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Correlation of damage of steel moment-resisting frames to a vector-valued set of ground motion parameters

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ABSTRACT: Seismic risk analysis extends probabilistic seismic hazard analysis (PSHA) so as to quantify potential threats in terms that stakeholders are most interested in, such as monetary losses, injuries and deaths, and/or recovery time. The interface between PSHA and risk analysis is the ground motion parameter (GMP), which characterizes the ground shaking at a site in terms of at most a few quantities. The most commonly used GMP, of course, is pseudo-spectral acceleration (S_a). For structures whose response is (i) not highly inelastic and (ii) governed by a single fundamental mode of vibration, S_a is clearly a useful GMP, due to its strong correlation with the response of such structures. However, for many other structures, alternative GMPs that account for the effects of inelasticity, higher modes of vibration, and energy considerations can prove to be even more useful. The study described in this paper investigates the correlation of such alternative GMPs with the response (and thereby damage) of model steel moment-resisting frame buildings. A vector of GMPs that includes S_a, higher-mode pseudo-spectral accelerations, and an inelastic fundamental-mode spectral acceleration is demonstrated to be particularly promising.

1 MOTIVATION

The availability of reliable damage and loss estimates for structures in seismic regions is crucial to different stakeholders such as owners, tenants, insurance and reinsurance companies, and public organizations responsible for post-earthquake emergency resource management. Ideally, loss forecasts could be obtained by mining ground motion, structural damage, and loss data collected from past earthquakes and using statistical tools and engineering principles to develop sound damage and loss estimation procedures. In the United States, however, only in the last few years has a large network of recording stations been deployed and a significant database of ground motions recordings become available (although still insufficient in number in areas very close to rupturing faults). In addition, field data on damage and losses are not systematically collected and the sparse available data are not sufficient to establish robust statistical models for estimating earthquake-induced damage and losses.

As a result, modern loss estimation procedures are forced to tackle this challenging problem in an alternative way that is based on engineering analysis and analytical computations rather than purely on empirical data. The problem is usually divided into four sequential parts that are more manageable. The *first* step of this procedure is related to establishing, via nonlinear structural analyses, which characteristics of the ground shaking are best related to the level of induced building deformation. The *second* part deals with understanding what level of physical damage may be suffered by all the structural components (e.g., beams and columns) and non-structural components (e.g., interior partitions and glazing) when subject to different levels of deformation. The *third* part deals with identifying repair strategies that may be adopted to fix each component that may be in a given state of damage (e.g., cracks of a certain size in a partition wall) after an earthquake. The *fourth* and last step quantifies the overall performance of the structure in terms of repair cost, downtime, and life safety. The core of the present study fits into the first one of these four steps, namely in the ground motion/structural response interface.

2 OBJECTIVES

More specifically, this study investigates the power of several ground motion intensity parameters in predicting deformation levels for a structure. The goal is combined prediction of different but statistically correlated measures of the building response, such as the peak deformation at a number of stories along the height of the building. The peak deformation at a story provides useful information on the state of physical damage likely to be suffered by the structural and non-structural components located at that story. The use of multiple measures of building deformation to estimate losses is an improvement over the customary use of a single measure, such as the maximum lateral deformation at the roof level alone or the peak lateral deformation at the story where it is largest, as it can lead to more precise damage and loss estimates. As candidate predictors of response we have considered, among others, ground motion parameters that are related to the level of energy that is input into and absorbed by a structure during ground shaking. The correlation between the response measures is accounted for during the prediction exercise via a statistical technique known as multivariate multiple linear regression.

3 DATA SETS

As mentioned earlier, this study uses the results of nonlinear dynamic analyses of model buildings subjected to suites of historical ground motion records to evaluate the predictive power of alternative ground motion parameters. The investigation focuses on steel moment-resisting frame (SMRF) buildings and earthquake ground motions pertinent to the Southern California area, but the results should be applicable to other (similar) seismic regions as well. Brief descriptions of the earthquake records and building models used in this study are provided below. For additional information, the reader is referred to Luco *et al.* (2005).

