Estimation of fragilities by the modified intensity measures (IMs)

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Abstract. Fragility curves are commonly computed to estimate structural system performance. Seismic fragilities are the probability that the structural response of a system overcomes prefixed limit states for given seismic intensity measure. The most widespread procedure to estimate seismic fragility curves is based on scaling seismic accelerograms by a reference intensity measure (e.g. single/multiple ordinates of the pseudo-acceleration response spectrum or peak ground acceleration). Recently, it was shown that this methodology gives limited if any information on the structural seismic performance when the dependence between the intensity measure and the system demand parameter of interest (e.g. max inter-story displacement) is weak. However, the widespread method is currently applied in Performance-Based Earthquake Engineering because it is simple and it overcomes the problem of the limited number of natural recorded ground motions available for fragility analysis.

In this work a general approach to improve the accuracy in fragilities estimation when the dependence between the intensity measure and the demand parameter is weak and the widely used method does not give accurate results is presented. The proposed algorithm is based on a linear transformation of samples of a given intensity measure, which improves the correlation with a set of demand parameters. Fragility curves are obtained using the transformed intensity measure samples and compared with those estimated with the standard approach. The effectiveness of the proposed algorithm is demonstrated for a linear elementary oscillator and complex multi-degree of freedom structural system.

Keywords: Seismic intensity measures, Modified seismic intensity measures, Fragility analysis, Fragility cureves, Earthquake engineering, Complex mdof structural systems.

1. Introduction

In Performance-Based Earthquake Engineering (PBEE) the evaluation of structural efficiency by fragility analysis is formalized through a methodology with a probabilistic basis. The greatest interest for structural engineering is focused to two parameters in PBEE, that are the seismic intensity measure IM and the system demand parameter D, which reflect the seismic hazard and the structural response, respectively. These parameters are used to develop the fragility analysis and

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therefore build the fragility curve. Seismic fragilities quantify the probability that the structural response of a system overcomes specified limit states for given seismic intensity measure (IM). The intensity measure is an intermediate variable that connects the seismic fragility analysis with the structural analysis, and the demand parameter depends intensely on the chosen IM. Specific features are required of an ideal IM, it should be efficient and sufficient. The efficiency is inherent to the low dispersion that should be characterize the demand parameters and IM, while the sufficiency implies that D evaluated by a seismic ground motion acceleration with a IM value should be only dependent on the value of this IM, and not on other seismic ground motion features (i.e. fault mechanisms, magnitude, etc).

The common method used in PBEE to estimate the seismic fragility curves, recommended by Federal Emergency Management Agency (FEMA), is based on scaling the seismic accelerograms with a reference intensity measure IM (FEMA, 2012). This method is widely applied because it is simple and, together with Monte Carlo simulation, it overcomes the problem of the limited number of natural recorded ground motions available for fragility analysis. Generally, two groups of IMs are considered to define the seismic fragilities in fragility analysis: (i) functional of samples of seismic ground acceleration process $A(t)$, such as peak ground acceleration (PGA); (ii) functional of filtered version of samples of $A(t)$, e.g. single/multiple ordinates of pseudo-acceleration response spectrum $S_a(T)$ for different structural system periods T (O'connor and Ellingwood, 1992; Lopez Garcia and Soong, 2003; Sevieri et al., 2020). In particular, the IMs in the second group, that are widely used to define the fragilities, depend on the system demand parameter D (e.g. max inter-story displacement) on which the analysis is based (Kwong et al., 2014; Ebrahimian et al., 2015; Kwong et al., 2015a; Kwong et al., 2015b).

Recently, it was shown that the method in (FEMA, 2012) gives limited if any information on the structural seismic performance when the dependence between the IM and D is weak (Grigoriu, 2016). When the two variables (i.e. IM and D) are not correlated it is a clear violation of the efficiency condition that the IM must possess. The dependence between these variables plays a fundamental role on the accuracy in fragility analysis (Ciano et al., 2018a; Ciano et al., 2020a). In particular, this dependence depends on the seismic direction, the intensity measure and the demand parameter considered. For the same IM the dependence can vary significantly with different seismic directions, with which the fragility analysis is developed. The fragilities defined as function of $S_a(T)$ for nonlinear single degree of freedom (SDOF) system to a seismic acceleration process $A(t)$ have large uncertainties when D and $S_a(T)$ are weakly correlated. Furthermore, the fragilities defined as function of multiple ordinates of $S_a(T)$ have poor improvements in reference to the case of single ordinate of $S_a(T)$. It was demonstrated that the dependence between IMs and various system demand parameters, D, is weak for nonlinear system and also for complex multi-degree of freedom (MDOF) linear structures (Grigoriu, 2016; Ciano et al., 2018a; Ciano et al., 2020a). The method in (FEMA, 2012) based on scaled seismic ground motion acceleration is very useful, this is not questioned, but it needs the use of efficient IM to give accurate results. The dependence problem can be solved by defining the fragilities as functions of the parameters of the law of $A(t)$. This approach was introduced in (Kafali and Grigoriu, 2007) and used in (Radu, 2017; Radu and Grigoriu, 2018; Ciano et al., 2019) to estimate fragility surfaces. However, these surfaces require a high computational cost, and they are dependent on moment magnitude and source to site distance.

