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Accounting for Structural Response Correlation in EDP-Based Scenario Seismic Risk Assessment

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ABSTRACT

Incorporating structure-to-structure dependence in regional seismic risk assessment remains a significant challenge, particularly in scenario-based analyses where damage and losses must be estimated simultaneously for large building portfolios. While previous studies have introduced correlation directly at the damage-state level, such approaches require multiple correlation models and additional assumptions to address inter- and intra-damage-state dependencies. This study presents an alternative framework in which correlation is introduced at the level of engineering demand parameters (EDPs), enabling a more direct and consistent treatment of structural dependence. Demand–intensity models are derived for a simulated building taxonomy using cloud analysis, explicitly accounting for both record-to-record and building-to-building variability. Collapse is treated separately through a taxonomy-level fragility function, while non-collapse damage states are assigned based on correlated EDP realisations. The proposed approach is applied to a scenario-based assessment of the 1999 Chi-Chi earthquake, considering a portfolio of reinforced concrete frame buildings. Several correlation models are examined, incorporating structural properties and spatial separation. Results demonstrate that neglecting response correlation leads to a substantial underestimation of the probability of widespread damage. When correlation is included, the likelihood of observing the damage patterns obtained from non-linear time history (NLTH) analyses increases by more than an order of magnitude. The findings highlight the importance of accounting for structural response correlation in regional seismic risk assessments and show that EDP-based formulations offer a practical and theoretically consistent framework for doing so.

Keywords: seismic risk, damage correlation, structural demand, loss exceedance

INTRODUCTION

One aspect of performing regional seismic risk assessments that remains a challenge is the incorporation of a structure-to-structure damage correlation into the analysis, as mentioned by Heresi and Miranda (2023) in their formalisation of the regional performance-based earthquake engineering (RPBEE) framework. This correlation incorporates into the framework the expected statistical dependence on the response of different structures during an event, due to common strengths or deficiencies that structures might have for being constructed in the same region, during the same time period with common design and construction practices. However, some efforts have been made to develop methodologies that allow this dependency to be incorporated into the analysis in different ways, as will be discussed later.

Simultaneously quantifying the losses of many different structures for a particular earthquake scenario, as required when performing a regional seismic risk assessment, can be particularly challenging. In an ideal scenario, a specific fragility function would be derived and used for each building located in the region, however, the difficulty of obtaining the amount of information at the required level of detail, in addition to the computational demand that this task would require

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make it an unfeasible solution to the problem. A more realistic solution consists of grouping structures with similar characteristics and expected responses into so-called taxonomies, in a way that a common fragility function can be used for all the buildings inside the taxonomy. Taxonomy fragility functions are generally derived using different methods for a specific damage state (DS), defined as the exceedance of certain threshold of a selected engineering demand parameter (EDP). Some EDPs that are commonly used to define DS are the peak storey drift (PSD) and the displacement of an equivalent single degree of freedom (SDOF) oscillator. However, any EDP that has been studied to be linked with the damage level of the structures can be used.

The incorporation of different statistical variables, such as the mentioned damage correlation or a spatial correlation of intensities, make it very hard to estimate risk analytically, so Monte Carlo simulations typically are used to sample the DSs of the different structures from fragility functions, to quantify the probabilistic distribution of damage and losses, which is generally called scenario-based assessments. However, the link that exists between EDP and DS means that an alternative procedure could be used in which the EDP is sampled at first to assign later the corresponding DS by checking if the damage threshold was exceeded for each of the buildings. For this procedure fragility functions would no longer be needed, requiring instead a statistical model to estimate directly the EDP for a given intensity measure (IM) level, which are commonly referred to as demand-intensity models. This constitutes the main drawback of this approach, since those models might not always be available for all the taxonomies in a region. In some cases, for instance, in which the fragility functions were derived from cloud analysis, the determination of a demand-intensity model is an intermediate step of the general procedure, so even though the models might not have been published they still exist. Contrarily, on cases in which empirical fragility functions are used, which constitutes the ideal scenario, demand-intensity models are inexistent and very hard to derive, unless there are instrumented buildings in the region.