3.1 *Historical Ground Motion Records*

A total of 140 recorded ground motions from 20 earthquakes are considered in this study, all obtained from the PEER Strong Motion database (http://peer.berkeley.edu/smcat). Only the strike-normal component of each ground motion is used. These motions include a "near-source" and an "ordinary" set of 70 motions each, recorded at distances (R_{close}) less than and greater than 16 km (but not more than 36 km) from the source, respectively. The recordings are from earthquakes of moment magnitudes (M_w) between 5.7 and 7.5. This selection of records is made in order to evaluate whether alternative GMPs relate to structural response equally well for different values of M_w and R_{close}. To prevent the confounding influence of soil properties on the structural response, ground motions recorded only at sites classified as NEHRP D or C ("stiff soil" or "very dense soil and soft rock"), or a Geomatrix site code B-D (when the NEHRP classification is unavailable) are considered. All of the ground motion records used in this study have been scaled (in amplitude only) by a factor of two, in order to induce significant nonlinear response in the structures considered. For 4 of the 140 records, collapse of one of the structural models used in this paper occurs. These 4 records are ignored here, and hence the results presented are conditional on non-collapse; the issue of collapse can be treated separately (e.g., Shome & Cornell, 2000).

3.2 *Building Models for Nonlinear Dynamic Analysis*

The structures considered in this research are the 3-story, 9-story, and 20-story steel moment-resisting frame (SMRF) office buildings designed for Los Angeles conditions by practicing engineers as part of the SAC Steel Project (FEMA 355C, 2000). The designs were carried out according to pre-Northridge earthquake practices (i.e., *UBC*, 1994). The 9-story building is the focus of this paper.

For the nonlinear dynamic analyses conducted, centerline two-dimensional models of each relatively symmetric (in plan) building are prepared in DRAIN-2DX (Prakash *et al.*, 1993). Reflecting design practices before and after the 1994 Northridge earthquake, the SMRF buildings are modeled with brittle and with ductile connections, respectively; their hysteretic behaviors are illustrated in Fig. 1. In the brittle building models, the connections fracture at the plastic rotation thresholds implied by FEMA 351 (2000). The fraction of the plastic moment to which the moment capacity drops upon fracture is set to 20%. Besides the ductile and brittle models, an elastic model of each building is also considered, as a point of reference. The fundamental period of all three 9-story building models is 2.3 seconds.

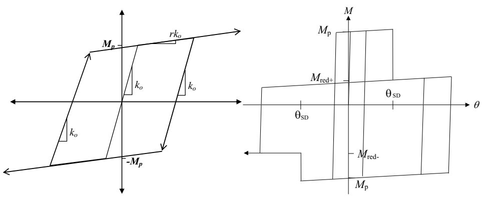

Figure 1. Illustration of the moment-rotation hysteretic behavior for the connections in the ductile (left) and brittle (right) building models.

4 GROUND MOTION PARAMETERS

As this study investigates ground motion parameters (GMPs) that can be used in seismic risk modeling, only GMPs for which predictive "attenuation relations" are available (or under development) are considered here. As described below, these include (i) linear elastic spectral accelerations, (ii) inelastic spectral accelerations, and (iii) linear elastic and inelastic input and absorbed energy-equivalent accelerations. The use of a vector combination of these GMPs will typically require, in addition to the individual attenuation relations, information regarding the correlation between the GMPs. Models of the correlation between linear elastic spectral accelerations at different periods (e.g., Inoue, 1990), and between inelastic and linear elastic spectral accelerations at the same period (e.g., Tothong & Cornell, 2005) are available. If other combinations of GMPs prove to be more strongly correlated with nonlinear structural response (and thereby with damage and loss), new correlation models can be developed – a relatively straightforward task.

4.1 *Linear Elastic Spectral Accelerations*

Currently, the most widely used ground motion parameter is S_a, the 5%-damped pseudo-spectral acceleration (i.e., the peak displacement response of a linear elastic oscillator, converted to units of acceleration). Numerous attenuation relations exist for S_a, and probabilistic seismic hazard curves in terms of S_a are freely available from the USGS website. Compared to peak ground acceleration (PGA), formerly the most widely used GMP, several studies (e.g., Shome *et al*., 1998) have shown that S_a at (or near) the fundamental period of the structure of interest, $S_a(T_1)$, is more closely related to the response of moderate to long period structures.