This paper presents a general approach to improve the accuracy in fragilities estimation when the dependence between the intensity measure IM and the demand parameter D is weak and the widely used method in Performance-Based Earthquake Engineering (FEMA, 2012) does not give accurate results. This general approach is based on a modified version of the current intensity measure method. In particular, once an IM is chosen it is mapped in a suitable space where D and the IM are correlated. The proposed algorithm is based on a linear transformation of samples of a given IM, which improves the correlation with a set of demand parameters. Fragility curves are obtained using the transformed IM samples and compared with those estimated with the standard approach. Numerical results are reported for a simple linear SDOF system and for a real multi-degree of freedom structural system.

Finally, the effectiveness of this general approach is demonstrated for both linear SDOF and real complex MDOF system by comparing the fragility estimates obtained with a chosen seismic intensity measure and the its modified version.

2. Background

Let I be the set of demand parameters which yield a structural failure. The fragility can be defined as

$$P_f(\xi) = P(D \in I \subset \mathbb{R} | IM = \xi) = E[1(D \in I | IM = \xi)] = \int_I f_{D|IM}(x|\xi)\, dx \tag{1}$$

i.e. the probability that a structural system enters a damage state given a ground motion with scalar/vector intensity measure $IM = \xi$. The quantities $1(\cdot)$ and $f_{D|IM}(\cdot|\xi)$ indicate the indicator function and probability density function (PDF) of the conditional variable $D|(IM = \xi)$, respectively. The fragility in (1) is usually estimated from the structural response to scaled seismic time histories, $a(t)$ of the stochastic process $A(t)$ (Baker, 2010), and its accuracy depends on the scaling procedure, the sample size and the IMs properties.

When D and IM are strongly dependent, the random variable $D|IM$ has small variance, i.e. $f_{D|IM}(\cdot|\xi)$ is concentrated about its mean value. On the contrary, when D and IM are weakly dependent the random variable $D|IM$ has large variance. In the limit, $f_{D|IM}(\cdot|\xi)$ becomes a δ-function or D and $D|IM$ have the same PDF when D and $D|IM$ are perfectly correlated or independent, respectively (Grigoriu, 2016). In the latter case, the fragility in (1) does not depend on ξ. Within this context, especially if (1) is estimated by the commonly used method (FEMA, 2012), it is crucial to quantify the dependence between the demand parameter D and various IM definitions to implicitly determine whether or not fragilities, defined as function of the commonly used IMs, can provide useful information for PBEE of actual complex MDOF linear and nonlinear structural systems. If the dependence between D and IM is strong, the fragility $P_f(\xi)$ gives accurate information (Ciano et al., 2018a; Ciano et al., 2020a). The opposite holds when the dependence between D and IM is weak. It is worth noting that, the efficiency condition which the IM must respect is a consequence of the correlation between D and IM. The violation of this condition is determined when D has a large dispersion for given IM, i.e. D and IM are independent. Several statistical tools can be used to investigate the dependence between the random variables D and IM, which includes correlation coefficients, copula models and multivariate extreme value theory (Grigoriu, 2016). In this work the correlation coefficient is used to quantify the dependence between D and IM.

2.1. Intensity measure (IM)

The IMs used in PBEE to scale seismic acceleration ground motion are divided into three broad categories:

1. non-structures-specific scalar IMs;
2. structures-specific scalar IMs;
3. vector-valued IMs.

A complete classification of the most known IMs in literature is reported in (Ebrahimian et al., 2015). In this work, two most common scalar version of IMs are considered to estimate the fragilities

$$IM_1 = PGA \tag{2}$$

$$IM_2 = S_a(T_1, \zeta_1) \tag{3}$$

where T_1 is the first period of the MDOF structural system with associated damping ratios ζ_1. The period T_1 is taken to in account since it is the fundamental one of the structure as is customary in literature (Ebrahimian et al., 2015).

2.2. Fragilities estimation

The seismic fragility analysis, as also recommended by FEMA, is commonly based on a four-steps algorithm consisting of scaling seismic accelerograms by a reference IM:

1. selection of a finite set of intensity measures $\{\xi_k\}$, $k = 1, \ldots, N$;
2. generation of n_s independent samples $a_i(t)$, $i = 1, \ldots, n_s$ of $A(t)$;
3. for each of the values $\{\xi_k\}$ scale the n_s acceleration records, $a_i(t)$, in order to have the intensity level $IM = \xi_k$, $\xi_k > 0$;
4. for each of the values $\{\xi_k\}$ estimate fragility as

$$\hat{P}_f(\xi_k) = \sum_{i=1}^{n_s} 1(d_{k,i} \in I)/n_s \tag{4}$$

where $1(\cdot)$ is the indicator function and $d_{k,i}$, $i = 1, \ldots, n_s$, are samples of the demand parameters computed for each intensity level ξ_k by linear/nonlinear dynamic analysis. The previous four-steps algorithm are used to construction fragility curves in reference to the generic intensity measures, e.g. the Equations (2)-(3). The probability estimation that maximum system response exceeds a critical limit state in Equation (4) is common applied (O'connor and Ellingwood, 1992; Hwang and Huo, 1994; Song and Ellingwood, 1999; Schotanus et al., 2004).