The existence of these two different approaches for estimating damage in regional seismic risk assessments reflects the different ways in which different authors have proposed to incorporate the dependence in the response of different buildings into regional analysis. Some studies have tried to incorporate this dependence by calculating and including a correlation of observed EDPs, such as the ones developed by DeBock et al. (2014) and Kang et al. (2021), while, others have incorporated a direct correlation of damage, like Lee and Kiremidjian (2007) , Heresi and Miranda (2022) and Mejia and O'Reilly (2025). Finally, You et al. (2022) proposed a methodology to estimate and incorporate a correlation of any performance metric, that could be either the EDP, DS or even the losses directly.

Even though the overall effect in the final damage estimations should theoretically be the same if the correlation is incorporated directly at the DS level or at the EDP level, different considerations should be made when using either approach. One of the main issues of correlating the damage directly is related with how to deal with the different DSs a structure might have, since it is reasonable to believe that the correlation at a low DS such as "low damage" should not only be different from the one at a higher DS, like *"collapse"*, but should also be influenced by different structural characteristics. This means that a different correlation model should be developed separately for all the different DSs of all the different taxonomies found in the region. In addition to that, it might be necessary to consider an additional correlation between different DSs (like low damage with collapse), which would end up over complicating significantly the procedure. These different inter- and intra-DS correlations might not only be a function of different structural characteristics, but also of the experienced intensities on both sites.

On the other hand, the issue of the cross-DS correlation is directly accounted for when considering an EDP correlation, since the performance of the structures is already correlated independently from the resulting DS. This is the main advantage of this approach, since it only requires one correlation model. However, other aspects should be considered, like the fact that demand-intensity models are defined and calculated conditioned on a non-collapse condition, meaning that the evaluation of the collapse DS must be done separately. Another drawback of this procedure is, as mentioned earlier, the scarcity of demand-intensity models when compared to fragility functions, that could complicate the performance of the analysis. The drawbacks of this approach are deemed to be easier to solve when compared with the complexity of the correlated DS based approach, which is why the following sections will go deeper into the implications of the correlated EDP based approach through its application on a case study.

DEFINITION OF CASE STUDY

To study the results and understand the implications of using the EDP-based approach, a case study was developed. A single taxonomy was considered, composed of midrise, 4-storey, high-ductility concrete bare-frame buildings, constructed according to the standards required by Turkish the codes applicable between the years 2000 and 2018, defined by Hasanoğlu et al. (2025) as *tr_0018_dch*. The Built Environment Data Framework for Simulated Design (Ozsarac et al., 2025) adapted by Hasanoğlu for Turkish buildings, was used to generate a portfolio of 80 buildings with different characteristics in the selected taxonomy, to obtain both building-specific and the taxonomy's demand-intensity model.

Derivation of demand-intensity models

To derive demand-intensity models, a cloud analysis was performed on equivalent non-linear SDOF oscillators, whose behaviour was characterised from the capacity curve of the structures, obtained by performing a bilinearisation of the pushover curve. The forces and displacements of the multiple degrees of freedom (MDOF) building, denoted V and Δ, were transformed into the ones of the equivalent SDOF oscillator, F^* and Δ^*, with mass m^* as presented on Equations (*1*), (*2*) and (*3*). The transformation is performed based on the fundamental mode of vibration, whose modal shape is given by the vector Φ, with dimension equal to the number of stories of the building, n_{st}. It is important to consider that after obtaining the displacements of the SDOF oscillator from the non-linear time history (NLTH) analysis, to obtain the ones of the MDOF building the transformation presented on Equation (*2*) must be inverted. Given that the generated models that are being used are three-dimensional, the analysis was only performed using the capacity curve in one random direction.

