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CASE STUDIES ON RELATIVE SUFFICIENCY OF ALTERNATIVE INTENSITY MEASURES OF GROUND SHAKING

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ABSTRACT

In performance-based earthquake engineering, the uncertainty in the ground motion can be represented by probabilistic description of a parameter, known as the intensity measure (*IM*). Investigations are carried out herein for evaluating the predictive capability of a wide range of commonly-used scalar *IM*s for different demand parameters. To accomplish this goal, both the efficiency and sufficiency of the candidate *IM*s are taken into account. For the latter, the recently-proposed "*relative sufficiency measure*" is used which is on the basis of information theory concepts. This measure quantifies the suitability of one *IM* relative to another in terms of the amount of information gained (on average) in the representation of ground motion uncertainty. The relative sufficiency measure is calculated in an approximate manner based on a set of recorded ground motions. For corresponding evaluations, two existing RC frame structures are selected, and two sets of accelerograms, consisting of ordinary and pulse-like near-fault records, are used. It is concluded that the spectral acceleration at the first-mode period as well as a set of proposed structure-specified *IM*s, which are the modified versions of existing ones, are more informative, and intend to improve the correlations between the considered *IM*s and response quantities.

INTRODUCTION

In the light of probabilistic Performance Based Earthquake Engineering (PBEE) developed by the Pacific Earthquake Engineering Research Center (PEER; Cornell and Krawinkler 2000, Moehle and Deierlein 2004), the seismic risk can be expressed in terms of the Mean Annual Frequency (MAF) of exceeding a specified limit state (or the limit state frequency) denoted as λ_{LS}. The ground motion uncertainty in this methodology is represented by probabilistic description of a scalar parameter, or low-dimensional vector of parameters, known as the Intensity Measure, *IM* (Shome et al., 1998; Jalayer and Cornell, 2003; Luco and Cornell, 2007; Jalayer and Cornell, 2009). This is a more well-known methodology for representing the ground motion uncertainty compared to the rigours approach

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which consists of full probabilistic description of the ground-motion time history in terms of a stochastic model (see e.g. Jalayer and Beck, 2008). The site- and/or structure-specific *IM* serves as an intermediate variable (link) between the ground motion hazard and structural demand estimates, as follows:

$$\lambda_{LS} = \int_{im} P\left[D > C_{LS} \mid IM = im \right] \left| \mathrm{d}\lambda_{IM}\left(im\right) \right| \tag{1}$$

where D denotes the structural demand; C_{LS} is the capacity associated with the given limit state LS; λ_{IM} is the hazard of the site in terms of the MAF of exceeding a certain level of *IM*; and finally the conditional Complementary Cumulative Distribution Function (CCDF) $P[D|IM]$ is defined as the structural fragility for the desired limit state, *LS*.

The suitability of the adopted *IM* for representing ground motion uncertainty is a major concern in PEER PBEE to be addressed. Strictly speaking, the stronger the correlation of the predicted D's with respect to the adopted *IM*, the more accurate the result of the probabilistic risk assessment methodology. The current criteria for measuring the suitability of an *IM* in representing the dominant features of ground shaking are comprised of sufficiency, efficiency, scaling robustness, and the predictability through the probabilistic seismic hazard analysis (see Shome and Cornell, 1999; Giovenale et al., 2004; Luco and Cornell, 2007). Among these properties, the first two are of particular concern within present study. An *efficient IM* leads to a relatively small variability of $D|IM$; hence, a smaller number of nonlinear dynamic analyses (or equivalently earthquake records) is required in order to estimate the limit state fragility $P[D|IM]$ with adequate precision. A *sufficient IM*, on the other hand, has been defined as one that renders $P[D|IM]$ independent of other ground motion characteristics. Establishing the sufficiency criterion implies that a detailed ground-motion record selection is not necessary while keeping the same accuracy in seismic performance estimation.

The efficiency and sufficiency of an IM have been the focus of attention of many researchers. For instance, Shome et al. (1998) demonstrated that the 5% damped pseudo spectral acceleration at the first-mode period, $Sa(T_1)$, is more efficient than the peak ground acceleration, PGA. Nonetheless, for tall and long-period buildings as well as for near-source ground motions, $Sa(T_1)$ may not be efficient nor sufficient because of the limited spectral shape information (see Shome and Cornell, 1999; Luco and Cornell 2007). This is in part due to the fact that $Sa(T_1)$ accounts neither for contribution of higher modes nor for period lengthening owing to structural nonlinearity.

