the effect of nonlinearity.
	S_{di}	Inelastic spectral displacement S_{di} is the maximum displacement demand of a single degree of freedom system.[19] The responses of the single degree of freedom system are calculated using the smooth hysteretic model, a generic model developed by Sivaselvan and Reinhorn[20] using the characteristics of RC members.
	$Sa_{avg}(T_i : T_j)$	The geometric mean of SA between periods of T_i and T_j
	ASI	Acceleration spectrum intensity[21] $ASI = \int_{0.1}^{0.5} Sa(T)dT$
	SI	Spectrum intensity[22] $SI = \int_{0.1}^{2.5} Sv(T)dT$ (where Sv is spectral velocity)
	DSI	Displacement spectrum intensity[23] $DSI = \int_{2}^{5} Sd(T, 5\%)dT$ (where Sd is spectral displacement)
Peak-based IMs	PGA, PGV, and PGD	Peak ground acceleration, velocity, and displacement, respectively.
Cumulative and duration-based IMs	AI	Arias intensity[24] $AI = \frac{\pi}{2g}\int_0^{t_{max}} a(t)^2 dt$
	Ds_{5-75} (Ds_{5-95})	5-75% (5-95%) significant duration: The interval between the times at which 5% and 75% (95%) of Arias intensity are reached.[25]
	I_D	Cosenza and Manfredi index[26] (a dimension less metric of duration) $I_D = \frac{\int_0^{t_{max}} a(t)^2 dt}{PGA \times PGV}$ Where $a(t)$ and t_{max} are acceleration time history and the length of ground motion record, respectively.
	CAV	Cumulative absolute energy[27] $CAV = \int_0^{t_{max}} \lvert a(t) \rvert dt$

Abbreviations: RC, reinforced concrete; SA, spectral acceleration.

5 | METHODOLOGY

Incremental dynamic analysis (IDA),[30] multiple stripe analysis (MSA),[31] and cloud analysis[13] are the 3 possible methods to predict the structural responses over different IM levels and to create a probabilistic model between IMs and EDPs. As the IDA and the MSA both use the scaled GMs, the legitimacy of amplitude scaling of GMs over multiple IM levels is the main concern regarding these methods.[19,32] In contrast, the cloud analysis involves subjecting the structure to a set of as-recorded GMs without scaling them up and down. Hence, there is no concern regarding the bias in the structural responses because of GM scaling.[33] However, the existence of heteroscedasticity and the dependence of the results to the set of GMs are 2 main limitations with the cloud analysis.[30,31] In this paper, the cloud analysis is implemented to measure the efficiency of the described structural responses to various characteristics of GMs. As a large number of GMs are used herein, there is no concern with the dependence of structural responses to the set of GMs. In addition, a solution will be proposed to remove the associated heteroscedasticity with the cloud analysis.

For the purpose of this study, first, both the horizontal components of unscaled GMs are used for performing nonlinear dynamic analysis; 745 pairs GMs are used; therefore, for each structure, 1490 analyses and in total 5960 analyses (745 records × 2 horizontal components × 4 structures) are performed. Because the interpretation of the obtained data can be significantly affected by outliers, it is necessary to detect them before analyzing the data statistically. Mahalanobis distance[34] is applied herein for detecting outliers. Those samples in which their estimated Mahalanobis distance do not follow a chi-squared distribution are considered as outliers and removed from the data. In addition, estimating the structural collapse capacity is not the purpose of this study because most of unmodified GMs are not strong enough to induce instability in the structural systems. Hence, those GMs that led to MIDR greater than 5% are removed. With the considered MIDR threshold, only less than 3% of applied records exceed this threshold. Finally, a regression analysis is implemented to examine the efficiency of each IM over all IM levels. It is required to fit a linear regression to the model response for the regression analysis and consequently measuring the efficiency of IMs. A relationship between EDPs and IMs in the following form can be created.

$$\ln(EDP|IM) = \beta_0 + \beta_1 \ln IM + \epsilon \tag{1}$$

where β_0 and β_1 are constant coefficients and ϵ is the error term showing the difference between the predicted and computed value of EDP. To estimate the coefficients of β_0 and β_1, the linear least square regression analysis is implemented herein. In addition, the assumptions of normal distribution of the residuals, which is well accepted in the field of earthquake engineering, and constant variance (homoscedasticity) should be satisfied for the regression analysis. Finally, to estimate the efficiency of each IM, the dispersion ($\beta_{\mathrm{EDP|IM}}$) of the residuals should be computed. The IM that results in the lowest value of $\beta_{\mathrm{EDP|IM}}$ is the most efficient IM.

For evaluating the efficiency of an IM, 2 definitions of IMs including the IM value for the single component of GMs and the geometric mean of 2 horizontal components of GM (or GMRotI50) can be employed. The difference between these 2 definitions was previously investigated by Baker and Cornell[35] for SA. In the present study, the efficiency and the practicality of 2 definitions for all considered IMs are examined. Results in terms of $\beta_{\mathrm{EDP|IM}}$ presented in Figures S1 to S4, available at https://goo.gl/NqEd8q, reveal that for most IMs, the IM value for the single component of GMs is more efficient than the geometric mean IM of the 2 horizontal components of GMs as also addressed in the study of Baker and Cornell.[35] In general, using the IM value for the single component of GMs results in smaller standard deviation of the residuals in comparison with its counterpart. On the other hand, the IM for the geometric mean of 2 horizontal components of GMs is more practical as used in GMPEs. In the present study, the IM for geometric mean of 2 horizontal components of GMs is implemented because of its practicality and consistency with the seismic hazard.

6 | THE EFFICIENCY AND THE IMPORTANCE OF IMS

The purpose of this section is to take into account a large number of IMs and examine which of them correlate better with the structural responses. In addition, a large suite of unscaled GMs covering a wide range of magnitude, distance, and soil type are implemented, making the results independent of the applied GMs. Table S1 presents the standard deviation of the residuals for all IMs. As expected, for the 3-story building, $Sa(T_1)$ is the most efficient IM for estimating MIDR, while for the rest of buildings, spectrum intensity (SI) is the most efficient one. The efficiency of $Sa(T_1)$ decreases going from the 3-story to the 15-story building because MIDR depends more on the higher mode effects in tall buildings in comparison with short ones. As seen, $Sa(T_2)$ for the 9- and 15-story buildings is more efficient than $Sa(T_1)$, which commonly used as the representative of seismic hazard for all buildings. Interestingly, SI as a velocity-based IM is a better measure for capturing the structural damage in terms of MIDR than the geometric mean of SA over the period range from $0.2T_1{:}1.5T_1$, $Sa_{avg}(0.2T_1{:}1.5T_1)$, recommended by ASCE[36] 7-10 for selection and scaling of GMs. As well, peak ground velocity (PGV) among the peak-based IMs explains the smallest value of standard deviation, particularly for the long-period buildings.

With respect to MFA, the results, presented in Table S1, indicate that the most efficient IMs are $Sa_{avg}(T_1/5{:}T_1/3)$, PGA, and acceleration SI (ASI). It can be concluded that MFA is sensitive to IMs that are dominated with the high-frequency content of GMs (eg, PGA and ASI). These findings are in a good agreement with those reported in the literature.[3,4] Notably, the efficiency of ASI and PGA increases as the structure gets taller; however, it does not change a lot. In addition, $Sa_{avg}(0.2T_1{:}1.5T_1)$ performs better for estimating MIDR than MFA demonstrating that this period range is based on reducing the dispersion in the predicted MIDR. Interestingly, S_{di} results in approximately the same uncertainty for predicting both MIDR and MFA. Moreover, among those IMs representing the energy content of a GM, Arias intensity (AI) performs better for predicting both MIDR and MFA.