(1)
$$F^* = \frac{V}{\Gamma}$$

(2)
$$\Delta^* = \frac{\Delta}{\Gamma}$$

(3)
$$m^* = \sum_{\mathrm{i}=1}^{n_{st}} m_i \Phi_i$$

where:

(4)
$$\Gamma = \frac{\mathrm{m}^*}{\sum_{\mathrm{i}=1}^{\mathrm{n_{st}}} \mathrm{m_i} \ \Phi_\mathrm{i}^2}$$

For the cloud analysis, 500 records were selected using the GCIM-based scenario approach of Tarbali & Bradley (2015), targeting the mean and variability of the response spectrum predicted by the GMM of Aristeidou et al. (2024). The target spectrum was constructed for $Sa_{avg}(T)$, defined as the average spectral acceleration over a period range of 0.2 and 2.0 times the value of the period *T*, considering different values of T. Only active shallow crust earthquakes with moment magnitudes larger than 5.0 were considered, recorded at sites with $v_{s,30}$ larger than 180 m/s, excluding near-fault pulse-like ground motions. To reach larger observations in the non-linear range, the selected suite of records was reused with scale factors of 2.0 and 6.0.

A linear model was fitted to the data for each of the buildings considering as an IM the average spectral acceleration, $Sa_{avg}(T)$, in a range between 0.1 and 2.0 times a period of 0.67s, which is the average period of all the 80 considered oscillators. The EDP selected for the analysis is the PSD, which is calculated from the results of cloud analysis by assuming that the displacement of all storeys is always proportional to the fundamental modal shape of the building, so the resulting Δ^*, must be multiplied by Γ to obtain the displacement at the last storey of the MDOF building, and then by Φ to obtain the displacement at each storey. The points that exceeded a PSD of

5.0% were considered as collapses and were excluded from the regression. To have an idea of the results that were obtained, the demand intensity models calculated for Buildings 10 and 50 are presented on Figure 1. Building 10 has a fundamental period of 0.66s and a yield acceleration of 0.158g and Building 50 has a fundamental period of 0.62s and a yield acceleration of 0.24g, with both buildings having four stories and high ductility, as expected from the definition of the taxonomy.

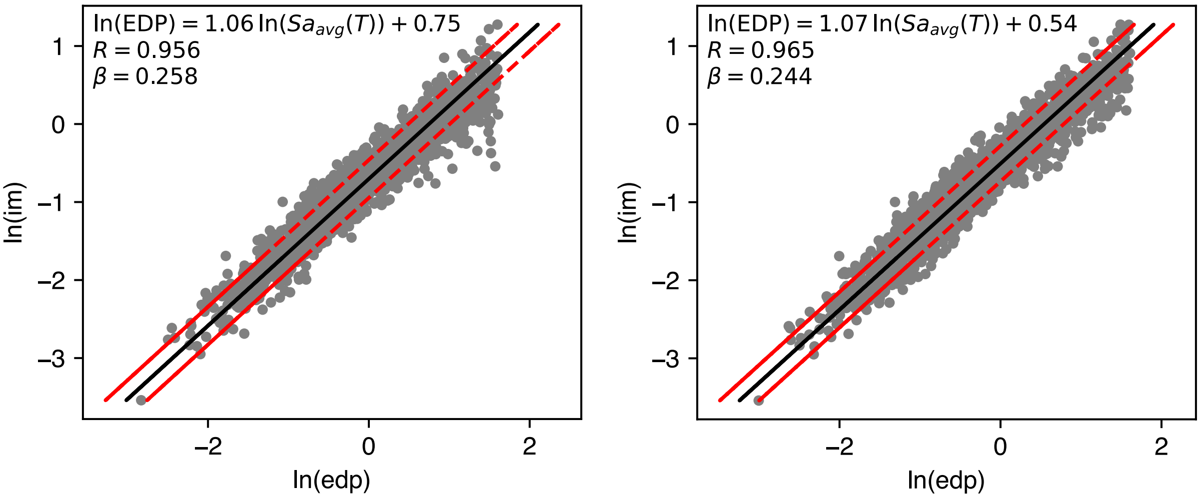

Figure 1 *Demand-intensity models for Buildings 10 (left) and 50 (right)*

Then the result of all buildings was combined to obtain the demand-intensity model of the whole taxonomy. For that it is important to account not only for the record-to-record variability, which is the value of the β presented on Figure 1, and represents and intra-building variability, but also the variability of the results for different buildings inside the taxonomy, which could be defined as an inter-building variability. The parameters for the taxonomy models can be calculated as:

(5) $$\mu_{EDP,tax|IM=im} = \frac{1}{n}\left(\sum_{i=1}^{n} a_i + \sum_{i=1}^{n} b_i \cdot \ln(im)\right)$$

(6) $$\beta_{intra,tax} = \frac{1}{n}\sum_{i=1}^{n} \beta_i$$

(7) $$\beta_{inter,tax} = \frac{1}{n}\frac{1}{m}\sum_{i=1}^{n}\sum_{j=1}^{m}\left(\mu_{EDP,build_i|im_j} - \mu_{EDP,tax|im_j}\right)^2$$

(8) $$\beta_{tot,tax} = \sqrt{\beta_{inter,tax}^2 + \beta_{intra,tax}^2}$$

where n is the number of buildings that are being combined into the taxonomy's model and m is a series of levels of *IM* = *im* that are used to estimate the value of $\beta_{intra,tax}$. The value of $\beta_{tot,tax}$ is the total dispersion of the distribution to use to sample a value of the EDP. The resultant demand intensity model is:

(9) $$\begin{gathered}\mu_{tax|IM} = 0.57 + 1.06 \cdot \ln\left(Sa_{avg}(T)\right)\\ \beta_{intra,tax} = 0.250\\ \beta_{inter,tax} = 0.133\\ \beta_{tot,tax} = 0.282\end{gathered}$$

Determination of Collapse Fragility

As previously mentioned, the demand-intensity models exclude collapse cases in a way that the calculated probability of exceeding certain EDP value is conditioned on non-collapse. To incorporate collapse into the analysis, Jalayer et al. (2017) proposed Equation (*10*) to account for the probability of collapse, with the parameters *a*0 and *a*1 being estimated from a logistic regression of the cases that resulted in collapse in the cloud analysis.

(10)
$$\mathrm{P(C|IM)} = \frac{1}{1 + \mathrm{e}^{(\mathrm{a_0} - \mathrm{a_1}\ln(\mathrm{IM}))}}$$

Then, the collapse fragility function can be considered as a normal distribution with mean μ_c and standard deviation β_c. The value of μ_c can be calculated as the $\ln(IM)$ that makes Equation (*10*) to be equal to 0.5, and β_c can be computed with Equation, with $\ln(IM)_{84}$ and $\ln(IM)_{16}$being the 84th and 16th percentiles, estimated as the $\ln(IM)$ that make Equation (*10*) equal to 0.84 and 0.16 respectively.

(11)
$$\beta_\mathrm{c} = \frac{\ln(\mathrm{IM})_{84} - \ln(\mathrm{IM})_{16}}{2}$$

The collapse fragility was estimated for each building. To obtain the taxonomy's fragility, the result for each building should be combined considering again the building-to-building variability of the results within the taxonomy, which is represented by the value of β_{inter}. So:

(12)
$$\mu_{\mathrm{tax}} = \frac{1}{\mathrm{n}} \sum_{\mathrm{i}=1}^{\mathrm{n}} \mu_{\mathrm{i}}$$

(13)
$$\beta_{\mathrm{intra,tax}} = \frac{1}{\mathrm{n}} \sum_{\mathrm{i}=1}^{\mathrm{n}} \beta_{\mathrm{i}}$$

(14)
$$\beta_{\mathrm{inter,tax}} = \frac{1}{\mathrm{n}} \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mu_i - \mu_{tax})^2$$

The results of the collapse fragility function for the taxonomy:

(15)
$$\begin{gathered} \mu_{\mathrm{collapse}} = 0.821 \\ \beta_{\mathrm{intra,tax}} = 0.320 \\ \beta_{inter,tax} = 0.031 \\ \beta_{tot,tax} = 0.322 \end{gathered}$$