3. Modified intensity measure (IM^*)

Let $X(t)$ be the response vector-valued process of an arbitrary MDOF structural system to the ground acceleration $A(t)$. The demand parameter is defined as

$$D^{(j)} = \max_{0 \leq t \leq \tau} |h(X(t))| \,, \quad j = 1, \ldots, m \tag{5}$$

where τ is the time length of $A(t)$, while $h(\cdot)$ is a function mapping the response $X(t)$ into the j-th system demand parameter (e.g. maximum displacement/acceleration) and m is the number of demand parameters of interest. The dependence between the random variables $D^{(j)}$, $j = 1, \ldots, m$, and IM is a measure to quantify the accuracy in the estimation of $P_f(\xi)$ (Ciano et al., 2020a). When this dependence is weak the widely used method in PBEE (FEMA, 2012) does not give accurate results. To overcome this issue it is proposed to replace samples of a chosen standard intensity measure IM with a suitable linear transformation that modifies the dependence with the selected demand parameters samples. In particular, for each n_s samples, $a_i(t)$, $i = 1, \ldots, n_s$, of the random process $A(t)$ the corresponding samples of IM and $D^{(j)}$ are evaluated, i.e. im_i and $d_i^{(j)}$, $i = 1, \ldots, n_s$. For each of these samples, the z-scores $z(d_i^{(j)})$ and $z(im_i)$, $i = 1, \ldots, n_s$, of the standardized random variables

$$z(D^{(j)}) = \frac{D^{(j)} - E[D^{(j)}]}{\sigma(D^{(j)})} \,, \quad j = 1, \ldots, m \tag{6}$$

$$z(IM) = \frac{IM - E[IM]}{\sigma(IM)} \tag{7}$$

are computed, respectively. It is worth noting that if the random variables defined in Equations (6) and (7) are linearly dependent, the correlation coefficient is equal to one and the scatter plots of pairs of samples $z(d_i^{(j)})$ and $z(im_i)$ describe straight line. Given the demand parameter $D^{(j)}$, for each pair of samples $z(d_i^{(j)})$ and $z(im_i)$ it is possible to evaluate the distance from perfect correlation

$$e_i^{(j)} = z(d_i^{(j)}) - z(im_i) \,, \quad i = 1, \ldots, n_s, \quad j = 1, \ldots, m \tag{8}$$

and estimate the average distance of the j demand parameters

$$\bar{e}_i = \frac{1}{m} \sum_{j=1}^{m} e_i^{(j)} \,, \quad i = 1, \ldots, n_s \,. \tag{9}$$

The samples obtained with Equation (9) can be considered as realizations of a vector $\bar{E}$. The linear transformation

$$im_i^* = [z(im_i) + \bar{e}_i]\sigma(IM) + E[IM] \,, \quad i = 1, \ldots, n_s \tag{10}$$

gives samples that can be considered the realizations of a new intensity measure IM^*.

The procedure reported above describes a general algorithm that can be used to transform any intensity measure IM (e.g. Equations (2) and (3)) into samples of its modified version, IM^*. It is worth noting that for $m = 1$ (i.e. one demand parameter or SDOF system), the correlation estimated from the n_s samples of D and IM^* is exactly one. When $m > 1$ it is not possible to have perfect correlation, but the correlation between $D^{(j)}$ and IM^* is significantly higher than the one estimated from samples of $D^{(j)}$ and IM.

It follows that the IM^* samples obtained with Equation (10) can be used to scale the ground acceleration records to build fragility curves that give more accurate information on the structural system performance when compared with the standard intensity measures.