Despite its advantages over PGA, $S_a(T_1)$ has been demonstrated (e.g., Bazzurro & Cornell, 2002) to be less than ideal for tall, long-period buildings (including, as will be demonstrated below, the 9-story SMRF building models considered in this study). For such structures, the contributions to the response from higher modes of vibration can be significant. For elastic structures, of course, the response to a given ground motion can be estimated via a weighted (by participation factors) combination of spectral accelerations at the first few modal periods (i.e., modal analysis). Accordingly, vector GMPs that include spectral accelerations at multiple modes are considered in this study. Because the spectral accelerations at periods of adjacent vibration modes can be highly correlated (especially if these periods are closely spaced), the higher-mode spectral accelerations in the vector are normalized by the spectral acceleration at the previous (lower) modal period [e.g., $S_a(T_2)/S_a(T_1)$ and $S_a(T_3)/S_a(T_2)$]. Such normalizations help to avoid collinearity problems in the regressions described below.

4.2 *Inelastic Spectral Accelerations*

Even for structures whose elastic response is dominated by only the first mode of vibration, it has been demonstrated that the linear elastic $S_a(T_1)$ can be less than ideal in terms of its correlation with nonlinear response to near-source ground motions (e.g., Luco, 2002). The same might be said for very-short-period structures (e.g., small woodframe houses) that tend to exhibit relatively large dispersions in nonlinear drift response, even for "ordinary" ground motions. In such cases, it is logical to consider inelastic counterparts to $S_a(T_1)$. In this study a bilinear (or "ductile," as depicted in Fig. 1) inelastic oscillator characterized by T_1, five-percent damping, a yield displacement d_y, and a post-yield strain-hardening ratio of 5% is used to compute an *inelastic* spectral acceleration, denoted here as $S_a^D(T_1,d_y)$, where the "D" refers to "ductile." An appropriate d_y level can be estimated from a nonlinear static pushover analysis of the structure of interest (e.g., Luco, 2002), but here d_y is based on the nonlinear dynamic interstory (and roof) drift results for the ductile and elastic models of the 9-story building. It is observed that the interstory drifts for these two models are nearly identical unless the ground motion spectral displacement is greater than 12 cm, so the yield displacement d_y is set equal to this value. Note that only a relatively simple modification of the elastic time-history analysis carried out to compute $S_a(T_1)$ is required to compute $S_a^D(T_1,d_y)$.

The inelastic spectral acceleration $S_a^D(T_1,d_y)$ is equal to $S_a(T_1)$ for low-amplitude ground motions that induce displacements less than d_y, so $S_a^D(T_1,d_y)$ could be used in lieu of $S_a(T_1)$. However, here $S_a^D(T_1,d_y)/S_a(T_1)$ is considered as an additional GMP that can be used in a vector with $S_a(T_1)$, in part because an attenuation relation for this ratio is under development at Stanford University (Tothong & Cornell, 2005). The strain hardening ratio of 5% chosen here is consistent with that study.

4.3 *Energy-Based GMPs*

It has long been thought that damage to a structure during an earthquake might be more strongly correlated with energy-based GMPs than with the more conventionally used spectral acceleration. Chou & Uang (2000), Sari & Manuel (1999), Manuel (2002), and Mollaioli *et al.* (2004) have considered energy-based GMPs such as "input energy" (e.g., Uang & Bertero, 1988) and "absorbed energy" (e.g., Chou & Uang, 2000). Like spectral acceleration, these energy-based parameters are derived from the response of an elastic or an inelastic oscillator, and hence are period-dependent. Establishing their values from recorded ground motions requires a level of effort similar to that for spectral acceleration. The energy-based GMPs, however, are directly related to the number and amplitudes of the cycles of oscillator response, and hence they implicitly capture the effects of ground motion duration that are missed by the more conventional spectral parameters. Attenuation relations exist for elastic input energy (Chapman, 1999), inelastic input energy (Lawson, 1996), and inelastic absorbed energy (Chou & Uang, 2000). The absorbed energy of an elastic oscillator can be directly related to spectral acceleration.

In this study, the energy-based GMPs described above are transformed into units of acceleration using the mass and period of the particular oscillator (see Luco *et. al.*, 2005 for details). The resulting linear elastic and inelastic GMPs are referred to as "input energy-equivalent acceleration," denoted $A_i(T_1)$ or $A_i^D(T_1,d_y)$, and "absorbed energy-equivalent acceleration," denoted $A_a^D(T_1,d_y)$. These energy-based GMPs are used in lieu of and in combination with the spectral acceleration-based parameters described in the previous two sections.