Several alternative *IM*s are proposed as multiplicative adjustments of $Sa(T_1)$ in order to explicitly overcome the aforementioned drawbacks (Shome and Cornell, 1999; Cordova et al., 2001; Mori et al., 2004; Luco and Cornell, 2007; Bianchini et al., 2009; Lin et al. 2011). All these studies looked for a single "broad-range" *IM* that will not only improve the efficiency for all damage levels of a given structure but also accounts for the computability of the ground-motion hazard (without the need of new attenuation relationships). In case of alternative scalar *IM*s, a series of spectrum-based as well as energy-based *IM*s have been investigated and proved that, generally, the velocity-based *IM*s are better correlated with deformation demands especially in the case of medium rise frame structures (Akkar and Özen, 2005; Riddell, 2007; Yakut and Yilmaz, 2008; Jayaram et al., 2010; Mollaioli et al. 2011). The two latter references have taken into account the effect of near-fault ground motions and the classification of the soil type.

As opposed to the scalar *IM*s, vector-valued *IM*s commonly comprise two parameters. The vector-valued *IM* consisting of $Sa(T_1)$ and spectral values at other periods has also been illustrated to be more sufficient with respect to $Sa(T_1)$ (Luco et al., 2005; Baker and Cornell, 2005). The vector-valued *IM* consisting of $Sa(T_1)$ and ε, has been thoroughly investigated by Baker and Cornell (2005) (ε is defined as the number of standard deviations by which $\ln Sa(T_1)$ differs from the predicted mean value from a ground motion prediction model). Consideration of ε provides information about the shape of a record's response spectrum. According to considerable efforts usually required for using the vector-valued *IM*s in the assessment-related analyses, the use of scalar *IM*s is still a defendable choice.

This study aims to investigate the predictive capability of a wide range of scalar *IM*s for demand parameters describing damage in the building structures. The efficiency and sufficiency of the considered *IM*s are taken into account in order to achieve this goal. Moreover, both ordinary and pulse-like near fault ground motions are considered herein. Generally, linear regression is carried out to define a probabilistic model for the probability distribution $D|IM$ (i.e., between various structural response parameters, *D*'s, and the desired *IM*s), which is directly used to evaluate the efficiency and sufficiency of *IM* in predicting various seismic structural response parameters. However, to investigate the relative sufficiency of the two *IM*s, it seems logical to express the criteria for measuring the suitability of one *IM* relative to another in terms of the information that it provides in order to predict the response quantities. Therefore, on the basis of the application of entropy and the concept of relative entropy, Jalayer et al. (2012) introduced a quantified measure which is called *relative sufficiency measure* (see also Jalayer and Beck, 2006). It is derived on the basis of information theory concepts in order to quantify the suitability of one intensity measure relative to another in representing ground motion uncertainty. This measure states on average how much more information about the designated structural response parameter one *IM* gives relative to another.

As the case study, two 4-story and 6-story existing RC moment-resisting frames located in the Mediterranean area are investigated, which are representative of existing buildings in this area. It is noteworthy that the considered frames are two-dimensional since the *IM*s for the response prediction of torsional buildings should be able to explicitly account for the torsional behavior especially in the low nonlinearity range (for more details, see Lucchini et al., 2011). Various seismic response parameters are calculated through non-linear dynamic analyses considering two different sets of ground motions consisting of ordinary and pulse-like records. A large set of scalar *IM*s is used, which was previously summarized in a comparative study by Mollaioli et al. (2013) for predicting seismic demands in base-isolated structures. Those *IM*s are composed of most commonly used ones in the literature as well as new *IM*s, which were attained by modifying the existing ones in order to obtain better correlation with the predicted demands.

It is revealed that the quantitative comparison of results on the basis of calculating the relative sufficiency measures for the studied *IM*s agrees well with previous qualitative-based conclusions of current practice.

METHODOLOGY

This study benefits considerably from one of the most efficient nonlinear dynamic procedures referred to as the *cloud method* (Jalayer and Cornell, 2003; Jalayer and Cornell, 2009; Elefante et al. 2011; Jalayer et al. 2014) in order to quantify the efficiency as well as the relative sufficiency of various *IM*s. In this method, structure is first subjected to a suite of *n* ground-motion records, and the designated structural response parameter, generally denoted as *D*, is calculated. By performing a simple linear regression in the logarithmic space on *D* versus the candidate IM, the statistical parameters corresponding to the lognormal distribution of $D|IM$ can be extracted, i.e., the expected value is modeled by a linear regression equation with parameters *a* and *b*, while the standard deviation is estimated by the standard error of the regression:

$$\mathbb{E}\left[\ln D \mid IM\right] = \ln \eta_{D|IM} = \ln a + b \ln IM\,,\;\; \sigma_{\ln D|IM} = \beta_{D|IM} = \sqrt{\frac{\sum_{i=1}^{n}\left(\ln D - \ln \eta_{D|IM}\right)^2}{n-2}} \tag{2}$$

where $\eta_{D|IM}$ and $\sigma_{\ln D|IM}$ (or equivalently $\beta_{D|IM}$) are the median and standard deviation, respectively. It is worth noting that in case of having vector *IM*s, a multivariate linear regression model can be applied. The estimated dispersion $\beta_{D|IM}$ serves as quantitative measure for predictive efficiency of the candidate *IM*; for instance, *IM*s resulting in standard errors in order of 0.20-0.30 are normally considered as those having a proper efficiency, while the range 0.30-0.40 is still considered as reasonably acceptable (Mollaioli et al., 2013).