In reference to NHE, the efficiency of all IMs significantly declines in comparison with MIDR and MFA, indicating that accurate predicting of NHE using a single IM is impossible. Thus, a larger number of GMs are required for estimating NHE than for MIDR and MFA. With this in mind, in case of NHE, the best and the least efficient IMs are *SI* and I_D, respectively. In addition, among the average spectral response-based IMs, $Sa_{avg}(0{:}10$ seconds$)$ displays a good efficiency. For predicting NHE, cumulative absolute energy (CAV) results in the least dispersion among the cumulative and duration-based IMs.

The efficiency analysis finds those IMs introducing a small variability in an EDP given an IM, but it does not precisely indicate the importance of each IM. In this study, the adjusted form of R-squared (R^2) as a unit-less statistic is chosen as a criterion to judge the importance or the ability of IMs in capturing the variation of the structural responses. The values of R^2 for all considered cases are presented in Table S2. Noteworthy, in the present study, those IMs with $R^2 < 0.1$ are considered as candidates for being classified as unimportant IMs. As seen, in the case of cumulative and duration-based IMs, the effects of $Ds_{5\text{-}75}$ and $Ds_{5\text{-}95}$ on the peak-based damage measures can be ignored according to the R^2 values for these IMs, while their role, particularly $Ds_{5\text{-}75}$, on predicting NHE is considerable. This explains the significance of duration for forecasting the dissipated energy. Hence, to accurately estimate the response of the structural systems in terms of dissipated energy, the duration of GMs should be taken into account in GM selection. In addition, for GM selection based on the GCIM, there is no need to assign a weight to I_D for all considered EDPs because of its negligible R^2. Moreover, those GM parameters reflecting the low-frequency content of GMs [eg, peak ground displacement (PGD) and displacement SI (DSI)] and also SA at elongated periods are not important for estimating MFA. Furthermore, those GM features capturing between 10% and 40% of the variation in the structural responses are classified as IMs with the secondary importance in predicting the structural responses. For example, those IMs characterizing the high-frequency content of GMs are classified as IMs with the secondary importance for predicting MIDR.

7 | THE EFFICIENCY AND THE IMPORTANCE OF IMS OVER DIFFERENT EARTHQUAKE INTENSITY LEVELS

In the previous section, the efficiency and the importance of IMs in predicting the structural responses over all IM levels were scrutinized. To this end, similar to almost all studies in the technical literature,[3-5] one simple linear model between IMs and EDPs was fitted over all earthquake intensity levels and then efficiency and importance of IMs were examined. The question that arises is whether the efficiency and the importance of IMs are the same over different IM levels. This part of the paper, first, examines the accuracy of using one linear model over all intensity levels and then evaluates the influence of IMs on structural responses over various earthquake IM levels.

One of the assumptions that should be checked for the classical linear regression model to be valid is that there is no heteroscedasticity in the models, identified as a problem associated with the cloud analysis.[30,31] To check the heteroscedasticity of data, the Breusch-Pagan test[37] examining the dependency of the variance of the residuals on the independent variables is implemented herein. The null hypothesis in this test is that there is no heteroscedasticity in the data. The *P*-value, resulted from *F* test, less than 0.05 (with 95% confidence level) demonstrates that the null hypothesis can be rejected, and therefore, there is heteroscedasticity in the data.

The fitted models between $Sa(T_1)$ and MIDR for all buildings are shown in Figure 1. As can be seen, the *P*-values for the 3-, 6-, and 9-story buildings are less than .05, indicating that a single linear model is not able to provide an appropriate fit of the data. In addition, the *P*-values presented in Table S3 for the rest of IMs and EDPs explain that in most cases there is heteroscedasticity with the models. Thus, the residuals and the consequent inferences from the regression analysis all are suspect. Rather than using 1 model over all earthquake intensity levels, a bilinear model or a more complicated model (eg, a trilinear model or models with quadratic terms) could solve this problem with the cloud analysis. For the discussed cases above, aiming to remove heteroscedasticity in the data, the bilinear models are fitted to the data and displayed in Figure 2. The *P*-values depicted in Figure 2, which are greater than .05, explain that there is no heteroscedasticity in the residuals of the fitted bilinear models. The breaking points in terms of $Sa(T_1)$—as borders between the higher and lower IM levels—for the fitted models to

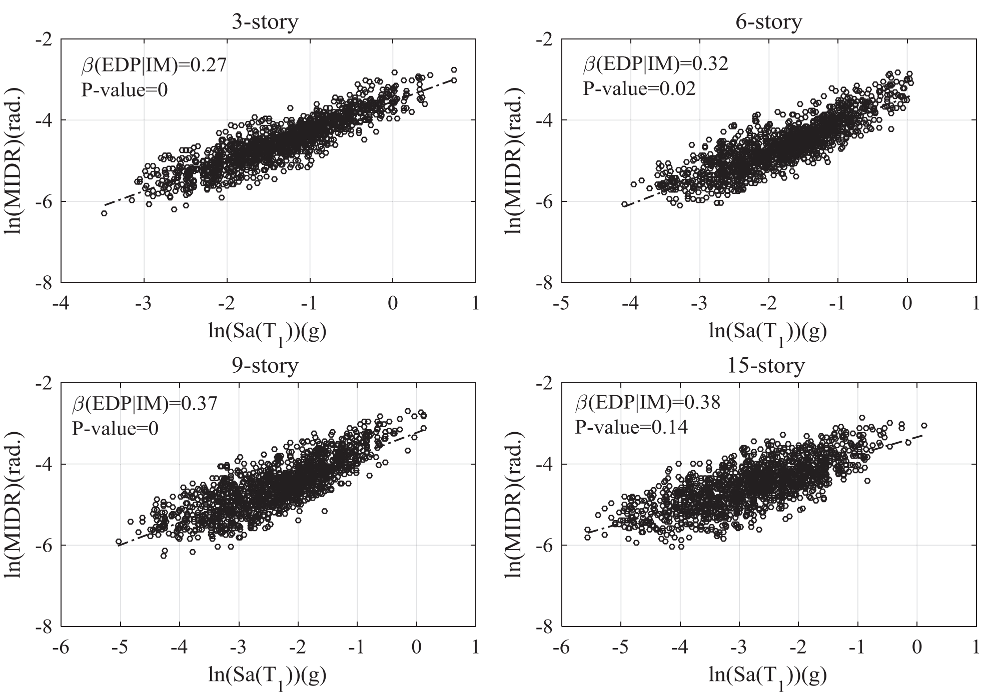

FIGURE 1 The linear fitted model between $Sa(T_1)$ and maximum interstory drift ratio (MIDR). EDP, engineering demand parameter; IM, intensity measure