5 STRUCTURAL RESPONSE MEASURES

In the structural engineering literature, various response measures have been proposed, based on experimental and theoretical studies, to explain damage observed in test structures under simulated ground motions or in actual structures struck by real earthquakes. We are interested in response measures that are well correlated to structural and non-structural damage, and thereby to monetary loss. Numerous studies (such as the SAC Steel Project) have indicated that peak interstory drift ratios (i.e., interstory drift normalized by story height) are closely related to both local demands and damage, and to global structural stability for steel moment-resisting frames and many other building types. Anticipating that the knowledge of more than a single structural response measure can help reduce (relative to a single response measure) the uncertainty in predicting structural damage and losses, a vector of peak interstory drift ratios for all stories is used in this study. While the emphasis is on the dependence of this vector on the alternative GMPs, the residual correlation between the interstory drift ratios, each denoted IDR_i for story i, is also evaluated via the regression methodology described in the next section. Although not reported here, a few scalar drift measures are also considered in this overall study, namely the maximum and the average IDR_i over all stories, and the peak roof drift ratio.

6 REGRESSION METHODOLOGY

The degree of correlation between the alternative GMPs and the structural response measures described above is evaluated here via multivariate multiple linear regression (e.g., Johnson & Wichern, 2002). A multivariate multiple linear regression (MMLR) analysis can be used to investigate the relationship between a vector of response variables (e.g., IDR_i's) and a vector of predictor variables (e.g., GMPs). MMLR is similar to the more widely used multiple linear regression (MLR), where a single response is related to several predictor variables. Computationally, MMLR yields the same regression model coefficients and the same residual variances as one would estimate with individual MLR computations for each of the response variables separately. However, MMLR also provides information on the residual correlation between the different response variables after regressing on the predictor variables. This information on the cross-correlation among the response variables is ultimately needed to accurately estimate damage and losses that, in general, will be dependent on several response measures jointly.

The multivariate multiple linear regression model employed is expressed mathematically as follows:

$$\ln(IDR_{i=1:n}) = \beta_{0i} + \sum_{j=1}^{r} \beta_{ji} \cdot \ln(GMP_j) + \ln(\varepsilon_i) \qquad (1)$$

where IDR_i is the peak interstory drift ratio for the i^{th} of n stories, β_{ji} is the model coefficient for the j^{th} of r GMPs (and the i^{th} story), and ε_i is the error term associated with the i^{th} story. Natural logarithms appear in Eq. 1 because a power law relationship is actually assumed between each IDR_i and the GMPs. Also, such a logarithmic transformation leads to the desired properties of linearity and homoscedasticity in the regressions (e.g., see Fig. 2 below). As in univariate linear regression, the expected value of each $\ln(\varepsilon_i)$ is zero, and its standard deviation can be denoted σ_i, but here the n error terms are correlated, with covariance matrix denoted by $\mathbf{\Sigma}$.

Unbiased least squares estimates of the model coefficients, denoted b_{ji}, and of the covariance of the error terms, denoted $\boldsymbol{S}$, are calculated as follows:

$$\boldsymbol{b} = (\boldsymbol{Z}^{\mathrm{T}} \cdot \boldsymbol{Z})^{-1} \cdot \boldsymbol{Z}^{\mathrm{T}} \cdot \ln(\boldsymbol{IDR}) \qquad (2)$$

$$\boldsymbol{S} = (\boldsymbol{e}^{\mathrm{T}} \cdot \boldsymbol{e}) \,/\, (n\text{-}r\text{-}1) \qquad (3)$$

In Eq. 2, $\boldsymbol{Z} = [\mathbf{1} \mid \ln(\boldsymbol{GMP})]$, where $\mathbf{1}$ is an m x 1 vector of ones and $\boldsymbol{GMP}$ is the m x r matrix of the ground motion parameters for all of the records (e.g., m=136 in this paper). The m x n matrix $\boldsymbol{IDR}$ in Eq. 2 contains the structural response data for all of the ground motion records. In Eq. 3, $\boldsymbol{e} = \ln(\boldsymbol{IDR}) - \boldsymbol{Z}\cdot\boldsymbol{b}$ is the m x n matrix of residuals.