In addition, for quantifying the sufficiency, the recently-developed relative sufficiency measure, denoted as $I(D|IM_2|IM_1)$, is utilized herein (see Jalayer et al. 2012). It can be interpreted as a measure for the average information gained about the performance variable *D* given IM_2 instead of IM_1. The relative sufficiency measure is expressed in units of bits of information. If $I(D|IM_2|IM_1)$ is positive, this means that on average IM_2 provides more information about D than IM_1; hence, IM_2 is more sufficient than IM_1. Similarly, if the $I(D|IM_2|IM_1)$ is negative, IM_2 is less sufficient than IM_1. This measure is expressed as:

$$I\left(D \mid IM_2 \middle| IM_1\right) \approx \frac{1}{n}\sum_{i=1}^{n}\log_2 \frac{p\left[D=d_i \middle| IM_2\right]}{p\left[D=d_i \middle| IM_1\right]} \tag{3}$$

where $\{d_i, i=1:n\}$ are the demand values calculated through non-linear time-history analysis performed for a suite of n ground motions. The probability distribution Function (PDF) $p[D|IM]$, considering a lognormal distribution with the parameters defined in Eq.(2), is calculated as follows:

$$p\left[D=d \middle| IM\right] = \frac{1}{d \cdot \beta_{D|IM}}\phi\left(\frac{\ln d - \ln \eta_{D|IM}}{\beta_{D|IM}}\right) \tag{4}$$

where $\Phi(\bullet)$ is the standardized Gaussian CDF, and equivalently, $\phi(\bullet)$ is the standardized Gaussian PDF. Hence, the relative sufficiency measure can finally be expressed as:

$$I\left(D \mid IM_2 \middle| IM_1\right) \approx \frac{1}{n}\sum_{i=1}^{n}\log_2\left(\frac{\beta_{D|IM_1}}{\beta_{D|IM_2}}\frac{\phi\left[\left(\ln d_i - \ln \eta_{D|IM_2}\right)/\beta_{D|IM_2}\right]}{\phi\left[\left(\ln d_i - \ln \eta_{D|IM_1}\right)/\beta_{D|IM_1}\right]}\right) \tag{5}$$

Jalayer et al. (2012) investigated that the relative sufficiency measure, which is calculated in Eq.(5) by an average for the suite of n real ground motion records, provides a preliminary ranking of candidate IM_2 with respect to the reference IM_1. Although this approximation can, in turn, be used for a fast screening of various candidate *IM*s, it may yield rather inaccurate measures. Therefore, they have proposed a refined method by using a stochastic ground motion model in conjunction with deaggregation of the seismic hazard at the site, and then estimating the expectation involved in the relative sufficiency measure's definition through Monte Carlo simulation. Although the refined estimates generally agree with the rough preliminary estimates, they revealed that the candidate *IM*s can be ranked fairly different. However, the simplified formulation in Eq.(5), although approximate, offers an efficient solution for comparing the IM's without the need to use a stochastic ground motion model.

NUMERICAL EXAMPLE

The case-study buildings are two three-bay 2-dimensional RC frames consisting of a 4-story and a 6-story structures designed according to a past code (DM 96, 1996). They are representative of existing buildings located in high seismic zones (i.e., "zone 1" according to the seismic hazard classification of DM 96). A schematic representation of the two frames is illustrated in Fig.1 (for more details about the building structures, see Mollaioli et al., 2013). The periods of the first three modes of vibration of the frames, obtained with a reduced cracked stiffness of the structural elements equal to half the initial elastic ones, are outlined in Table 1.

In this study, 139 earthquake ground motions (GMs) are selected from the Next Generation of Attenuation project database (PEER 2005), and used as input for the cloud analysis methodology. The suite of records is divided into two groups: (1) 80 ordinary GMs with closest distance ranging 0.34km≤ R ≤87.87km, and magnitude 5.74≤ M ≤7.90, and (2) 59 pulse-like near-fault GMs with 0.07km≤ R ≤20.82km from and magnitude 5.0≤ M ≤7.62 (see Mollaioli et al., 2013 for more details). For ordinary GMs, the component having larger spectral acceleration at the fundamental period of the considered superstructure is used; however, for pulse-like near-fault GMs, the fault-normal rotated component is selected. All the time histories are recorded on soil classified as type C or D, according to the NEHRP site classification based on the preferred V_{s30} values.