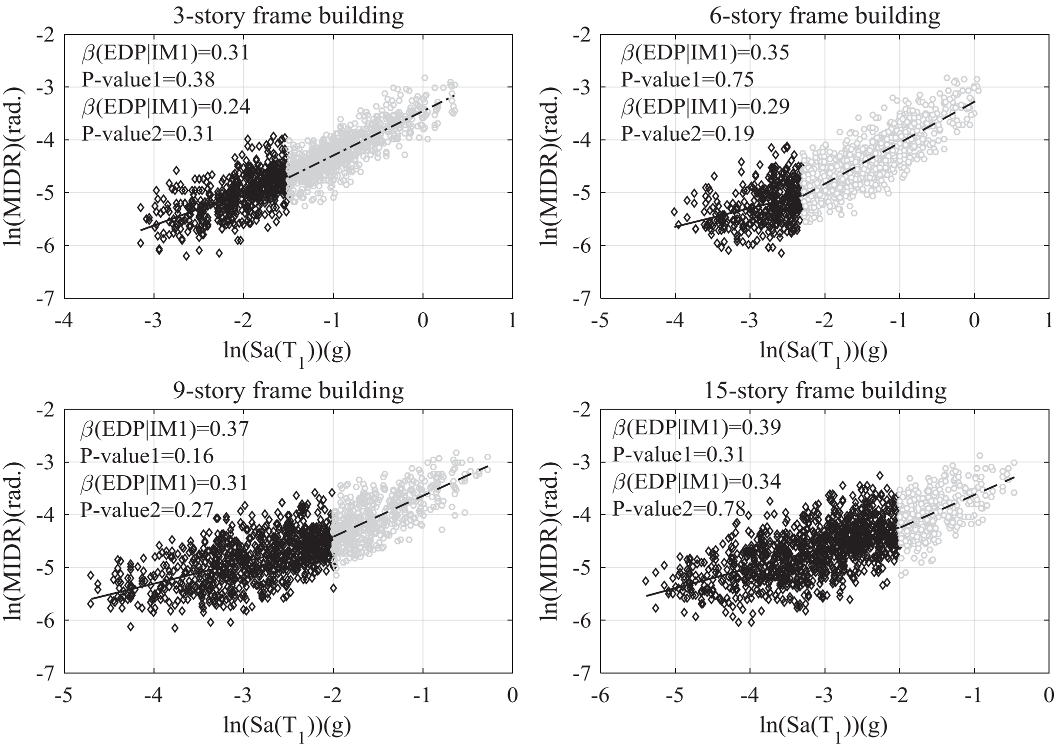

FIGURE 2 The bilinear fitted model between *Sa(T1)* and maximum interstory drift ratio (MIDR). EDP, engineering demand parameter; IM, intensity measure

the 3-, 6-, 9-, and 15-story buildings are, respectively, 0.22, 0.1, 0.14, and 0.14 g. These points are determined based on minimizing the residuals between the fitted data and the actual data.

The method applied above results in different breaking points equivalent to different intensity levels, which makes it impossible to reach an overall conclusion about the importance of IMs. In this section, $Sa(T_1)$ for the earthquakes with the probability exceedance of 2% in 50 years is considered as the breaking point to classify records into 2 different groups including low- and high-intensity GMs and produce bilinear models. According to the seismic hazard of the site where the buildings are assumed to be constructed, the values of $Sa(T_1)$ for the level of 2%-in-50-years are 0.43, 0.285, 0.196, and 0.14 g for the 3-, 6-, 9-, and 15-story buildings, respectively. Using this type of breaking point not only leads to solving the problem with the distribution of variance in the cloud analysis but also provides a basis to compare the importance of different IMs over the higher and lower IM levels. The standard deviation of the residuals and R^2 for the fitted bilinear models are presented in Tables S4 to S6. Furthermore, the *P*-values presented in Tables S7 to S9 indicate the validity of homoscedasticity assumption for the bilinear models. Therefore, there is no need for more complicated models as the results from the bilinear model are valid. In all these tables and henceforth, the lower level and higher level refer to the earthquake IM levels below and above the level of 2%-in-50-years.

The R^2 values in Table S4, with some exceptions, demonstrate that the importance of the most frequency response-based IMs in predicting MIDR is less in the higher IM level than that in the lower level. In addition, similar to the linear models, the bilinear models indicate that SI is the most important IM capturing a high percentage of variation in MIDR over both earthquake IM levels. With respect to MIDR, $Sa(1.5T_1)$, $Sa(2T_1)$, $Sa(3T_1)$, $Sa_{avg}(T_1{:}1.5T_1)$, $Sa_{avg}(1.5T_1{:}2T_1)$, $Sa_{avg}(2T_1{:}3T_1)$, *and* S_{di}, showing the effect of period elongation due to nonlinearity of structures, are not detected to be more important for earthquakes beyond the level of 2%-in-50-years. Generally, if the purpose of seismic analysis is to estimate MIDR, the results explain that failing to match the distributions of frequency response-based IMs of the selected GMs to those for the target may introduce a significant bias.

The results of linear models show that the sensitivity of MIDR to PGA is approximately the same for all buildings (with $R^2 = 0.25$). Although this weak correlation is expected between MIDR and PGA,[3] the bilinear fitted models (Table S4) interestingly demonstrate that the roles of IMs characterizing the high-frequency content of GMs in estimating MIDR noticeably increase over the higher IM level. When it comes to low-intensity earthquakes, MIDR exhibits a weak dependence to PGA. In addition, as the effect of higher modes increases, PGA gets more important in predicting MIDR. Furthermore, for the earthquake level beyond the level of 2%-in-50-years, the low value of R^2 might be interpreted that PGD and DSI are not important concerning MIDR, particularly in the long-period buildings. The plot presented in Figure 3 shows the relation between PGD and MIDR in the 15-story building, which confirms the unimportance of PGD for predicting MIDR over the high-intensity IM level. As seen, the *P*-value of the lower IM level is not as significant as that of the higher IM level, while the R^2 for the lower level is much larger than that for the upper level. It should be noted that the *P*-value is for examining the hypothesis test on homoscedasticity, rather than the hypothesis test on the coefficients (β_1 in Equation 1) being 0.

With respect to the shorter-duration shallow events, the findings of many studies[6-10] and also the linear model used in the previous section reveal the unimportance of GM duration in terms of $Ds_{5\text{-}75}$, $Ds_{5\text{-}95}$, and I_D on the peak-based structural responses. On the other hand, the results given in Table S4 indicate that using a simple linear model captures just a partial picture of the importance of duration-based IMs. The intensity of applied GM and the period of the building are the 2 factors that reveal the role played by GM duration on the peak-based structural responses. In the 9- and 15-story buildings, the importance of duration-based IMs regarding MIDR is considerable at the higher level, unlike the lower ones. In contrast, R^2 for the 3- and 6-story buildings explain that $Ds_{5\text{-}75}$, $Ds_{5\text{-}95}$, and I_D are not important in predicting MIDR. Noteworthy, unlike that found for large magnitude subduction earthquakes,[11] this observation does not illustrate that the longer-duration GMs lead to the larger structural deformations in the earthquake levels beyond the level of 2%-in-50-years. As depicted in Figure 4, or the 9- and 15-story buildings, the longer the duration of GM, the smaller the structural responses. This is due to the rapid release of energy associated with GMs from shallow events, as also noted in the study of Hancock and Bommer.[38] Figure 5 presents the time history for the interstory drift ratio at the fifth floor of the 9-story building subjected to 2 spectrally matched GMs with different significant duration. The figure confirms that the rapid release of energy for earthquakes from shallow events leads to more damage in terms of MIDR. Notably, for subduction events the greater damage is due to the larger number of strong cycles.[11] With reference to other metrics of GM duration, the importance of CAV, unlike AI, for predicting MIDR is markedly reduced in the higher IM level compared with that in the lower IM level by 41%, 56%, 76%, and 70% for the 3-, 6-, 9-, and 15-story buildings, respectively.

One may question whether using different GM classifications can lead to the same judgment about the influence of GM duration on MIDR. To answer this question, MIDR against $Ds_{5\text{-}75}$ for GMs with SI greater than the value of *SI* in the level of 2%-in-50-years is plotted in Figure 6. This figure indicates that the duration of GMs is approximately important to the same extent for all buildings at earthquake levels beyond the 2%-in-50-years. Therefore, the influence of GM duration on MIDR depends on the amplitude of applied GM and the type of record classification.