Performance of Damage Assessment

Since the collapse and non-collapse cases are accounted for separately, their assessment must also be performed in two different steps. The collapse assessment should be done first using the traditional DS based approach using the collapse fragility function. To incorporate into the collapse assessment the response correlation the method presented by Heresi and Miranda, (2022) can be used, considering a mathematically valid model for the correlation of the Gaussian Copula, denoted from now on as δ_{ab}^{c}. The EDP based assessment can be performed to the buildings that didn’t result in collapse from the respective assessment. The estimation of the EDPs of each building can be divided into two components: a deterministic one represented by the median value of the demand-intensity model; and a probabilistic one, represented by what are generally called residuals (ε), normally distributed variables with mean equal to zero and standard deviation equal to one. This way the EDP can be estimated from Equation (*16*).

$$\ln EDP \mid IM = im = \mu_{EDP|IM=Im} + \varepsilon \beta \quad (16)$$

It is possible then to generate a set of correlated EDP residuals if a mathematical model to estimate their correlation (δ_{ab}^{EDP}) is available. Then by estimating the values of $\mu_{EDP|IM=Im}$ by evaluating the demand-intensity model at the experienced IM it is possible to estimate the value of the EDP at each the buildings. Finally, the resulting DS can be assigned to each of the buildings based on which of the corresponding damage thresholds were exceeded.

EVALUATION OF EARTHQUAKE SCENARIO

To evaluate the impact of incorporating the response correlation on an EDP based assessment and validate its importance in the assessment a real earthquake rupture was evaluated, consisting of the 1999 Chichi earthquake (M_w =7.3). A NLTH analysis was performed to each of the 80 considered buildings using all the available records for that event, having as a result information of the actual observed EDP for each building at the location of each of the stations. If a DS is defined as exceeding a PSD of 0.5% and a random building is assigned to each of the locations, it is possible to have a hypothetical scenario in which the theoretical number of damaged buildings for that particular scenario is known, by counting for which stations the random building assigned to it resulted in an EDP larger than 0.5%. For the set of random buildings considered in this scenario the number of buildings exceeding the considered DS is equal to 75.

The EDP-based assessment can be performed then as previously described sampling from the taxonomy's collapse fragility function and demand-intensity model the resulting DS, conditioned on the actual IM recorded on the station on top of which each building is assumed to be located. After performing many realisations of this procedure, it is possible then to estimate the probability of observing a certain number of damaged buildings in that particular scenario. Different valid correlation models were considered, as a function of some structural properties that influence the response of the buildings, such as the absolute difference in the fundamental periods of vibration of the buildings (ΔT) and their yield accelerations from the bilinearised pushover curve (ΔSa_Y). The correlation models are also a function of the Euclidean distance between the buildings (h), to account for the similarities in the characteristics of the ground motions that might impact the results. The considered correlation models used for the analysis are presented in Table 1. Their parameters were calibrated from the results of NLTH analyses performed on recordings from different historical events, allowing them to be applied generally to any earthquake scenario, in a manner analogous to spatial correlation models for ground motion intensity measures.

Table 1 *Correlation models used for analysis*

Model	**Independent variables**	**Equation**
	Collapse cases	
HT	Euclidean Distance (h), Absolute difference in fundamental period (ΔT)	(*17*)
	Non-collapse cases	
HTS	h, ΔT, Absolute difference in yield acceleration (ΔSa_Y)	(*18*)
HT	h, ΔT	(*19*)
TS	ΔT, ΔSa_Y	(*20*)

(17) $$\delta_{a,b}^{C}(\mathrm{h},\Delta\mathrm{T}) = e^{\left(-\frac{h}{133\,km}\right)^{0.35}} \,.\, e^{\left(-\frac{\Delta \mathrm{T}}{0.67\,s}\right)}$$