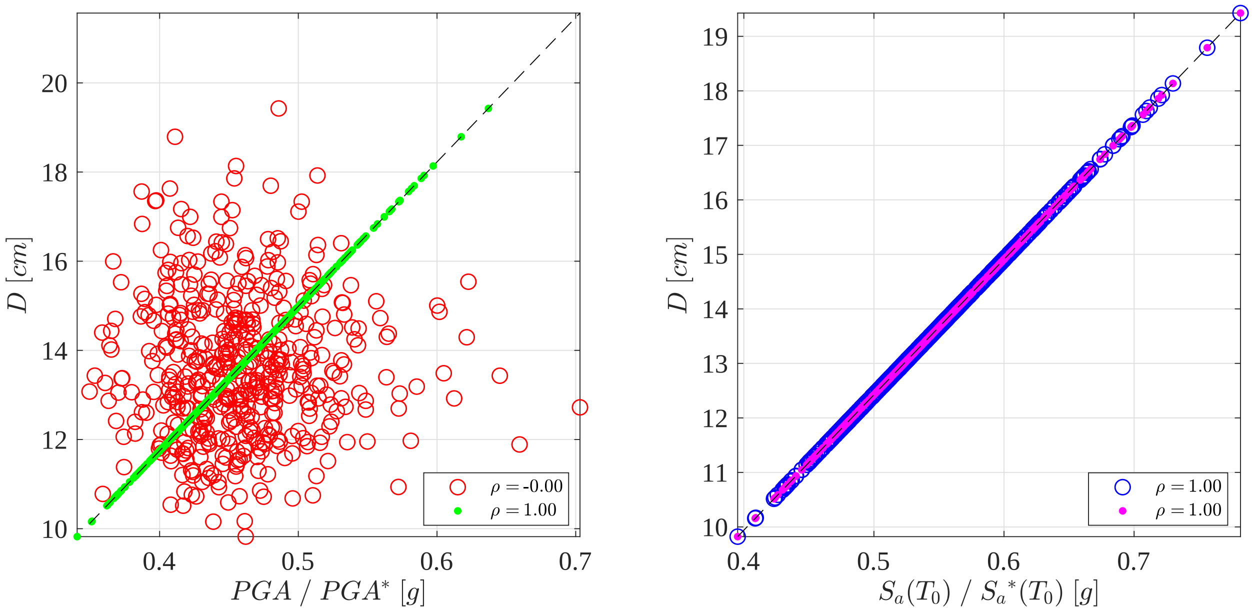

Figure 1. Scatter plots of $n_s = 500$ samples for linear SDOF system with $\omega_0 = 6.28$ rad/sec and $\zeta = 5\%$: (PGA, D) red circles, (PGA^*, D) green dots (left panel); ($S_a(T_0)$, D) blue circles, (${S_a}^*(T_0)$, D) magenta dots (right panel).

4. Single degree of freedom application

In this Section the results of linear SDOF system about fragility estimation are reported. The Monte Carlo simulation four-steps algorithm in Section 2.2 is used. To aim this, two different intensity measures IM_l, $l = 1, 2$, i.e. Equations (2)-(3), and their modified version are considered. In this context, the first period T_1 and ζ_1 in (3) coincides with the natural period T_0 and the damping ration ζ of SDOF system. The approach proposed in (Cacciola, 2010) is used for the generation of

n_s independent samples of $A(t)$ as spectra-compatible stochastic process.

Let $X(t)$ be the response process of SDOF oscillator under the spectra-compatible stochastic process $A(t)$ that satisfies the differential equation

$$\ddot{X}(t) + 2\zeta\omega_0\dot{X}(t) + {\omega_0}^2 X(t) = -A(t) \tag{11}$$

where $\omega_0 = 2\pi/T_0$ is the natural pulsation in rad/sec. The numerical solution of Equation (11) are developed for $\omega_0 = 6.28$ rad/sec, $\zeta = 5\%$ to compute the demand parameter $D = D^{(1)}$, $m = 1$, as the maximum absolute relative displacement, by Equation (5).

Figure 1 shows the scatter plot of $n_s = 500$ samples of D against the intensity measures PGA and $S_a(T_0)$, in red and blue circles, in left and right panel, respectively, together with the estimated correlation coefficient ρ. These two results for linear SDOF system, as reported in literature (Kafali and Grigoriu, 2007), demonstrated that the PGA and $S_a(T_0)$ are unsatisfactory and satisfactory intensity measure since ρ estimated in relation to D is zero and one, respectively. Moreover, the PGA is a inefficient IM because it determines a high dispersion on D, as opposed to $S_a(T_0)$.

Samples of the modified intensity measure PGA^* and ${S_a}^*(T_0)$ are evaluated to improve the dependence with the demand parameter. First, the n_s samples of the D and IM_l, $l = 1, 2$, are standardized using Equations (6) and (7) and the distance from the perfect correlation is evaluated by Equation (8) with $m = 1$. Second, the n_s average distances are evaluated using Equation (9).

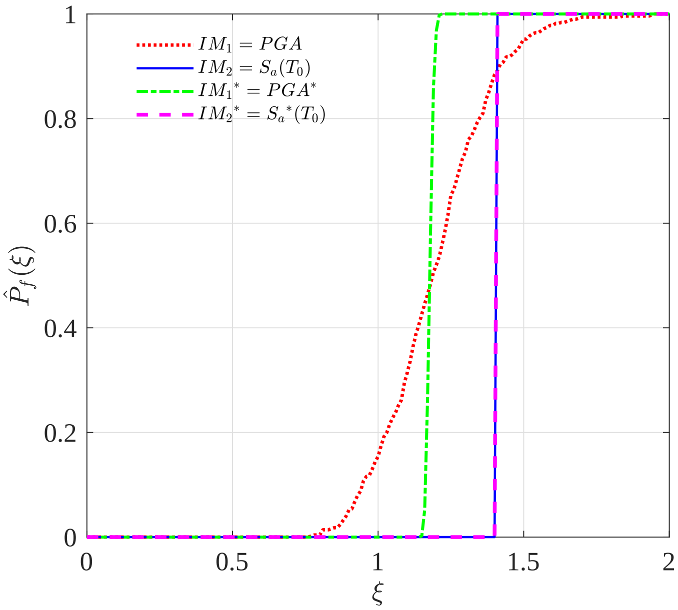

Figure 2. Fragilities against intensity level ξ considering different definitions of IMs and its modified version IMs^* for linear SDOF system with $\omega_0 = 6.28$ rad/sec, $\zeta = 5\%$ and limit state $\bar{D} = 35$ cm.

Finally, the samples of the modified intensity measure version IM_l^*, $l = 1, 2$, are computed by Equation (10). In particular, since $m = 1$ (SDOF system) the correlation between D and IM^* is exactly one and the samples computed using the Equation (9) coincide with the those by Equation (8). Continuing the reference to the Figure 1, in green and magenta dots the scatter plots of (PGA^*, D) and ($S_a{}^*(T_0)$, D) are shown on the left and right panel. Clearly, since D for the SDOF system is also equal to $S_a(T_0)/\omega_0{}^2$ the random variables $S_a(T_0)$ and $S_a{}^*(T_0)$, i.e. the results in blue circles and magenta dots, coincide.