As shown in Table S5, interestingly, all IMs perform better for predicting the structural response in terms of MFA at the higher IM level where the nonlinearity in the structure makes it difficult to accurately estimate the structural response in comparison with the lower IM level. In addition, like simple linear models, the results of bilinear model demonstrate that the important IMs for estimating MFA are PGA and ASI. Furthermore, among all the frequency response-based IMs, those IMs with strong correlations with PGA and ASI are important in predicting MFA. Thus, the difference between the distributions of these parameters of GMs and their theoretical distributions can lead to the bias in MFA. Among cumulative and duration-based metrics, AI, because of its strong correlation with PGA, is found to be strongly important for estimating MFA, particularly in the higher IM level and for the taller buildings. Moreover, $Ds_{5\text{-}95}$ is also detected to be important for all buildings in predicting MFA over IM levels with high-intensity. When it comes to $Ds_{5\text{-}75}$, it is only essential for estimating

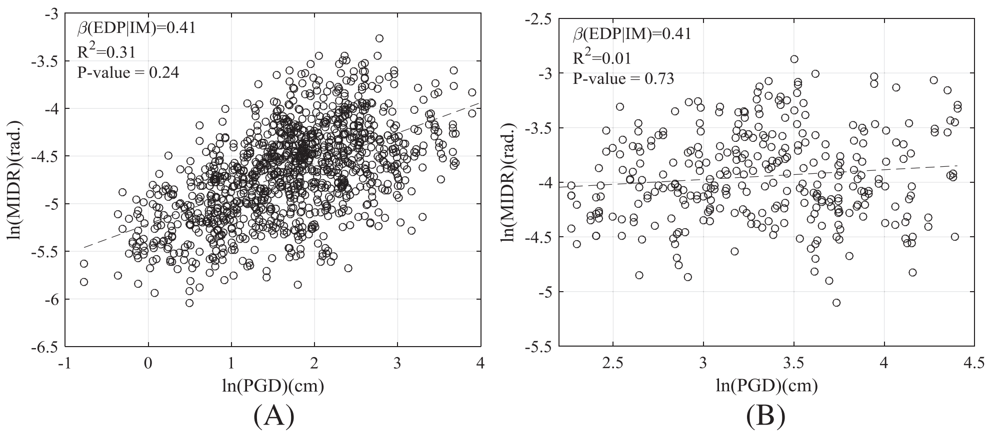

FIGURE 3 Maximum interstory drift ratio (MIDR) vs PGD for intensity levels (a) below and (b) beyond the level of 2%-in-50-years for the 15-story building. EDP, engineering demand parameter; IM, intensity measure

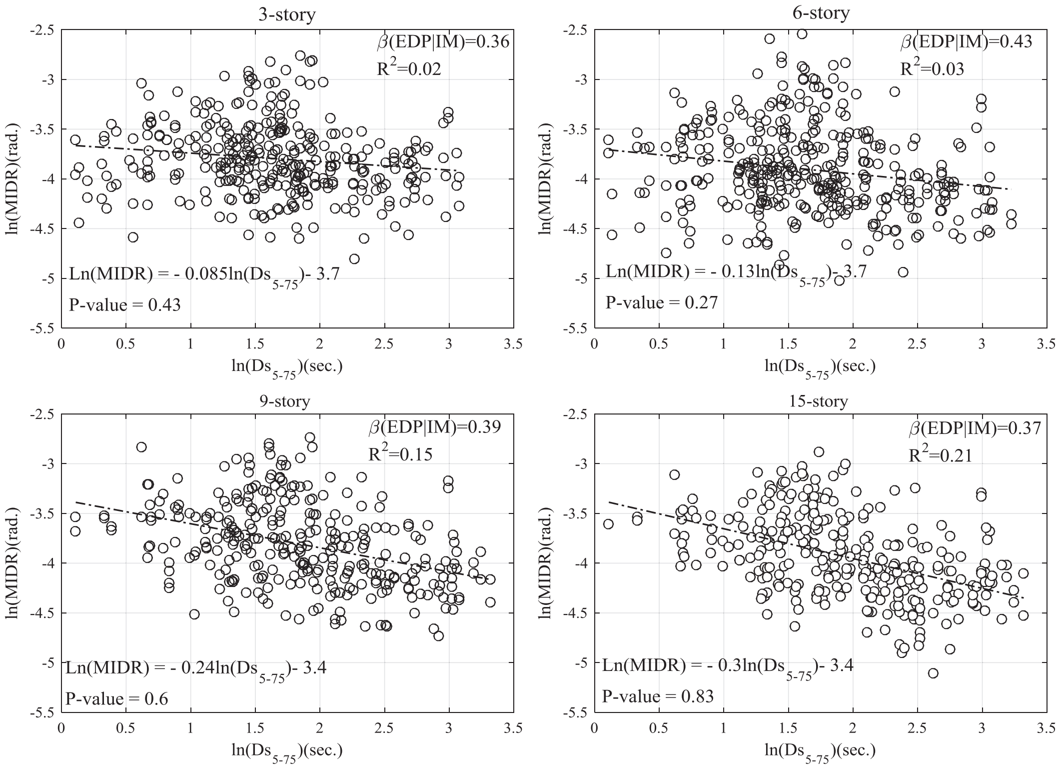

FIGURE 4 Maximum interstory drift ratio (MIDR) vs $Ds_{5\text{-}75}$ for intensity levels beyond the level of 2%-in-50-years. EDP, engineering demand parameter; IM, intensity measure

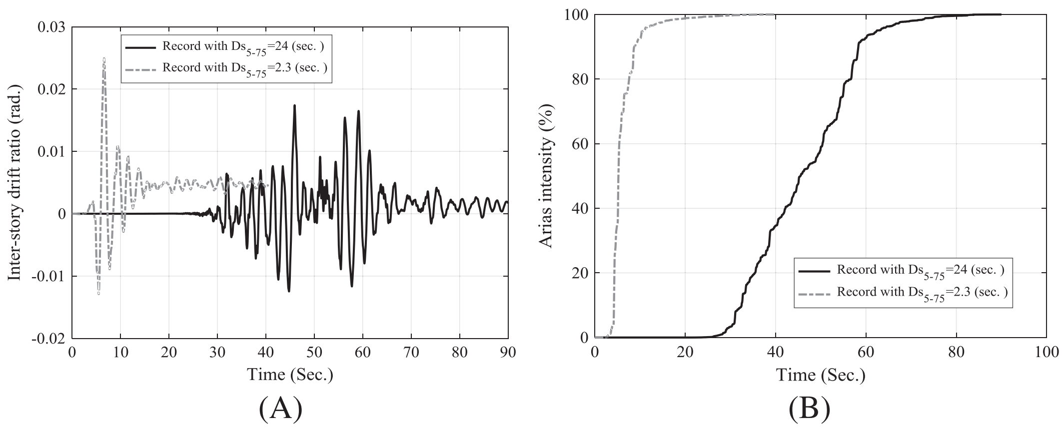

FIGURE 5 (A) Interstory drift ratio at the fifth floor of the 9-story building subjected to 2 spectrally matched ground motions ($Sa(T_1) = 0.5\ g$) with different significant duration and (B) Arias intensity for 2 ground motions

MFA in the case of the 9- and 15-story buildings in the higher IM level. Finally, Figure 7 verifies the previous finding that the longer the duration of GM the smaller the peak-based structural responses.

With respect to the dissipated energy, as presented in Table S6, the most important IMs at the lower level for the 3-, 6-, 9-, and 15-story buildings are SI, SI, CAV, and $Sa_{avg}(0.2T_1{:}1.5T_1)$, respectively. SI performs well in capturing the variation of NHE for all buildings, but not at the higher IM level. In contrast, CAV is efficient and important for both levels, particularly for the long-period buildings. In addition, $Ds_{5\text{-}75}$ and $Ds_{5\text{-}95}$, on average, capture approximately 35% and 25% of the variation of NHE in the lower level, respectively. At the higher IM level, significant duration is not as important as it is at the lower one, specifically for the buildings with longer periods. As a final point, unlike the peak-based damage metrics, the longer the duration of GMs the more the dissipated energy, presented in Figure 8.