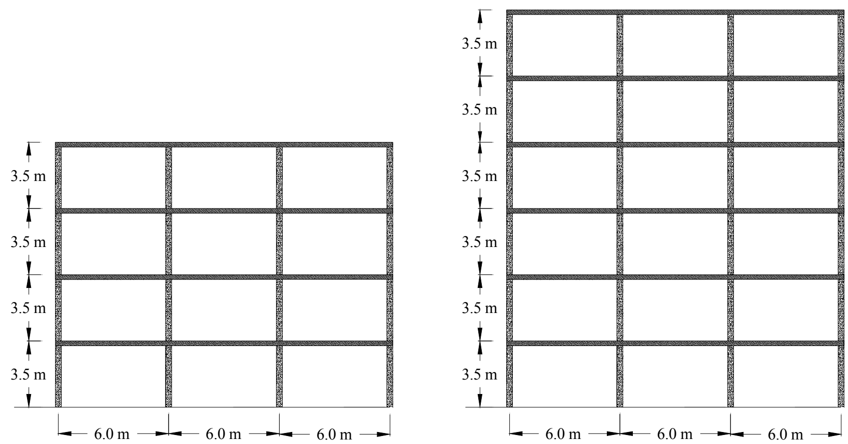

Figure 1. Schematic representation of the case-study RC frame structures

Table 1. Periods of the first three modes of vibration of the case-study frames

Frame	T_1 [sec]	T_2 [sec]	T_3 [sec]
4-story	0.97	0.33	0.20
6-story	1.17	0.40	0.24

The required non-linear dynamic analyses for the cloud analysis procedure are performed in OpenSees 2.2.2 (2010). The physical models of the two structures are built using Beam with Fibre-Hinges Elements for modelling beams and columns of the frames. The masses are concentrated at the nodes, and the stiffness of the floors is modelled with rigid diaphragm constraints. A Rayleigh damping proportional to the mass and tangent stiffness matrix is used, with coefficients calibrated to provide a 5% damping at the first and second mode periods of the undamaged structures. The effects of geometric nonlinearities are not considered in the analyses (see Mollaioli et al., 2013 for extra details on the modelling aspects of both structures).

INTENSITY MEASURES AND DEMAND PARAMETERS

The set of *IM*s under investigation in this study is identical to that used earlier by Mollaioli et al. (2013). This set was primary categorized as shown in Fig.2, and is outlined in Table.2.

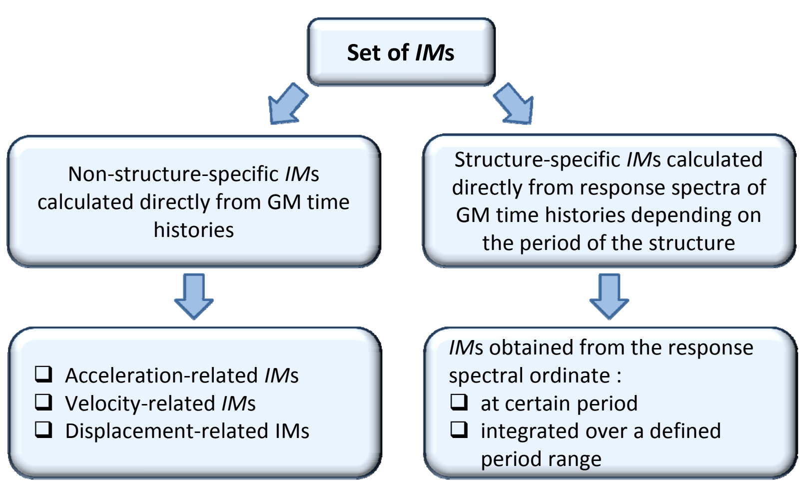

Figure 2. Categorization of the desired set of *IM*s (see Mollaioli et al., 2013)

Table 2. IMs considered in this study (see Mollaioli et al., 2013 for complete definition and related references of each *IM*)