Figure 2 reports fragility curves estimated by four-steps algorithm (Section 2.2) using the intensity measure definitions IM_l, $l = 1, 2$, and their modified version IM_l^*, $l = 1, 2$, for the system demand parameter D assuming limit state $\bar{D} = 35$ cm. In particular, the dotted red line regards to the PGA and it has poor information on the linear SDOF system performance since D and IM_1 are uncorrelated (left panel of Figure 1), while the best information are provided when ρ is unitary in order to the curve by PGA^*, dot dash green line, that becomes a $\delta-$function (see Section 2). This last aspect is also valid for the curves computed with $S_a(T_0)$ and $S_a{}^*(T_0)$, and them being equal (right panel of Figure 1) the continuous blue and dashed magenta lines coincide.

5. Complex multi-degree of freedom application

The procedure described in Section 2.2 is used to build fragility curves of a structural system of a school in Norcia (Italy) that was affected by the 2016 earthquake sequence. The fragility analysis is developed with standard intensity measures IM_l, $l = 1, 2$, (Equations (2) and (3)) and their

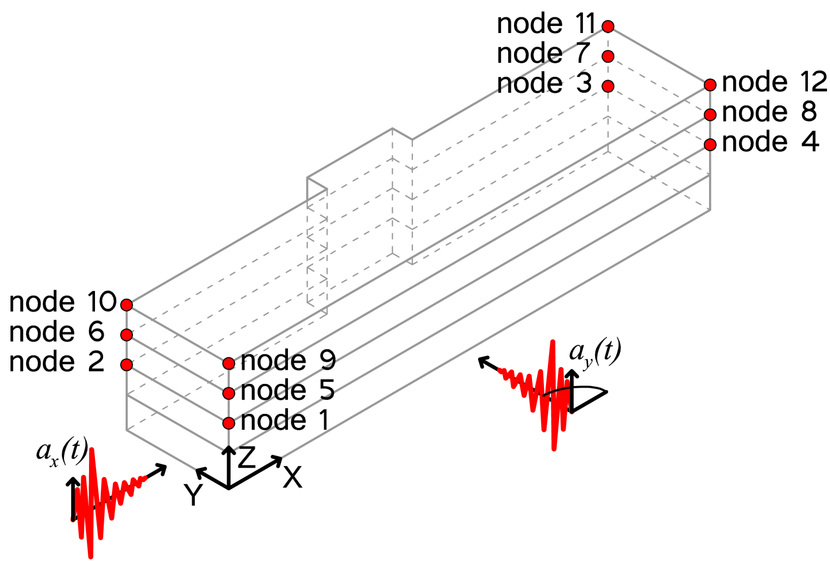

Figure 3. Seismic directions used in the analyses and reference node locations.

modified version that are computed with the proposed procedure in Section 3.

The structural system of the school building consists of a reinforced concrete frame (RCF) on four floors with a dissipative bracing system, made of Buckling-Restrained Axial Dampers (BRADs), and inverse beams foundation. The RCF and foundation are modeled with classical beam elements, while the BRAD elements are modeled with the constitutive law described in (Wen, 1976). The obtained numerical model details on the school building and the model modal parameters are reported in (Ciano et al., 2018a).

Linear analyses are performed to evaluate the structural response. In this work the maximum absolute displacement in the y-direction D_{dy} (Fig. 3) is considered as demand parameter in the fragility analysis.

The strong event recorded in Norcia on October 30th, 2016 is used to calibrate the non-stationary stochastic process $\boldsymbol{A}(t)$. Structural analyses are developed for each samples of the process $\boldsymbol{A}(t) = \{A_x(t); A_y(t)\}$, i.e. $\boldsymbol{A}(t)$ is a stochastic process with independent components, that acts in x and y global-directions of the finite element numerical model (FEM) (Figure 3). The non-stationary model described in (Grigoriu et al., 1988; Ciano et al., 2018b; Ciano et al., 2020b) is used to generate samples $a_x(t)$ and $a_y(t)$ of $A_x(t)$ and $A_y(t)$, respectively. The probabilistic model used for $\boldsymbol{A}(t)$ is