To evaluate whether the fitted models are biased, thanks to the abundance of GMs over some earthquake IM levels; the applied GMs are divided to 9 different bins based on their intensity with respect to $Sa(T_1)$. Then, the distance between the actual

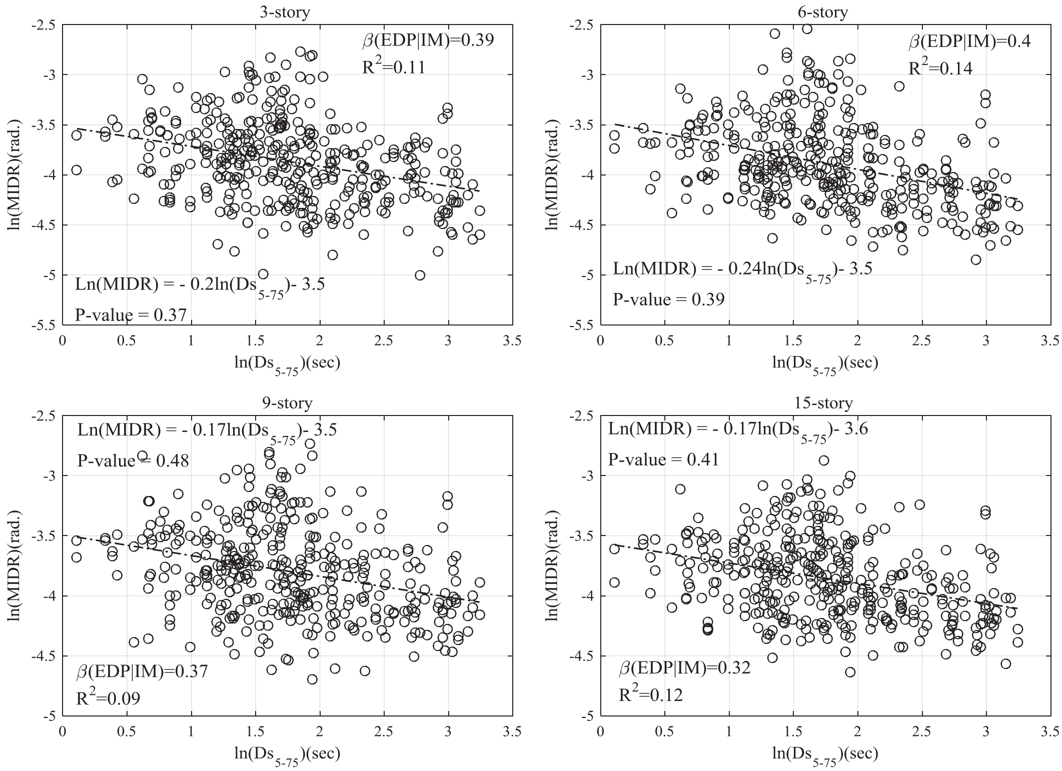

FIGURE 6 Maximum interstory drift ratio (MIDR) vs $Ds_{5\text{-}75}$ for intensity levels beyond the level of 2%-in-50-years (classification based on SI). EDP, engineering demand parameter; IM, intensity measure

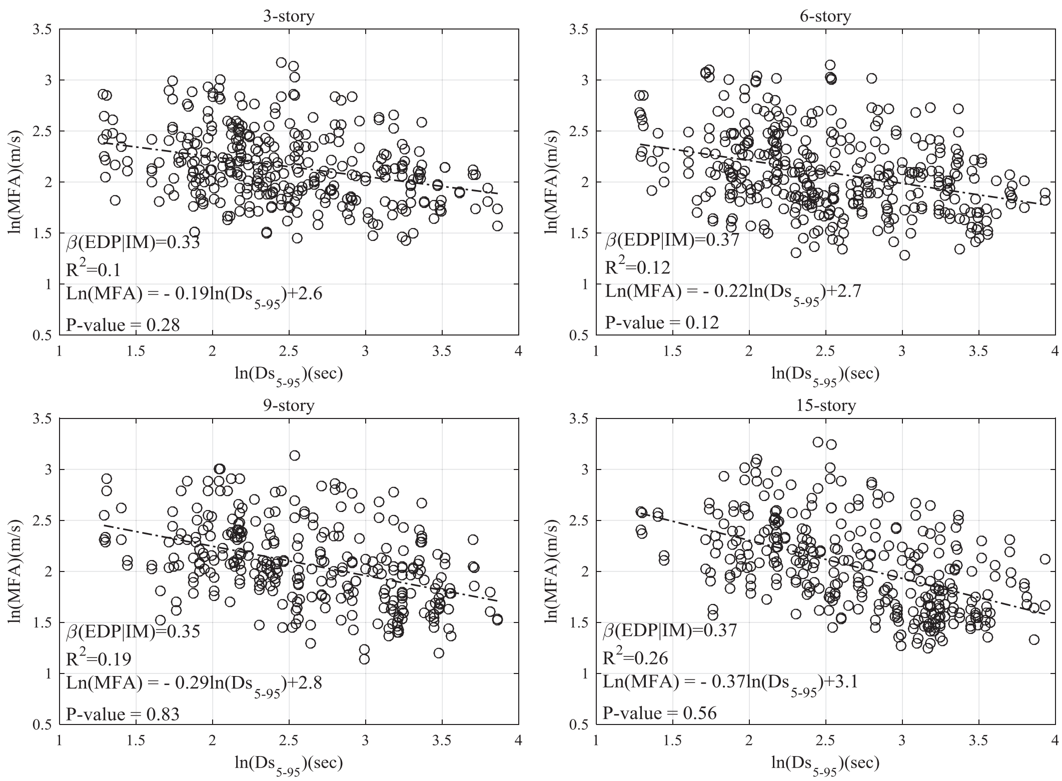

FIGURE 7 Maximum floor acceleration (MFA) vs $Ds_{5\text{-}95}$ for intensity levels beyond the level of 2%-in-50-years. EDP, engineering demand parameter; IM, intensity measure

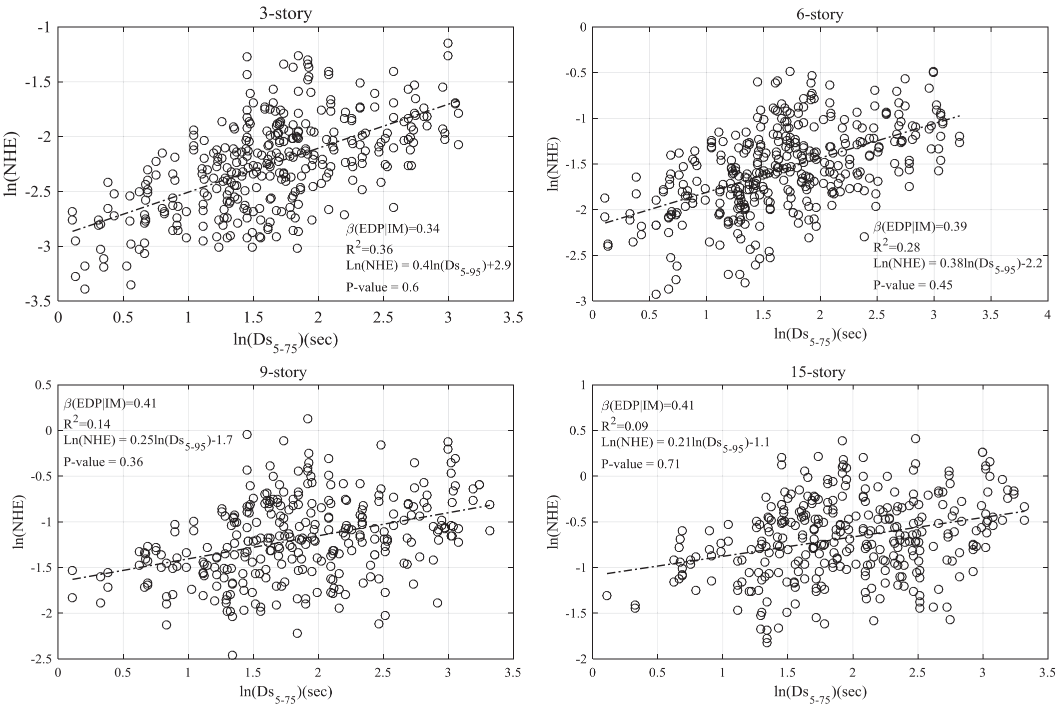

FIGURE 8 Normalized hysteretic energy (NHE) vs $Ds_{5\text{-}75}$ for intensity levels beyond the level of 2%-in-50-years [classification based on $Sa(T_1)$]. EDP, engineering demand parameter; IM, intensity measure

and predicted structural responses in terms of dispersion is computed for each bin separately. Figure 9 presents the dispersion for both fitted linear and bilinear models to MIDR in the 6-story building. As seen, there is a substantial increase in the dispersion of the linear model as the intensity of applied GMs increases, whereas a constant trend is observed in the case of the bilinear model over all bins. Notably, the linear models are dominated by low-intensity GMs because of their abundance. The same trend is also observed for the rest of IMs and EDPs, and therefore, it can be concluded that the linear models, unlike bilinear ones, are biased because of the abundance of data points in some IM levels.