Category	Class	Intensity Measure	
		Notation	Name
Non-structure-specific intensity measures	Acceleration-related	▪ *PGA*	Peak ground acceleration
		▪ *AI*	Arias intensity
		▪ *CAV*	Cumulative absolute velocity
		▪ I_a	Compound acceleration-related intensity
		▪ I_c	Characteristic intensity
	Velocity-related	▪ *PGV*	Peak ground velocity
		▪ *FI*	Fajfar intensity
		▪ I_v	Compound velocity-related intensity
		▪ *CAD*	Cumulative absolute displacement
		▪ *IV*	Incremental velocity
		▪ *SED*	Specific energy density
	Displacement-related	▪ *PGD*	Peak ground displacement
		▪ I_d	Compound displacement-related intensity
		▪ *ID*	Incremental displacement
Structure-specific intensity measures	Spectral (at fundamental period)	▪ *Sa*	Spectral acceleration
		▪ E_{Ir}	Relative input energy
		▪ E_{Ia}	Absolute input energy
	Integral	▪ *ASI*	Acceleration spectrum intensity
		▪ *VSI*	Velocity spectrum intensity
		▪ I_H	Housner intensity
		▪ $V_{EIr}SI$	Relative input equivalent velocity spectrum intensity
		▪ $V_{EIa}SI$	Absolute input equivalent velocity spectrum intensity
		▪ *MASI*	Modified *ASI*
		▪ *MVSI*	Modified *VSI*
		▪ MI_H	Modified I_H
		▪ $MV_{EIr}SI$	Modified $V_{EIr}SI$
		▪ $MV_{EIa}SI$	Modified $V_{EIa}SI$

Integral-based structure-specified *IM*s, which are evaluated by integration of the spectral values over a given period range, can explicitly account for higher-mode effects as well as period lengthening due to structural softening. In this group, modified proposals for the structure-specific *IM*s are also introduced, which are obtained from the existing ones by changing the period range of integration to be within the interval [$0.5T_1$, $1.25T_1$], where T_1 is the first-mode period of the structure. This period range is based on the provision made by many codes which states that response spectra for the suite of GMs should not be less than the design response spectrum for periods ranging from $0.2T_1$ to $1.5T_1$~$2.0T_1$ (see e.g. Eurocode 8, 2003). Since in most case, the upper bound of $2.0T_1$ seems to be excessive (e.g., see Katsanos et al. 2009), the integration period range of modified integral *IM*s are set to be within the above-mentioned range.

The demand parameters (*D*'s or also known as engineering demand parameters) considered in this study are outlined in Table.3, as follows:

Table 3. Demand parameters considered in this study

Notation	Name	Definition
MRDR	Maximum Roof Drift Ratio	the ratio of the peak lateral roof displacement (with respect to the base) to the building height / well correlated with the overall structural damage, and global instability
MIDR	Maximum Inter-story Drift Ratio	the maximum value of the peak inter-story drift ratio (drift normalized by the story height) over all stories / closely related to local damage, instability, and story collapse
MFA	Maximum Floor Acceleration	the maximum value of the peak floor absolute acceleration over all stories / reflects the level of non-structural damages

RESULTS IN TERMS OF EFICIENCY

The standard deviation of residuals corresponding to *MRDR*, *MIDR* and *MFA*, obtained from the regression model of ln*MRDR*|*IM*, ln*MIDR*|*IM* and ln*MFA*|*IM*, respectively, for both case-study buildings subjected to ordinary and pulse-like ground motions are illustrated in Fig.3.