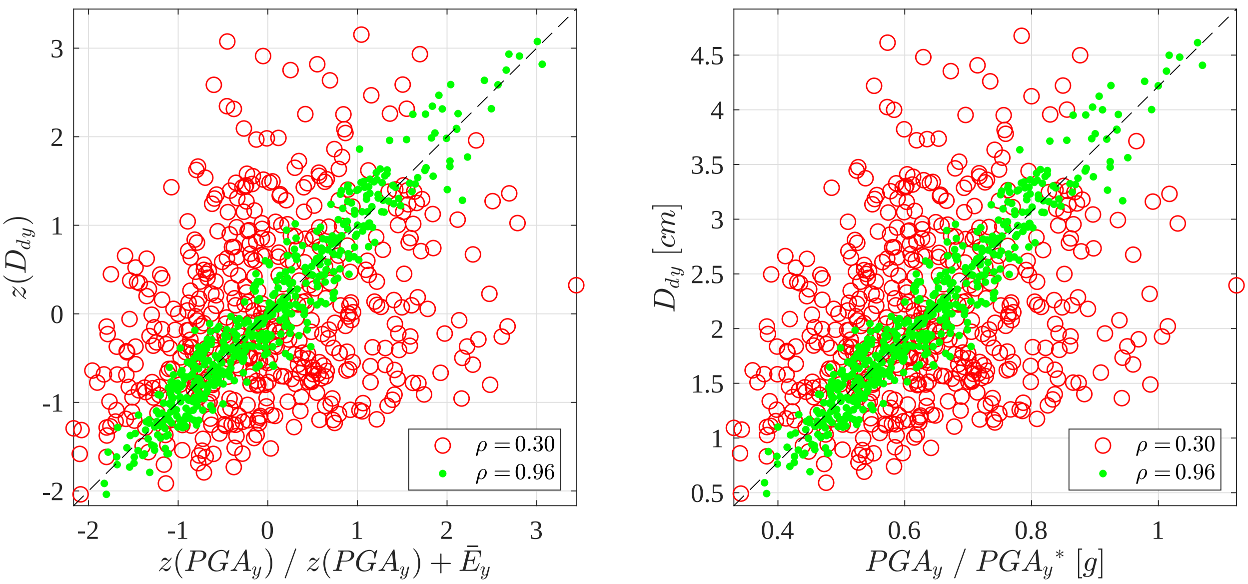

Figure 4. Scatter plots of $n_s = 500$ samples at node #10: $(z(PGA_y),\, z(D_{dy}))$ red circles, $(z(PGA_y) + \bar{E}_y,\, z(D_{dy}))$ green dots (left panel); $(PGA_y,\, D_{dy})$ red circles, $(PGA_y{}^*,\, D_{dy})$ green dots (right panel).

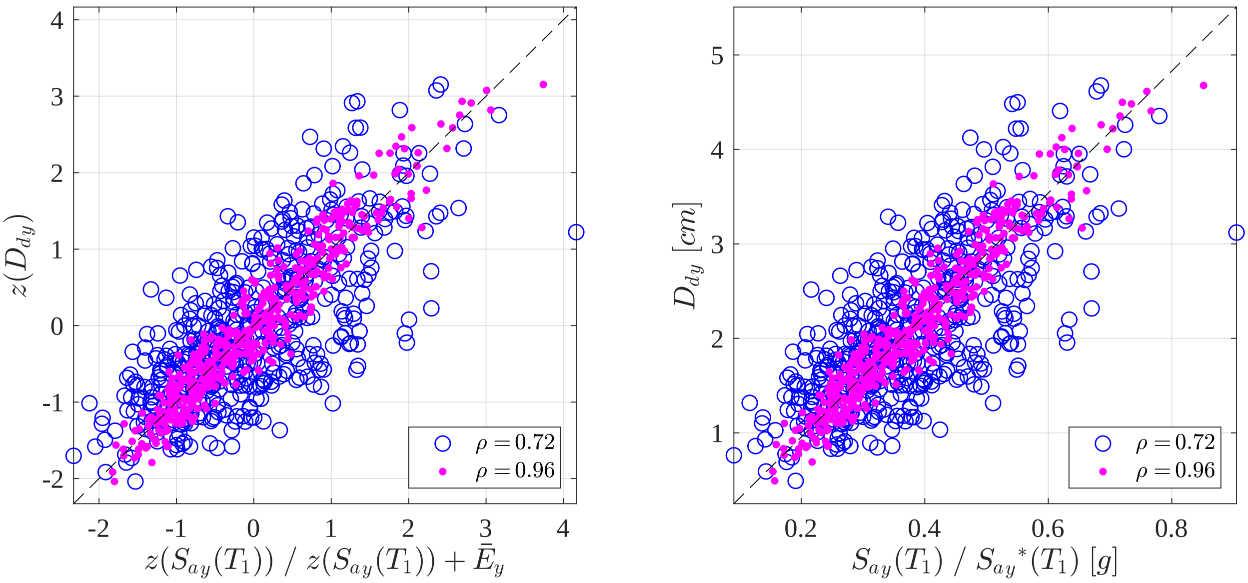

Figure 5. Scatter plots of $n_s = 500$ samples at node #10: $(z(S_{ay}(T_1)), z(D_{dy}))$ blue circles, $(z(S_{ay}(T_1))+\bar{E}_y, z(D_{dy}))$ magenta dots (left panel); $(S_{ay}(T_1), D_{dy})$ blue circles, $(S_{ay}{}^*(T_1), D_{dy})$ magenta dots (right panel).

calibrated with actual time histories recorded at the school base during the October 30th, 2016 earthquake.

The demand parameter D_{dy} is obtained by a three-step Monte Carlo algorithm: (i) n_s ground motion acceleration time series $a_n(t)$ of the process $A_n(t)$, $n = x, y$, are generated using the method proposed in (Grigoriu et al., 1988); (ii) linear time domain numerical dynamic structural analyses are used to obtain response samples $\boldsymbol{x}(t)$ of $\boldsymbol{X}(t)$ assuming proportional damping ratio $\zeta = 5\%$; (iii) n_s samples of the random vector $D_{dy} = \{D_y^{(1)}, D_y^{(2)}, \ldots, D_y^{(m)}\}$ are computed using Equation (5). In this case study the maximum absolute displacement in y-direction at the $m = 12$ node positions shown in Figure 3 are selected as demand parameters.