The covariance matrix $\boldsymbol{S}$ gives estimates of (i) the individual standard deviations of the IDR_i's given the set of GMPs, which in this study are used to compare the predictive power of alternative GMPs, and (ii) the residual correlation between pairs of IDR_i's, which one would need in order to probabilistically describe building losses that depend on all of the IDR_i's. Although not reported in this paper, the statistical significance of the estimated model coefficients (in terms of p-values) is also used to compare the predictive power of alternative GMPs.

7 REGRESSION RESULTS

Using the multivariate multiple linear regression model described above, the vectors of structural response measures (***IDR***) obtained from nonlinear dynamic analyses of the 9-story SMRF building models (elastic, ductile, and brittle) are regressed on various combinations of the different GMPs introduced in Sect. 4. Since the residual standard deviations of the IDR_i's for a given GMP are directly related to the uncertainty in predicting structural responses to ground motions, they are used here to compare the predictive power of the different GMP choices. The regression results are presented separately for the following three categories of ground motion parameters: (i) first-mode elastic, (ii) multi-mode elastic, and (iii) first-mode inelastic and higher-mode elastic.

7.1 *First-Mode Linear Elastic GMPs*

The first-mode linear elastic GMPs considered in this study are (i) $S_a(T_1)$, the 5%-damped pseudo-spectral acceleration at the fundamental period of the structure (2.3 seconds for the 9-story building), (ii) $A_i(T_1)$, the input energy-equivalent acceleration, also at T_1 and for 5% damping, and (iii) a vector GMP containing $S_a(T_1)$ and the ratio $A_i(T_1)/S_a(T_1)$.

Although not reported here in detail, the residual (given the GMP) standard deviations of the interstory drift measures considered in this study are, in fact, not appreciably different for the three GMP alternatives. This is true for not only the 9-story building models considered in this paper, but for the 3- and 20-story models as well. The results only confirm our expectations, given that $A_i(T_1)$ is highly correlated with $S_a(T_1)$. Furthermore, the structural response parameters considered in this study are interstory drifts, and hence one might expect the displacement-based $S_a(T_1)$ to be a better predictor of the structural response. In what follows, only the regression results for $S_a(T_1)$ are presented.

The log-log linear fits and the residual standard deviations, σ_i, obtained from regressing the vector of response measures IDR_i (i = 1 to 9) on $S_a(T_1)$ alone are shown in Fig. 2 for the ductile model of the 9-story building. The corresponding residual correlations between the nine interstory drifts are given in Table 1. From Fig. 2 it is apparent that the IDR_i values in lower stories (below, say, the 7th story) are well predicted by the first-mode $S_a(T_1)$. At higher stories, however, the residual standard deviations are larger, indicating that $S_a(T_1)$ alone is less effective there in predicting IDR_i. This indicates that the response predictions at higher stories will be more uncertain than those at lower stories if such predictions are based on a first-mode elastic GMP.

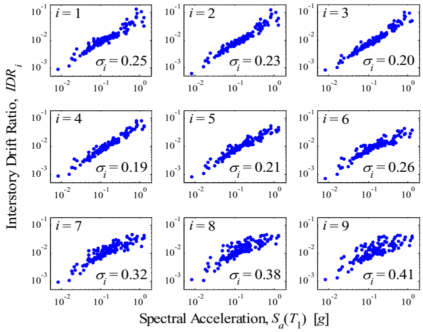

Figure 2. Results of regressing interstory drift ratios (IDR_i's) on $S_a(T_1)$ for the ductile 9-story SMRF building model. The residual dispersion for each of the stories, σ_i, is indicative of the predictive power of this GMP.

As might be expected, the residual (given the GMP) IDR_i values at adjacent stories of the ductile 9-story building model are highly correlated with each other, as demonstrated in Table 1. Certain other pairs of residuals are also strongly correlated – e.g., those at the 5th and 9th stories. These correlations among interstory drift residuals at non-adjacent stories likely result from the contributions to these drifts from factors other than the first-mode type of vibration (e.g., contributions from higher modes).

From Fig. 3, which compares the values of σ_i for all three models of the 9-story building (and for other GMP sets to follow), it is evident that σ_i is smallest (at all stories) for the elastic model and largest for the brittle model. Although not reported here in detail, the values of σ_i for the 3- and 20-story building models also analyzed in this study are generally smaller and larger, respectively, than those presented here for the 9-story models. Like the larger dispersions seen at higher stories of the 9-story models, the differences in σ_i values between the three building heights can be attributed to the contributions of higher modes. In the next subsection we discuss the results of regressing on vectors of elastic GMPs at multiple modes. By including more

Table 1. Residual correlations between the interstory drift ratios, after regressing on $S_a(T_1)$, of the ductile 9-story SMRF building model.