Overall, for GM selection, the results of bilinear models should be implemented, as the simple linear models are not statistically valid models. Based on the numerous GM selections and conducting nonlinear dynamic analyses for the purpose of this study, weights should be allocated to those IMs with $R^2 > 0.4$. The assigned weights should be in proportion with the predictive power of IMs (the value of R^2). On the other hand, no weight is required to be assigned to those unimportant IMs with $R^2 < 0.1$. In addition, weights should be assigned to those IMs with $0.1 < R^2 < 0.4$, which are weakly correlated with important IMs. Otherwise, their distributions might be biased regarding the target. The neglecting these IMs with secondary importance can consequently lead to a bias in the structural responses.

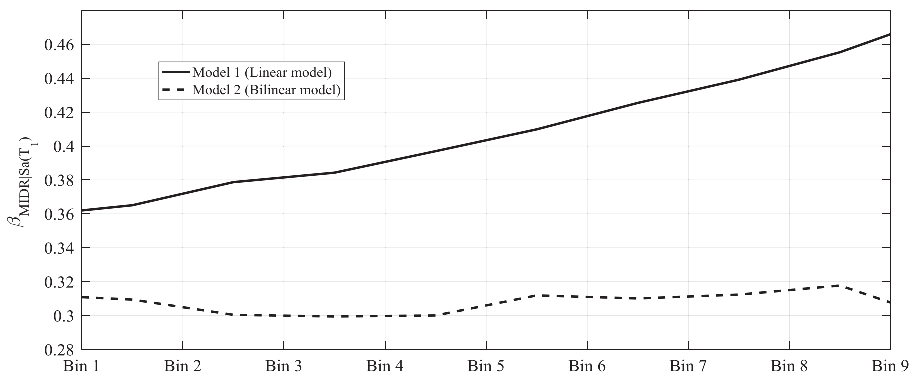

FIGURE 9 The dispersion for the fitted models to predict maximum interstory drift ratio (MIDR) in the 6-story building over different bins

8 | EFFECTS OF WEIGHT VECTORS ON THE STRUCTURAL RESPONSES

In this section, an illustrative example is presented to demonstrate how an inappropriate weight vector affects the structural responses. For this purpose, the EDP in terms of MIDR over 20 different IM levels with the exceedance probabilities from 50% to 0.005% in 50 years subjected to 2 different sets of GMs are taken into account. SI, as the most or, at least, one of the most important IM for capturing MIDR, is selected as the conditioning IM, and the distribution of other IMs is computed given this IM based on the method described by Bradley.[1,2] Then, over each level, 20 GMs are selected from the considered database based on 2 different methods. In the first case (called Method 1 henceforth), at all IM levels, weights are assigned to all those IMs whose importance was recognized through simple linear models. The considered IMs are *Sa(T)*—for 14 vibration periods including 0.05, 0.1, 0.2, 0.3, 0.5, 0.75, 1, 1.5, 2, 3, 4, 5, 7.5, 10 seconds—PGA, ASI, PGV, PGD, DSI, CAV, $Ds_{5\text{-}75}$, and $Ds_{5\text{-}75}$. Based on the results of simple linear models, as presented in Table S2, there is no need to allocate a weight to significant duration because of its unimportance concerning MIDR. In the second set of GMs (called Method 2 henceforth), the attention is given to those IMs identified essential based on the bilinear models. In this regard, according to the results of the lower IM level presented in Table S4, for earthquake intensity levels below the level of 2%-in-50-years, all previous IMs except PGA and ASI are taken into account. Otherwise, based on the higher IM level presented in Table S4, weights are attributed to *Sa(T),* PGA, ASI, PGV, CAV, $Ds_{5\text{-}75}$, and $Ds_{5\text{-}75}$. As mentioned earlier, weights are allocated in proportion to the value of R^2. Remarkably, the unbiased distributions of the selected GMs are observed for all applied GM parameters with respect to the target. If the distribution of an IM is biased, more weight should be assigned to it to reach to a set of GMs with the unbiased distribution for that IM.

The MSA, which makes enable to consider different GMs over different intensity levels, is implemented for performing nonlinear dynamic analysis; 6400 nonlinear dynamic analyses (4 structures × 20 IM levels × 20 GMs × 2 methods × 2 horizontal components) are conducted. The structural responses in terms of fragility curves showing the probability of exceeding 2% MIDR for all buildings are presented in Figure 10. This level of MIDR is equivalent to the life safety limit state proposed in FEMA356. Maximum likelihood estimation is applied for deriving the fragility curves.[39] Markedly, the same conditioning IM is considered for all cases, and therefore, any difference in the structural responses can be attributed to the assigned weight vectors. As seen, the structural responses are different for Methods 1 and 2 in all cases, except for the 3-story buildings. The results, not presented here, explain that in the case of using other conditioning IMs [eg, $Sa(T_1)$, and $Sa(1.5T_1)$] more differences between the structural responses can be observed. It should be emphasized that for the present sets of GMs the weight vectors are chosen based on 2 statistical procedures, even though one them is less accurate. Therefore, the difference between structural responses would be more substantial in the case of using arbitrary weight vectors. The results confirm that using different weight vectors in the GCIM framework might results in different sets of GMs and, consequently, different structural responses.

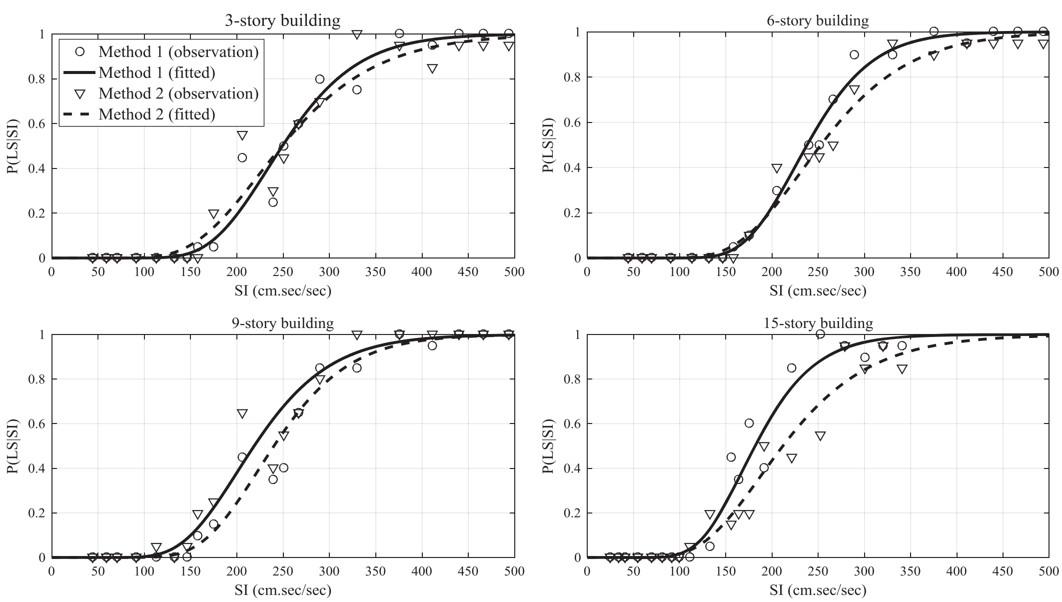

FIGURE 10 Probability of exceeding life safety (LS) given SI, *P(LS|SI),* for 4 considered buildings subjected to 2 set of ground motions