The dependence between the random variables $D_y^{(j)}$, the two IMs in Equations (2) and (3) and their modified version are investigated. In particular, the results regards the max absolute displacement in y-direction $D_{dy} = D_y^{(j)}$, $j = 10$, (Fig. 3), and the two intensity measures IM_{ly}, $l = 1, 2$, estimated from samples of $A_y(t)$ are shown in Figures 4 and 5, respectively, together with the estimated correlation coefficient ρ. These results are computed for $n_s = 500$ samples. The results presented in the right panel of Figure 4 (red circles) demonstrate that the peak ground acceleration in the y-direction, $PGA_y = IM_{1y}$, represents an unsatisfactory intensity measure given the low value of the correlation coefficient, $\rho = 0.30$, between D_{dy} and IM_{1y}. The fragility estimated using this IM would provide poor information on the seismic structural performance. Referring to right panel of Figure 5 (see blue circles), the same holds for $IM_{2y} = S_{ay}(T_1)$ since the conditional random

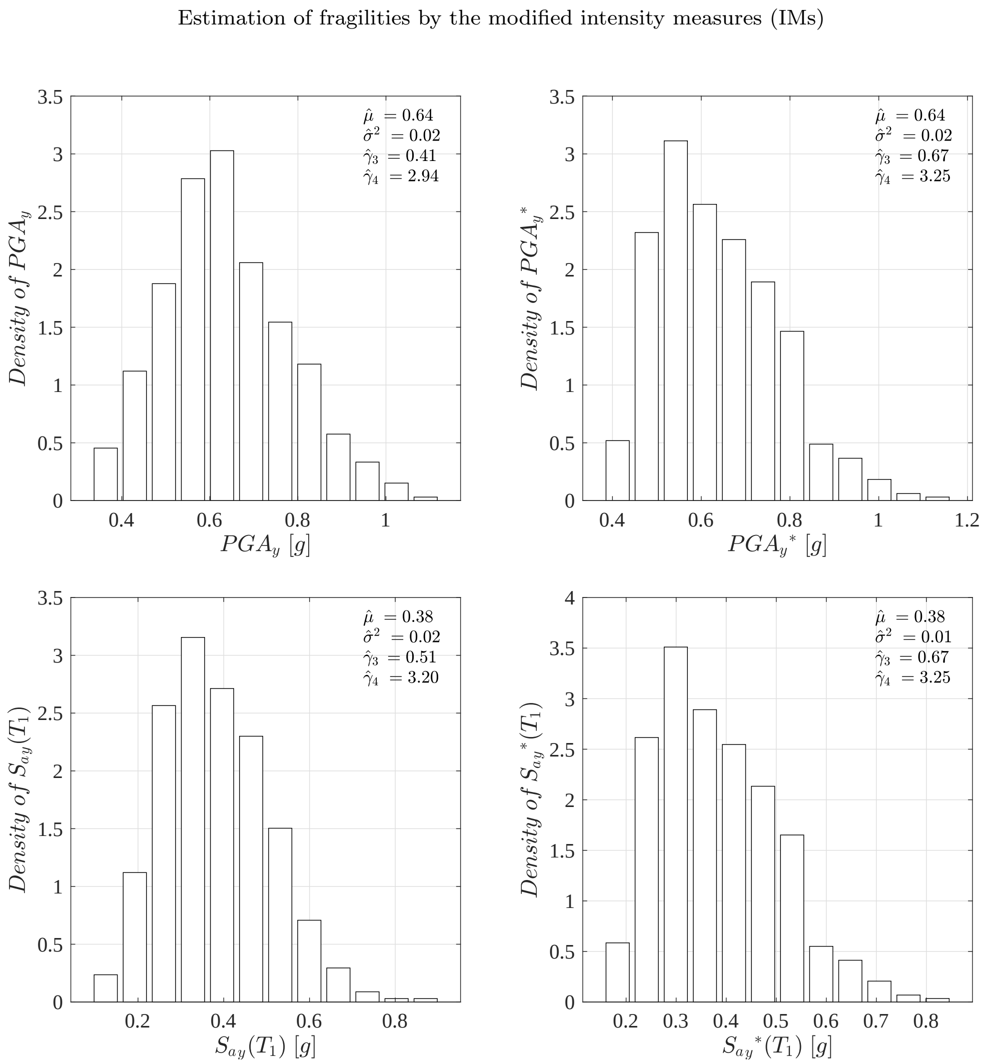

Figure 6. Estimated PDF for $n_s = 500$ samples of PGA (left top panel), PGA^* (right top panel), $S_a(T_1)$ (left bottom panel) and $S_a{}^*(T_1)$ (right bottom panel).

variable $D_{dy}|IM_{2y}$ has large variance (i.e. D_{dy} and IM_{2y} are low correlated). In general, when using the intensity measure in Equation (3), it was demonstrated that IM_{2n}, $n = x, y$, can be both strongly and weakly correlated with the demand parameter depending on the selected structural response of interest and the earthquake direction (Ciano et al., 2020a).