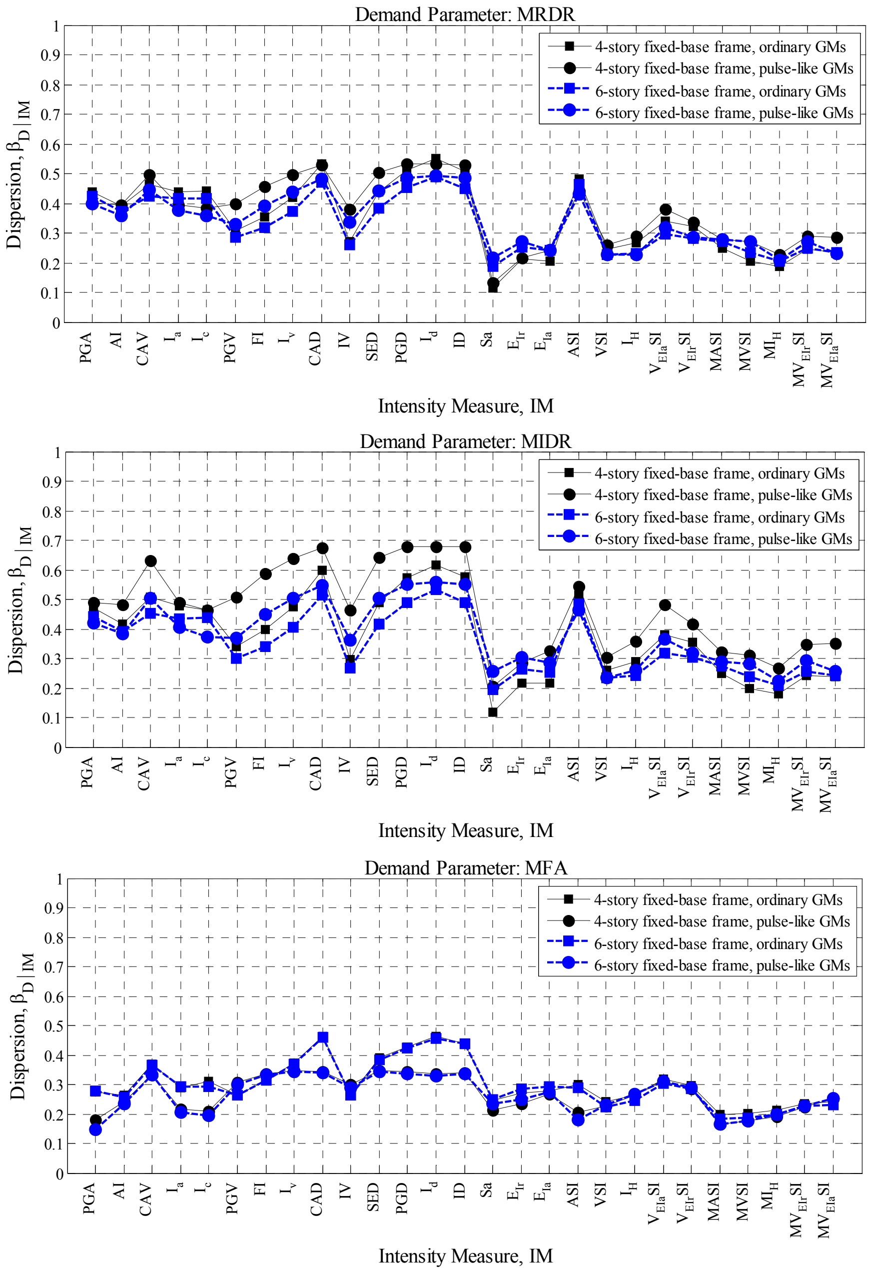

Figure 3. The standard deviation (dispersion) of residuals of the demand parameters MRDR, MIDR and MFA, obtained from the cloud analysis for both buildings subjected to ordinary and pulse-like ground motions

According to Fig.3, the following observations can be made:

- The dispersion values obtained from cloud regression for the *MIDR* are generally higher than those for *MRDR*. The latter is less sensitive, especially for 4-storey building, to the pulse-like ground motions with respect to the former. This is likely to be interpreted by the fact that *MRDR* reflects more the overall deformation of structures compared to *MIDR*.

- *Sa* is generally the most efficient *IM* among all for predicting *MRDR* and *MIDR*, since the structures considered in this study are significantly dominated by the first mode of vibration.
- For *MRDR* and *MIDR*, the non-structure-specific *IM*s, especially the velocity-related ones for predicting *MIDR*, are more influenced by the pulse-like GMs instead of ordinary GMs.
- The modified structure-specific *IM*s, specifically MI_H, are competitively efficient with respect to *Sa* for *MRDR* and *MIDR* and in the 6-story building. This is for the reason that this frame is more flexible and more influenced by higher modes of vibration compared to the 4-story building. Since these modified *IM*s are defined by integration of spectral values in certain range of period, they are capable of taking into account the effect of higher mode influence as well as lengthening of the period due to inelasticity.
- In predicting the *MFA*, both *PGA* and modified structure-specific *IM*s are more efficient than other considered *IM*s.
- Strictly speaking, the structure-specific *IM*s are more sufficient.

The lowest dispersion takes place for *Sa* in predicting *MRDR* using ordinary GMs, and the highest one happens for I_d in predicting *MIDR* by applying pulse-like GMs, where both cases are for the 4-story frame building. The associated cloud regressions are illustrated in Fig. 4 for both extreme cases.