(18) $$\delta_{a,b}^{EDP}(\mathrm{h},\Delta\mathrm{T},\Delta Sa_y) = e^{\left(-\frac{h}{3.48\,km}\right)^{0.12}} \,.\, \left(0.93\, e^{\left(-\frac{\Delta \mathrm{T}}{0.67\,s}\right)} + 0.07\ \cos(11.45\,\Delta Sa_y)\right)$$

(19) $$\delta_{a,b}^{EDP}(\mathrm{h},\Delta\mathrm{T}) = e^{\left(-\frac{h}{5.10\,km}\right)^{0.13}} \,.\, e^{\left(-\frac{\Delta \mathrm{T}}{0.25\,s}\right)}$$

(20) $$\delta_{a,b}^{EDP}(\Delta\mathrm{T},\Delta Sa_y) = 0.92\, e^{\left(-\frac{\Delta \mathrm{T}}{0.67\,s}\right)} + 0.08\ \cos(11.50\,\Delta Sa_y)$$

After performing 100000 realisations the probability of exceeding more than a certain number of damaged buildings is calculated with all the considered correlation models, obtaining the results presented on Figure 2. It can be seen that including any correlation in the response of the buildings has a significant impact in the probability of exceeding a large number of damaged buildings, as was already expected based on the results of previous studies (i.e., Heresi & Miranda, 2022 and Mejia & O'Reilly, 2025). It can also be observed that exceedance curves obtained with the HT and the HTS models are almost identical, suggesting that, at least for the considered taxonomy, the impact of ΔSa_y in the estimation of the EDP correlation might be negligible. On the other hand, it can also be seen that the exceedance curve obtained with the TS model is significantly overestimating the results when compared with the case in which the response of different buildings is independent, indicating that the distance between the buildings is a variable that should be considered when defining correlation models such as the ones used for this study.

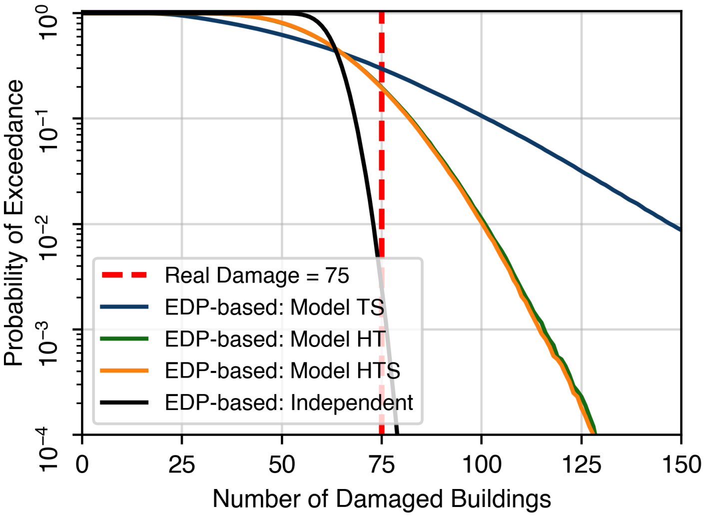

Figure 2 *Probability of exceeding a certain number of damaged buildings for Chi-Chi earthquake*

Now, when looking specifically at the probability of exceeding the observed number of damaged buildings based on the results of the NLTH analyses performed on the actual stations that are being considered in the study, which is 75 buildings, it can be seen that the probability of exceeding that particular number is of 0.25% if no correlation model is considered, meaning that the observed damage would be very unlikely to occur for the recorded intensities in that particular earthquake. When correlations models are included, that probability rises to 19.5%, 19.8% and 29.7% using the HTS, HT and TS models respectively. This means that even if the observed number of damaged buildings on that earthquake was overall larger than what would have been expected, the probability of observing that scenario is more likely to occur when the response correlation is included. It was verified that the unlikeliness of the observed scenario was not caused by any bias in the demand-intensity models, as can be observed in the results presented on Figure 3, in which the residuals of the taxonomy's demand-intensity model for all the buildings and records used to derive it are normally distributed with a mean equal to zero and standard deviation equal to 1.0, and also that there is no clear bias due to the magnitude of the considered event.