9 | THE EFFICIENCY AND THE IMPORTANCE OF VECTOR-VALUED IMS OVER DIFFERENT EARTHQUAKE INTENSITY LEVELS

A sensitivity analysis using more than 1 parameter of GM helps in finding, which features of GMs can jointly result in a true estimate of structural responses. The goal of this section of study is to carry out the sensitivity analysis using a combination of IMs. Multiple linear regression analysis[40] is implemented and the normalized regression coefficients are interpreted as direct measures of sensitivity. A stepwise regression is implemented to establish a relationship between IMs and EDPs. In addition, a test for detecting multicollinearity is carried out and the variables with variance inflation factor[40] above 3 are removed. Second, the regression analysis is done step by step and the partial F test is applied to examine whether adding an IM to the model makes the predictive power of the model stronger. Because of the existence of heteroscedasticity with the linear models, bilinear form of the multiple regression is implemented in this section. Like the fitted model to the single IMs, GMs are classified into 2 bins based on their intensity as measured by $Sa(T_1)$ values, and then, a model is fitted to each bin of GMs. Table 2 shows the final fitted bilinear models associated with their R^2 values and the standard deviation of residuals for all buildings and EDPs.

As shown in Table 2, for the lower IM level, 4 terms including $Sa(T_1)$, $Sa(T_2)$, $Sa(T_3)$, and PGA are effective in predicting MIDR in the long- and moderate-period buildings. In low-rise buildings, MIDR is estimated using only 2 or 3 metrics in terms of SA. This difference in the dependence of MIDR to different parameters is due to increasing the effect of higher modes as the structures get taller. Furthermore, at the higher IM level for high-rise buildings, adding other properties of GMs to the models, which only comprise SI, does not result in a statistically significant increase in the predictive power of models. On the other hand, for low-rise buildings, a combination of SI, ASI, and $Sa(T_1)$ is required to accurately predict the structural response in terms of MIDR. As seen in Table 2, there is not any duration-based IM on the multiple bilinear models for MIDR while the single bilinear models revealed the importance of GM duration over the rare earthquake IM levels. It should be noted that the multiple models usually leave out 1 of the 2 correlated independent variables (or IMs). Thus, the absence of an IM, which recognized as important using the results of single bilinear models, in the multiple bilinear models is because of the fact that it is

TABLE 2 The fitted models associated with their R^2 and $\beta_{EDP|IM}$ to predict different EDPs

EDP	IM level	Number of stories	Model	R^2	$\beta_{EDP\vert IM}$
MIDR	Lower level	3-story	$Ln\ (MIDR) = 0.74 \ln Sa(T_1) + 0.3 \ln Sa(T_2)$	0.71	0.23
		6-story	$Ln\ (MIDR) = 0.54 \ln Sa(T_1) + 0.4 \ln Sa(T_2) + 0.13 \ln Sa(T_3)$	0.73	0.22
		9-story	$Ln\ (MIDR) = 0.33 \ln Sa(T_1) + 0.5 \ln Sa(T_2) + 0.21 \ln Sa(T_3)$	0.75	0.25
		15-story	$Ln\ (MIDR) = 0.09 \ln Sa(T_1) + 0.5 \ln Sa(T_2) + 0.3 \ln Sa(T_3) + 0.18 \ln PGA$	0.77	0.22
	Higher level	3-story	$Ln\ (MIDR) = 0.4 \ln Sa(T_1) + 0.33 \ln SI + 0.11 \ln ASI$	0.60	0.23
		6-story	$Ln\ (MIDR) = 0.11 \ln Sa(T_1) + 0.7 \ln SI$	0.67	0.24
		9-story	$Ln\ (MIDR) = 0.78 \ln SI$	0.70	0.23
		15-story	$Ln\ (MIDR) = 0.83 \ln SI$	0.72	0.22
MFA	Lower level	3-story	$Ln\ (MFA) = 0.56 \ln PGA + 0.29 \ln AI$	0.65	0.21
		6-story	$Ln\ (MFA) = 0.6 \ln PGA + 0.34 \ln AI$	0.75	0.17
		9-story	$Ln\ (MFA) = 0.6 \ln PGA + 0.35 \ln AI$	0.79	0.17
		15-story	$Ln\ (MFA) = 0.33 \ln PGA + 0.63 \ln AI$	0.80	0.16
	Higher level	3-story	$Ln\ (MFA) = 0.54 \ln PGA + 0.34 \ln ASI$	0.80	0.15
		6-story	$Ln\ (MFA) = 0.30 \ln PGA + 0.65 \ln ASI$	0.86	0.15
		9-story	$Ln\ (MFA) = 0.34 \ln PGA + 0.62 \ln ASI$	0.88	0.14
		15-story	$Ln\ (MFA) = 0.34 \ln PGA + 0.62 \ln ASI$	0.91	0.13
NHE	Lower level	3-story	$Ln\ (NHE) = 0.58 \ln Sa(T_1) + 0.2 \ln Sa(T_2) + 0.3 \ln CAV + 0.12 \ln Ds_{5-75}$	0.82	0.33
		6-story	$Ln\ (NHE) = 0.55 \ln SI + 0.45 \ln CAV$	0.84	0.33
		9-story	$Ln\ (NHE) = 0.48 \ln SI + 0.55 \ln CAV$	0.85	0.34
		15-story	$Ln\ (NHE) = 0.52 \ln SI + 0.53 \ln CAV$	0.86	0.32
	Higher level	3-story	$Ln\ (NHE) = 0.26 \ln Sa(T_1) + 0.14 \ln Sa(T_2) + 0.38 \ln CAV + 0.35 \ln Ds_{5-75}$	0.75	0.20
		6-story	$Ln\ (NHE) = 0.33 \ln SI + 0.5 \ln CAV + 0.23 \ln Ds_{5-75}$	0.79	0.20
		9-story	$Ln\ (NHE) = 0.44 \ln SI + 0.46 \ln CAV + 0.32 \ln Ds_{5-75}$	0.74	0.22
		15-story	$Ln\ (NHE) = 0.28 \ln SI + 0.61 \ln CAV + 0.22 \ln Ds_{5-75}$	0.68	0.24

Abbreviations: EDP, engineering demand parameter; IM, intensity measure; MFA, maximum floor acceleration; MIDR, maximum interstory drift ratio; NHE, normalized hysteretic energy.

correlated with the included variables. Specifically, if the models contain 1 of the 2 correlated IMs (which both contribute to the structural responses), then the impact of the excluded IM will be attributed to the included IM. Hence, the reason for the absence of GM duration in the multiple bilinear models is that it is moderately negatively correlated with the included IMs[41] and its impact on the structural responses is attributed to the included IMs.

The established models for MFA, presented in Table 2, demonstrate that the models are more powerful for the higher IM levels. In lower IM levels, no significant improvement is observed in the predictive power of models in comparison with those single IMs, particularly in the case of low-rise buildings. Interestingly, when it comes to high-intensity GMs, the models display at least 21% improvement in capturing the variation of MFA with respect to single IMs. As seen, at the higher earthquake level, a combination of PGA and ASI, both displaying the high-frequency content of GMs, should be taken into account. In addition, for high-intensity earthquakes, including the duration-based IMs in the models does not result in a better fit. Like MIDR, it can be inferred that the decreasing influence of GM duration, shown in Figure 7, is indirectly considered in the models through PGA and ASI because of their moderate negative correlations with significant duration.