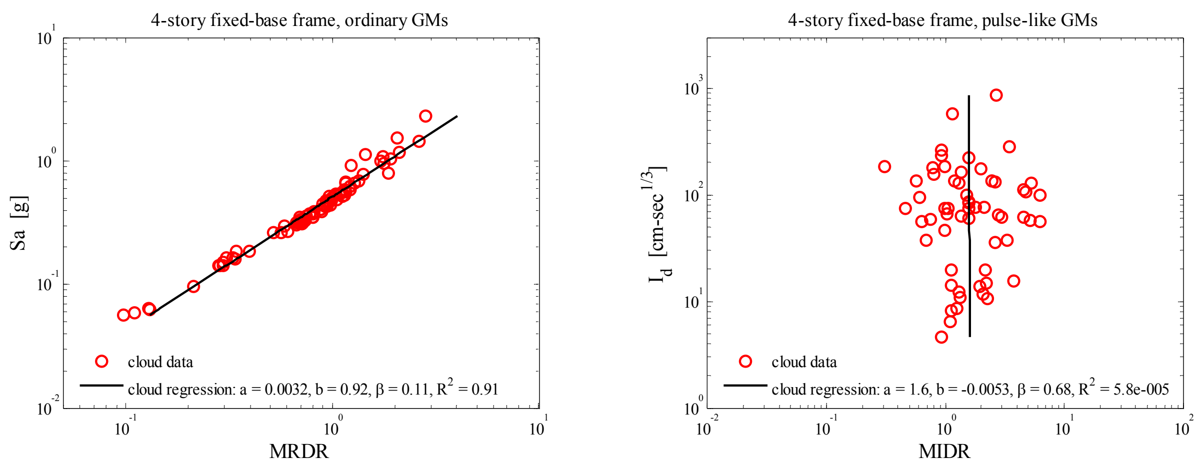

Figure 4. Cloud regression plots of the most efficient *IM* (left) and the least efficient one (right)

RESULTS IN TERMS OF SUFFICIENCY

The relative sufficiency measure in this section is calculated in an approximate manner as explained previously. Based on Eq.(5), the probability models for the structural response *D* given each candidate intensity measure is calculated based on the cloud analysis. Subsequently, the relative sufficiency measure is calculated in an approximate manner as the average of the logarithmic term on the right-hand side of Eq.(5) for the set of recorded ground motions.

The reference intensity IM_1 is taken to be *PGA*, and the relative sufficiency measure for the other *IM*s are calculated relative to *PGA*. The relative sufficiency measures are shown in Fig.5 for the given demand parameters. Those results reveal that how much bits of information, on average, the desired *IM* gives about the structural demand compared to *PGA*. The positive values show that on average the considered *IM* provides more information (i.e., is more sufficient) than *PGA* about the structural response; similarly, negative values (which are marked with a red star in the middle on the data point) provide on average less information (i.e., are less sufficient) than *PGA*. With respect to Fig.5, the following results can be attained:

- The results in terms of relative sufficiency measure are similar for both demand parameters *MRDR* and *MIDR*.

- In general, *Sa* and to lower degree the MI_H are the most sufficient *IM*s among the candidate ones for predicting the demand parameters *MRDR* and *MIDR*. Moreover, structure-specified *IM*s, especially the modified integral ones, are more sufficient compared to the non-structure-specified *IM*s.
- There is no apparent difference between the influence of ordinary and pulse-like GMs to the sufficiency of *IM*s corresponding to *MRDR* and *MIDR*, especially in case of the structure-specified *IM*s. Nevertheless, the velocity-dependent *IM*s appear to be more sufficient compared to other non-structure-specific *IM*s, in case of ordinary GMs.
- For the prediction of MFA, the modified integral IMs are more sufficient than PGA in case of ordinary GMs. However, for pulse-like GMs, PGA seems to be the most sufficient one.