Story	Residual IDR Correlation, ρ_{ij}								
i	j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8	j=9
1	1	0.93	0.74	0.67	0.41	0.32	0.23	0.27	0.29
2	*	1	0.85	0.64	0.28	0.16	0.09	0.15	0.14
3	*	*	1	0.81	0.30	0.11	0.02	0.08	0.10
4	*	*	*	1	0.70	0.44	0.22	0.28	0.33
5	*	*	*	*	1	0.82	0.53	0.54	0.56
6	*	*	*	*	*	1	0.79	0.74	0.72
7	*	*	*	*	*	*	1	0.95	0.86
8	*	*	*	*	*	*	*	1	0.94
9	*	*	*	*	*	*	*	*	1

GMPs in the predictor set we expect to achieve lower variability in the response measures.

7.2 *Multi-Mode Linear Elastic GMPs*

The relatively large dispersions of IDR_i observed at the higher stories of the 9-story SMRF building models when only a first-mode elastic GMP is used suggests that including higher-mode spectral accelerations, for example, in a vector GMP may improve the predictive power (i.e., reduce the residual standard deviations). The multi-mode linear elastic ground motion parameters considered in this study include the vectors $\{S_a(T_1), S_a(T_2)/S_a(T_1)\}$, $\{S_a(T_1), S_a(T_2)/S_a(T_1), S_a(T_3)/S_a(T_2)\}$, and other similar vector combinations of spectral accelerations and/or input energy-equivalent accelerations $A_i(T_k)$ (see Luco *et al.*, 2005 for details). As discussed earlier for the first-mode linear elastic GMPs, the inclusion of $A_i(T_k)$ for higher modes does not appreciably improve the predictive power beyond the improvement that results from the inclusion of $S_a(T_k)$ for higher-modes. Hence, only the results for the vector combinations of spectral accelerations are reported here.

The residual standard deviations obtained from regressing the vector of response measures IDR_i (i = 1 to 9) on the vector ground motion parameter $\{S_a(T_1), S_a(T_2)/S_a(T_1)\}$ are shown in Fig. 3 for the three 9-story building models. Overall, we see significant reduction (relative to using $S_a(T_1)$ alone) in the residual standard deviations at the higher stories, which is where the second mode is expected to contribute more to the response. On the other hand, at the lower stories of the ductile and brittle building models it is apparent that the second-mode ground motion parameter $S_a(T_2)/S_a(T_1)$ does not improve upon the predictive power of $S_a(T_1)$ alone.

In addition to reducing the dispersions of IDR_i, including $S_a(T_2)/S_a(T_1)$ with $S_a(T_1)$ in a vector GMP decreases the residual correlations between the story drifts, as demonstrated in Fig. 4 for the ductile 9-

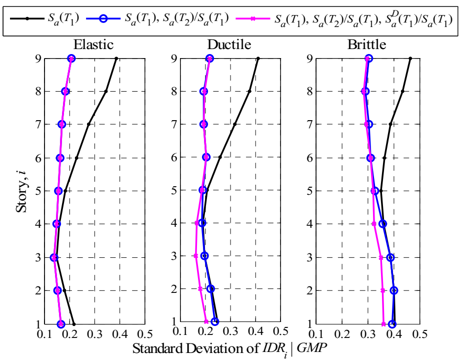

Figure 3. Residual dispersions of interstory drift ratios (IDR_i's), for all three 9-story SMRF building models, after regressing on alternative ground motion parameters (GMPs).

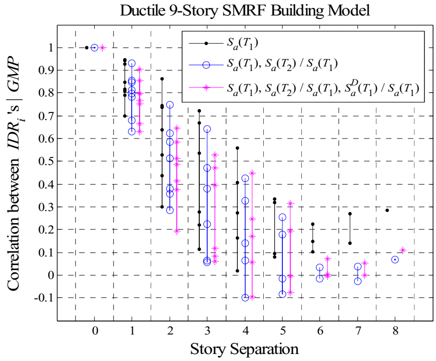

Figure 4. Residual correlations between interstory drift ratios (IDR_i's) of the ductile 9-story SMRF building model after regressing on alternative ground motion parameters (GMPs), plotted against the number of stories separating the IDR_i's.

story model. This is particularly true at the upper stories, where the second mode contributes significantly to the structural response. Reducing the residual correlations is expected to reduce the uncertainty in loss estimates, which are (roughly speaking) additive functions of the IDR_i values.