The results presented in Table 2 demonstrate that the predicted models for estimating NHE are able to explain more than 82% of the variation on NHE at the lower IM level. In addition, the results illustrate that NHE is well estimated by the combination of SI and CAV in most buildings at the lower IM level. Concerning low-intensity IM levels, the capability of models in capturing the variability of NHE compared with single IMs at least increases by factors of 22%, 18%, 20%, and 18% for the 3-, 6-, 9-, and 15-story buildings, respectively. For the earthquake level beyond the level of 2%-in-50-years, the variation of NHE can be captured implementing 3 parameters including SI, CAV, and $Ds_{5\text{-}75}$. As well, the role of cumulative and duration-based IMs, on average, increases from about 50% at the lower level to 70% at the higher level.

The main concern about the proposed models is how they can be implemented in GM selection. In this regard, the following discussion of the ways in which the established models can be applied for GM selection is given.

1. One potential of the developed vector-valued IMs is to be implemented as the conditioning IM in the GCIM framework because of their strong correlation with the structural responses. Using the developed vector-valued IMs as the conditioning IM ensures increasing the efficiency of the estimated structural responses in comparison with using a single IM as the conditioning IM. However, to develop the distribution of single IMs conditioned on the vector valued-IMs, the empirical correlations among the vector-valued IMs and the single IMs are required in addition to GMPEs. To solve this problem, new GMPEs can be indirectly established using the existing GMPEs for single IMs such as the one derived by Bradley[23] for DSI. In addition, the empirical correlation between a single IM and the vector-valued IMs can be determined using the procedure described in the study of Bradley.[23]
2. As the next potential of the proposed models, the coefficient of single IMs in the multiple bilinear models, after being normalized to have a sum equals to unity, can be applied as weight vector for GM selection based on the GCIM framework. In this case, the distributions of the mentioned IMs in Table 2 should be the same as the ones for the target, while other IMs can be simply ignored. Neglecting other IMs does not necessarily lead to the biased distributions of them. In this regard, the correlation between the neglected IMs and the considered ones may cause the unbiased distributions of the selected GMs for the neglected IMs.[2] Moreover, an IM with strong correlation with the structural responses based on the results of single bilinear models, which it is not included in the multiple bilinear models can be considered as the conditioning IM. For instance, for GM selection for estimating NHE in a case of a long-period RC building in the earthquake level below the level of 2%-in-50-years, $Sa(T_1)$ can be implemented as the conditioning IM. Then, a focus should be put on matching the distributions of CAV, SI, and $Ds_{5\text{-}75}$ for the selected GMs with those for of the target.

One may ask about the merits and demerits of using the results of single and multiple bilinear models as weight vectors for GM selection. It should be mentioned that in the case of single bilinear models, GMs should be selected in a way that the unbiased distributions are obtained for IMs with $R^2 > 0.1$. Because the number of IMs with $R^2 > 0.1$ is large, selecting such sets of GMs over high earthquake intensity levels might be impossible in some cases. The solution is to ignore those IMs with the lowest importance according to their R^2 values. To this end, first, it must be checked whether it is possible to select sets of GMs with the unbiased distributions for all IMs with $R^2 > 0.1$. If not, then, those IMs with the lowest importance should be ignored from the process. The process should be repeated to reach the desired set of GMs. In addition, for GM selection based on the single bilinear models, an understanding about the correlations between IMs is required. Strong correlations between IMs may lead to the unbiased distributions of particular IMs without allocating any weights to them. Specifically, for an IM with $0.1 < R^2 < 0.4$, it should be checked whether its distribution is unbiased without assigning any weight. If not, the weight should be allocated to that IM and the selection process should be repeated. Overall, these issues tend to make the application of the single bilinear models more time-consuming than the multiple bilinear models, which involve using a limited number of IMs for

GM selection. On the other hand, as mentioned earlier, the multiple bilinear models do not determine the conditioning IM. Therefore, using the results of multiple bilinear models for GM selection involves using the results of single bilinear models to determine the conditioning IM.

These questions remain, "Is one of the single and multiple bilinear models superior to another one in GM selection?" and "Whether the structural responses resulted from GMs selected based on these 2 methods are the same?" The answer is that both of single and multiple bilinear models could be considered as valid methods for GM selection because both of them are based on 2 statistical procedures. However, the selected sets of GMs based on these methods are not expected to be the same. Hence, they may produce different structural responses because of the record-to-record variability.

10 | CONCLUSIONS AND SUMMARY

This article provides the analyst with an understanding regarding the degree to which different aspects of GMs affect the structural responses of RC moment-resisting buildings over different earthquake intensity levels. Furthermore, the findings enable the analyst to decide which properties of GMs should be considered in GM selection based on the GCIM. In this regard, cloud analysis was implemented to establish probabilistic seismic demand models between EDPs and IMs. A large number of as-recorded shallow crustal GMs that a structure may experience were considered to make the results independent of the set of applied GMs. The efficiency and the importance of various IMs in predicting MIDR, MFA, and NHE were evaluated. Finally, several models were proposed for estimating the expected structural responses. The following conclusions are drawn:

1. The results confirmed that in most cases the IM value for a single component of GMs is more efficient than the geometric mean IM of the 2 horizontal components of GMs to predict the structural responses.
2. Based on the simple linear models, it was found that SI, PGA, and SI serve as the most efficient and important IMs for forecasting MIDR, MFA, and NHE, respectively. In addition, these models revealed no importance of the duration-based IMs on the peak-based structural responses, while GM duration effect is noticeable in the case of the energy-based structural response.
3. It was shown that the simple linear models are not able to resolve the issue of heteroscedasticity in the cloud analysis. In addition, they do not present an accurate picture from the importance of IMs in predicting the structural responses. To this end, the bilinear models, which differentiate between low- and high-intensity GMs, were applied for establishing a probabilistic relation between IMs and EDPs.
4. The bilinear models explained that the importance of IMs, except duration-based IMs, for predicting MIDR and NHE at the higher IM level is less than that at the lower IM level because of the nonlinearity of structures. With reference to MFA, however, IMs for earthquakes corresponding to high-intensity levels are more important than those corresponding to low-intensity level.
5. The results for bilinear models demonstrated that GM duration also has impacts on the peak-based structural responses for earthquake intensity levels beyond the level of 2%-in-50-years. Moreover, the findings highlighted the difference between the mechanism of damage that are caused by shallow and subduction events. In the case of shallow events, the greater damage is associated with the more rapid release of energy, while for subduction earthquakes, the greater damage is due to the larger number of cycles.
6. Weak correlations between the high-frequency contents of GMs and MIDR were detected at low-intensity earthquake levels, while their roles in predicting MIDR were found to be considerable for high-intensity earthquakes. In contrast, the low-frequency contents of GMs, interestingly, have negligible influence on all structural responses, particularly for high-rise buildings, in the earthquake levels beyond the level of 2%-in-50-years.
7. The bilinear models, for most buildings, detected SI, PGA, and CAV as the most efficient and important IMs over all IM levels for estimating MIDR, MFA, and NHE, respectively.
8. An illustrative example was provided to illustrate how the results of this study should be applied in GM selection based on the GCIM framework. In addition, the case study example explained that inappropriate weight vectors might results in the biased distribution of structural responses. Moreover, the findings of this study suggest using the bilinear models for GM selection. Otherwise, implementing the simple linear models leads to a bias in the structural responses.
9. A detailed discussion on the application of the derived multiple bilinear models shown that these models can be used as the conditioning IM in the GCIM framework. As an alternative, it was demonstrated how the coefficients for single IMs in the multiple bilinear models could also be employed as weight vectors in the GCIM framework.

In general, the findings of this study are very convincing, although time consuming, to be used for the seismic analysis of RC moment-resisting frame buildings. On the other hand, the generalization of this method for alternative structures with different seismic resisting systems can be considered as a limitation. Another limitation is that this study has focused on structures located in regions where their seismic hazard is dominated by shallow crustal earthquakes. Therefore, future research is required to examine the effects of GM's properties on the seismic response of different structural systems located at regions with different seismic tectonic characteristics.

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SUPPORTING INFORMATION

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