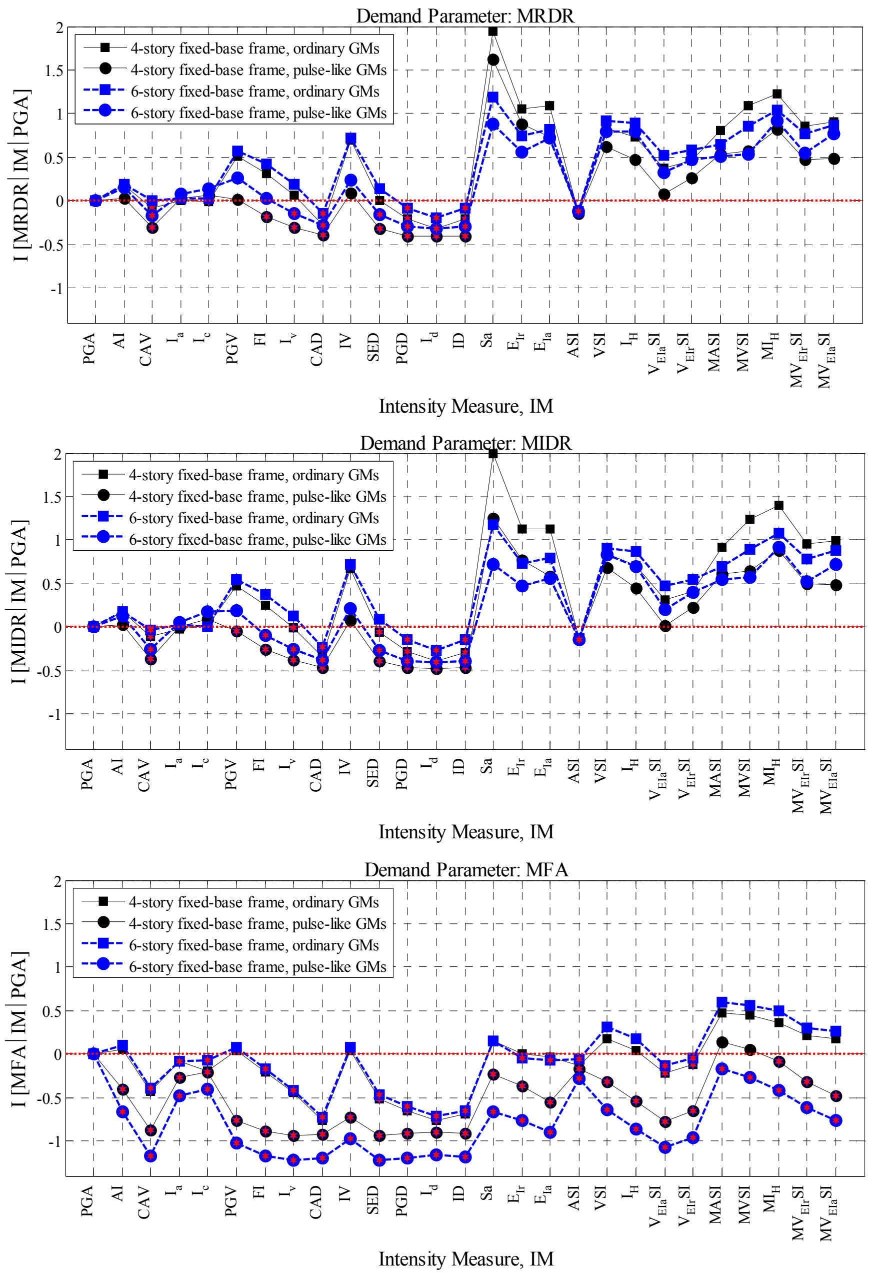

Figure 5. The relative sufficiency measures for alternative *IM*s with respect to *PGA* for the demand parameters *MRDR*, *MIDR* and *MFA* corresponding to both buildings, considering ordinary and pulse-like ground motions

CONCLUSIONS

The capability of a wide range of intensity measures (*IM*s) in predicting the structural response of building structures are investigated in terms of efficiency and sufficiency. In this work, cloud analysis is employed by using a suite of ground motion records in order to construct a lognormal probability distribution for describing the demand parameter that is conditional on the adopted *IM*. The estimated dispersion serves as a quantitative measure for predictive efficiency of the candidate *IM*. Moreover, an approximate version of the information-based measure of the relative sufficiency of alternative *IM*s, derived earlier by Jalayer et al. (2012) is adopted. This relative sufficiency measure quantifies the amount of information gained (on average) about a designated structural response parameter by adopting one *IM* instead of another.

The case-study buildings are two typical 4-story and 6-story existing RC moment-resisting frames in the Mediterranean area. The considered demand parameters are Maximum Roof Drift Ratio (*MRDR*), Maximum Inter-story Drift Ratio (*MIDR*), and Maximum Floor Acceleration (MFA). Furthermore, the candidate *IM*s are those adopted by Mollaioli et al. (2013), which are categorized as structure-dependent and structure-independent *IM*s. The former subset is furnished also by (proposed) modified versions of existing *IM*s, with the intent of improving the correlations with response quantities. The investigations are made for both ordinary and pulse-like near-fault ground motion records.

In terms of efficiency assessment, it is revealed that spectral acceleration at the first-mode period, denoted as *Sa*, is the most efficient *IM* for predicting *MRDR* and *MIDR*. On the other hand, the modified Housner *IM*, i.e. MI_H, presents competitive efficiency. For predicting *MFA*, *PGA* and modified structure-specific *IM*s, which account for higher mode of vibration and the inelasticity of structures, seem to be proper predictors. In addition, the proposed modified *IM*s are generally more efficient than the corresponding spectrum intensity.

In terms of relative sufficiency measure, *Sa* and to a lower degree MI_H are the most sufficient *IM*s among the candidate ones for predicting the demand parameters *MRDR* and *MIDR*. In addition, there is no apparent difference between the ordinary and pulse-like GMs in predicting *MRDR* and *MIDR*, especially in case of the structure-specified *IM*s. Furthermore, for predicting *MFA*, the modified integral IMs are more sufficient than PGA in case of ordinary GMs. However, for pulse-like GMs, *PGA* seems to be the most sufficient *IM*.

It should be finally highlighted that the resulting relative sufficiency values are conditioned on the choice of the probability model for describing $D|IM$. Moreover, the approximate formula presented in Eq. (5) is based on the assumption that various plausible ground motions are equally likely to take place.

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