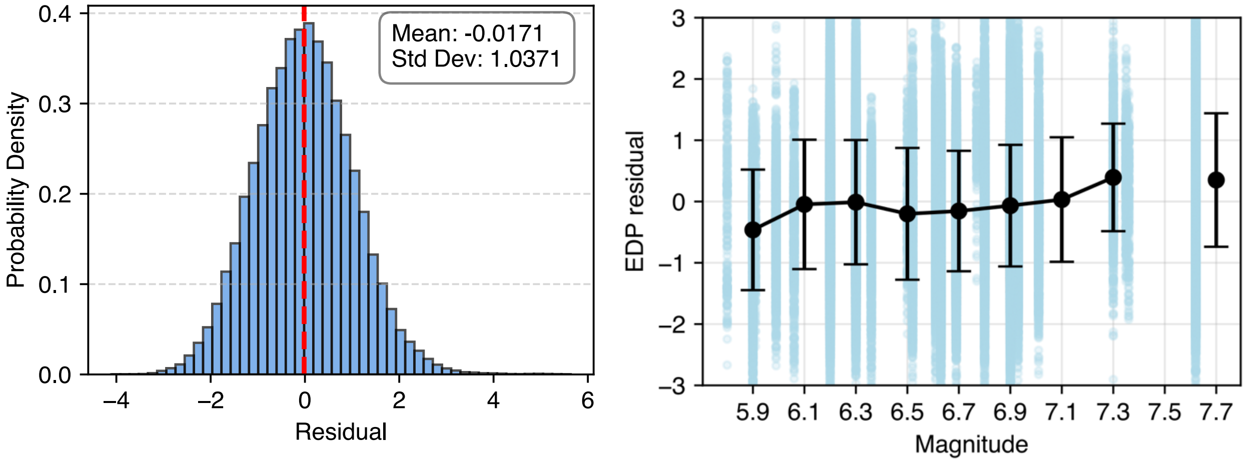

Figure 3 *Verification of residuals of taxonomy's demand-intensity model*

CONCLUSIONS

In this study, it was presented how the correlation in the response of different buildings can be incorporated in an EDP based regional seismic risk assessment in an analogous way to which typical DS based assessment are performed. The use of this approach simplifies significantly the incorporation of the correlation into the analysis, since only two correlation models are needed, in comparison to the complexity of the DS based approach in which a specific correlation model is needed for each DS in addition to correlation models for each of the possible correlation between different DSs. It was also presented how the incorporation of this variable into the analysis impacts the overall results of the assessment performed to the 1999 Chi-Chi earthquake considering a portfolio of simulated buildings. It was observed how even when the real recorded intensities are used and the only source of variability in the results is given by the response of the structures, the incorporation of the response correlation significantly impacts the probability of observing large scale damage.

When comparing the results of the assessment with the hypothetical observed damage, that can be calculated by performing NLTH analyses to the buildings using the real records of the considered event, it can be seen that the probability of observing that particular outcome if response is assumed to be independent is almost negligible, of around 0.25%. However, when different correlations models are considered, it can increase to values of around 20% or even 30%, making the probability of occurrence of the observed scenario substantially more plausible and consistent with the damage patterns obtained from NLTH analyses, and underscoring the importance of accounting for response correlation. It is important to remember, however, that these results are specific to the considered taxonomy, and different conclusions could be drawn for scenarios involving buildings of different taxonomies.

The derivation of the correlation models is a future development of this work. Geostatistical tools could be used to fit models to observed damage patterns from simulated damage scenarios of real events, such as the case study considered in this study, in an analogous way to which spatial correlation models of intensities are developed. Nevertheless, fitting models with many explanatory variables while guarantying the resulting correlation matrix to be positive semidefinite, which is a specific mathematical property of correlation matrices, can be challenging. In this context the application of alternative approaches, such as Bayesian inference, can be explored to determine robust models for the estimation of response correlation.

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