Although not reported here in detail, the inclusion of $S_a(T_2)/S_a(T_1)$ in a vector GMP also significantly reduces the dispersions in IDR_i at the upper stories of the 20-story building models considered in this study. In fact, unlike for the 9-story models, including the third-mode term $S_a(T_3)/S_a(T_2)$ reduces the dispersions even further for the 20-story models. As expected, however, for the 3-story building models there is little reduction in the residual standard deviation (at any story) brought about by the using a multi-mode GMP vector instead of $S_a(T_1)$ alone. This is because the response of the 3-story models is mainly governed by the first mode. For these models, the remaining dispersion of IDR_i given $S_a(T_1)$ is indicative of the effects of inelasticity (ductile or brittle) not captured by the first-mode elastic GMP.

7.3 *First-Mode Inelastic & Higher-Mode Linear Elastic GMPs*

Building upon the multi-mode linear elastic GMP vectors that are found to better predict the nonlinear response of the 9- and 20-story building models, here we discuss whether addition of the first-mode *inelastic* GMPs described in Sect. 4.2 further improves the predictions. The first-mode inelastic GMPs considered in this study include $S_a^D(T_1,d_y)$, the inelastic spectral acceleration, and $A_i^D(T_1,d_y)$ and $A_a^D(T_1,d_y)$, the analogous inelastic first-mode input and absorbed energy-equivalent accelerations. Although not reported here in detail, in no cases (across buildings and stories) does the introduction of $A_i^D(T_1)/S_a(T_1)$ or $A_a^D(T_1)/S_a(T_1)$ in lieu of $S_a^D(T_1)/S_a(T_1)$ reduce the residual standard deviation, σ_i, by more than a couple of percentage points. In fact, in some cases, the predictive power of the GMP vector containing $S_a^D(T_1)/S_a(T_1)$ is clearly superior, and hence regression results for this GMP only are presented here.

The regression results shown in Fig. 3 confirm that for the elastic model of the 9-story building there is no benefit in including the inelastic first-mode GMP. For the ductile and brittle 9-story building models, however, the addition of $S_a^D(T_1)/S_a(T_1)$ to the multi-mode elastic ground motion parameter $\{S_a(T_1),\ S_a(T_2)/S_a(T_1)\}$ does significantly improve the prediction of the IDR_i responses at lower stories (below, say, the 3rd), though the improvement is minimal at the higher stories (where higher modes dominate). As a result, the predictive power of the vector ground motion parameter $\{S_a(T_1),\ S_a(T_2)/S_a(T_1),\ S_a^D(T_1)/S_a(T_1)\}$ is comparable across all stories, name 0.15-0.20 and 0.30-0.35, respectively, for the ductile and brittle models. The larger dispersions for the brittle model suggest that perhaps a “brittle” rather than “ductile” inelastic spectral acceleration might further improve the prediction of story drifts, an option not investigated in this study.

Although not reported here in detail, including $S_a^D(T_1)/S_a(T_1)$ with $S_a(T_1)$ in a vector GMP also significantly improves the predictive power for the ductile and brittle (the latter to a lesser extent) 3-story building models considered in this study. It is expected that the benefits of including $S_a^D(T_1)/S_a(T_1)$ would also be significant for even shorter period structures. The improvement, however, may be minimal for long-period structures (such as the 20-story building), because the inelastic GMP will be roughly equal to its elastic counterpart (according to the “equal displacements rule”).

8 SUFFICIENCY OF GMP

Recall that the regressions described above result in estimates of (i) the median (or geometric mean) structural response, via the regression coefficients, and (ii) the logarithmic standard deviation of the response (σ_i), both for a given level of ground motion. Assuming that the conditional response is lognormally distributed, the regression results can be used to compute the probability of exceeding a specified response conditioned on the ground motion level, denoted here as $G[IDR_i|GMP]$. Note that this conditional complementary cumulative distribution function (CDF) for all ground motion levels can be convolved with the ground motion hazard to obtain a hazard curve in terms of nonlinear structural response (e.g., Bazzurro & Cornell, 1994).