The initial correlation between the chosen m demand parameters and the IMs described above can be improved using the procedure presented in Section 3. Samples of the demand parameters and the two intensity measures in Figures 4-5 are first transformed into their standardized versions using Equations (6) and (7) and the distance from perfect correlation is evaluated by Equation (8) for each of the m demand parameters. Then, the n_s average distances are evaluated using Equation

(9) and used to correct the samples of $z(IM_{ly})$, $l = 1, 2$. The last step is to evaluate samples of the modified intensity measure IM^* using Equation (10). In particular, the left panels of Figures 4 and 5 report the scatter plots and the correlation coefficients before and after the correction in the standardized space, i.e. $(z(IM_{ly}), z(D_{dy}))$, and $(z(IM_{ly}) + \bar{E}_y, z(D_{dy}))$, $l = 1, 2$, respectively. The right panels report the scatter plots of the same samples (before and after the correction) linearly transformed back into their original space by Equation (10), i.e. (IM_{ly}, D_{dy}), and $({IM_{ly}}^*, z(D_{dy}))$, $l = 1, 2$, respectively. In these figures the scatter plots with $IM_{1y} = PGA_y$ are red circles and green dots, before and after the correction, respectively, while those with $IM_{2y} = S_{ay}(T_1)$ are blue circles (before) and magenta dots (after).

The two figures demonstrate the ability of the proposed algorithm to improve the correlation between the selected demand parameters and intensity measures for the MDOF system case. This will result into an improved accuracy in the fragility curves.

Is interesting to note that the linear transformation of the intensity measure samples obtained in this case study does not significantly change the intensity measures first four statistical moments. Figure 6 shows the probability density functions (PDFs) and the first four statistical moments estimated from samples of the original intensity measures IM_{ly}, $l = 1, 2$ (left panels) and their modified versions ${IM_{ly}}^*$ (right panels). In particular, the top panels show the results for $IM_{1y} = PGA_y$, while the bottom panels refer to $IM_{2y} = S_{ay}(T_1)$.

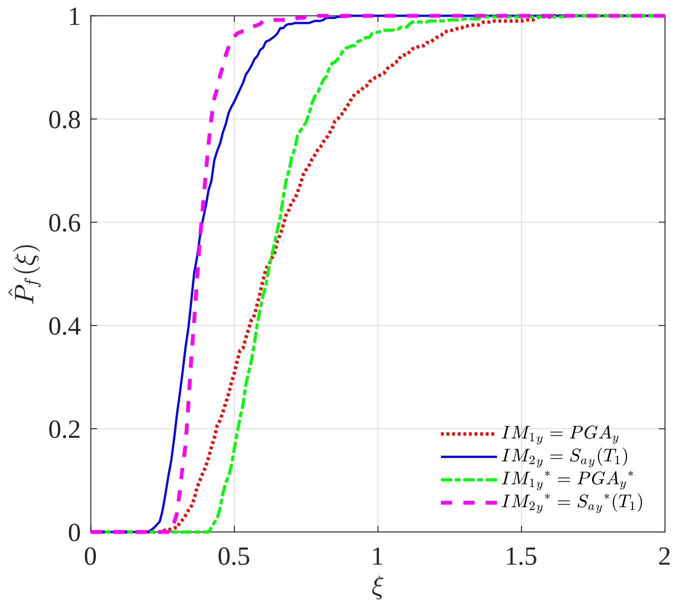

Figure 7. Fragilities against intensity level ξ for different definitions of IMs and its modified version IMs^* at node #10, maximum absolute displacement D_{dy} for limit state $\bar{D}_{d_y} = 2$ cm.

Figure 7 reports the obtained fragility curves of the demand parameter D_{dy} at node #10 for limit state $\bar{D}_{d_y} = 2$ cm. It is worth noting that the fragility curves obtained with the modified intensity measures (dash-dotted green and dashed magenta lines) are steeper than those estimated using the original intensity measures (dotted red and continuous blue lines). This is consistent with the lower variability (i.e. lower variance) of the conditional random variable $D|IM^*$. In general, for a prefixed value of ξ the fragility curves obtained with IM and the respective IM^* provide conflicting information on the structural seismic performance (Fig. 7).

6. Conclusion

In Performance-Based Earthquake Engineering the seismic fragilities are commonly estimated by widespread approach based on scaling the seismic accelerograms with a reference intensity measure (IM). The ideal intensity measure should be efficient and sufficient, this means that IM should determine a low dispersion in the structural system demand parameter D and enclose information, without dependence on other variables, for the evaluation of D, respectively. As a consequence, the application of widespread method requires a strong dependence between the demand parameter D of the structural system, on which the fragility analysis is based, and the IM used for scaling in order to have accurate fragilities. The approach provides limited if any information on the seismic performance of the structural system for weak dependence between D and IM.

This work presents a general approach to improve the accuracy in fragilities estimation when the dependence between the intensity measure IM and the demand parameter D is weak and the widely used method in Performance-Based Earthquake Engineering does not give accurate results. The general approach is based on a modified version of the current intensity measure method. In particular, samples of any chosen intensity measure IM are linearly transformed in order to improve the correlation with a set of selected demand parameters. The new samples can be considered as realizations of a modified intensity measure IM^* and used to scale the ground acceleration records to build fragility curves that give more accurate information on the structural system performance when compared with the standard intensity measures.

The effectiveness of the proposed method in improving the fragility curves accuracy was demonstrated on linear single degree of freedom system and an actual multi-degree of freedom structural system of a school building in Norcia (central Italy). The results demonstrate the effectiveness of the modified seismic intensity measure in fragility analysis. Work is in progress to investigate the accuracy of fragilities based on modified intensity measures in nonlinear structural systems.

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