For some ground motion parameters more so than for others, the regression results, and therefore $G[IDR_i|GMP]$, can depend on the set of earthquake records used (e.g., "near-source" versus "ordinary," as described in Sect. 3.1) even if the record sample size is very large. A "sufficient" GMP, however, will provide approximately the same regression results regardless of the types of ground motions considered (Luco, 2002). A major advantage of the use of a sufficient GMP is that the regression of nonlinear structural response on such a GMP can be carried out for an arbitrary set of earthquake records, rather than for a set of records carefully chosen so that their characteristics match those of the earthquake scenarios that control the hazard at the particular building site.

The sufficiency of $S_a(T_1)$ and $\{S_a(T_1),\ S_a(T_2)/S_a(T_1),\ S_a^D(T_1)/S_a(T_1)\}$ with respect to (i) ground motions from relatively large versus small magnitude earthquakes, and (ii) near-source versus ordinary ground motions, is illustrated in Fig. 5. Recall that the near-source ground motions considered are defined as those with R_{close}<16km, and the large

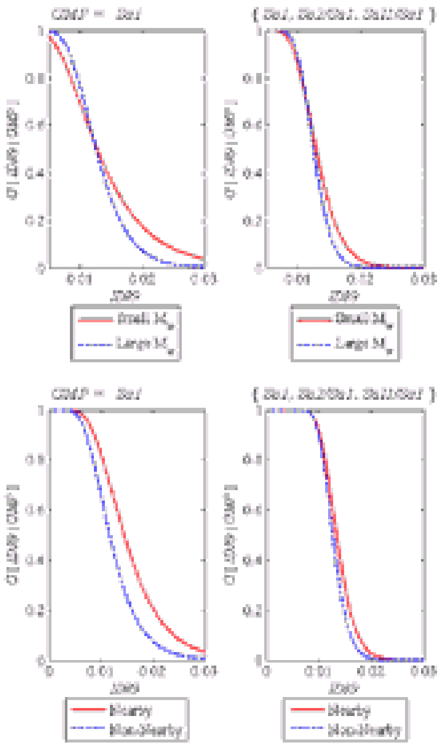

Figure 5. Complementary cumulative distribution functions (CCDFs), conditioned on two alternative ground motion parameters (GMPs), for the ninth-story drift ratio, IDR_9.

magnitude earthquakes are taken to be those with M_w>6.5. The $G[IDR_i|GMP]$ results are shown for IDR_i responses at only the ninth story of the ductile 9-story building model, but the results at other stories exhibit similar trends. The ground motion level considered for these figures is the median level across the full set of earthquake records.

Note from Fig. 5 that the $G[IDR_i|GMP]$ results are more similar across distance (nearby vs. non-nearby) and magnitude (small vs. large) ranges when the GMP is comprised of the first-mode inelastic and higher-mode elastic vector $\{S_a(T_1),\ S_a(T_2)/S_a(T_1),\ S_a^D(T_1)/S_a(T_1)\}$. Hence, not only does this vector GMP predict nonlinear structural response better than the conventional $S_a(T_1)$, it appears to be more "sufficient" as well.

9 CONCLUSIONS

Using elastic, ductile, and brittle models of three different steel moment-resisting frame buildings (of 3, 9, and 20 stories) and 140 historical ground motion records, different scalar and vector ground motion parameter (GMP) sets are used as predictor variables to estimate various response measure vectors, including peak interstory drift ratios for individual stories (IDR_i). In general, we find that a GMP vector that includes a higher-mode elastic spectral acceleration [e.g., $S_a(T_2)/S_a(T_1)$] and first-mode *inelastic* spectral acceleration [e.g., $S_a^D(T_1)/S_a(T_1)$], in addition to the first-mode elastic spectral acceleration [i.e., $S_a(T_1)$], better predicts nonlinear structural response than $S_a(T_1)$ alone, as demonstrated in this paper for the 9-story building. The energy-based GMPs considered (elastic and inelastic input and absorbed energy), however, do not appreciably improve the predictive power of such vectors due, in part, to their strong correlations with their corresponding spectral accelerations. Usefully, the GMP vector $\{S_a(T_1),\ S_a(T_2)/S_a(T_1),\ S_a^D(T_1)/S_a(T_1)\}$ is demonstrated to be "sufficient" – as such, careful selection of specific ground motions for nonlinear dynamic analysis is less important if this GMP set is used.

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