ECEE2026
18th European Conference on Earthquake Engineering

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

Tomas Mejia[1], Gerard J. O'Reilly[1]

1- Centre for Training and Research on Reduction of Seismic Risk (ROSE Centre), Scuola Universitaria Superiore IUSS di Pavia, Pavia 27100, Italy

⋮

Corresponding Author: tomas.mejiasaldarriaga@iusspavia.it

Abstract

Regional seismic risk assessments commonly assume independent structural responses when estimating damage across building portfolios, despite the fact that structures subjected to the same earthquake often exhibit correlated responses arising from similar structural behaviour and common deficiencies. Previous approaches have attempted to address this issue by introducing correlation directly at the damage-state level, which typically requires multiple correlation models and additional assumptions. This study investigates an alternative framework in which structural response correlation is introduced at the level of engineering demand parameters (EDPs). Demand–intensity models derived through cloud analysis are used to simulate correlated EDP realisations, from which damage states and economic losses are subsequently computed. The methodology is applied to a scenario-based assessment of a portfolio of reinforced concrete frame buildings subjected to the 1999 Chi-Chi earthquake. Results indicate that neglecting structural response correlation can significantly underestimate the likelihood of widespread damage and economic loss, highlighting the importance of explicitly accounting for response dependence in regional seismic risk assessments.

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

1- INTRODUCTION

Regional seismic risk assessments aim to estimate the distribution of damage and losses across large building portfolios subjected to earthquake scenarios. Within the regional performance-based earthquake engineering (RPBEE) framework [1], an important challenge is the incorporation of structure-to-structure response correlation, that considers the expected dependency on different buildings in a region due to shared design practices, construction characteristics, regional ground-motion patterns, among others. In regional assessments, these dependencies are generally neglected or considered in a very simplified manner, which can lead to inaccurate estimates of widespread damage and associated consequences.

In practice, regional assessments typically group buildings with similar characteristics into so-called taxonomies, allowing the use of a common fragility function (FF) to represent all the structures that were grouped together. These fragility functions are derived by defining damage states (DS) through thresholds of engineering demand parameters (EDPs), such as peak storey drift (PSD). Then, on scenario-based assessments, Monte Carlo simulations are commonly used to sample DSs from FFs to estimate regional damage and loss distributions. Previous studies have attempted to incorporate dependence by directly correlating damage states or (e.g., [2], [3]). For instance, Mejia & O'Reilly [4] studied the impact of incorporating this variable into a regional assessment, estimating the correlation to be used for different DSs from the results of non-linear time history (NLTH) analyses. While this approach is straightforward conceptually, it introduces several complications. Different DSs may exhibit different correlation structures, requiring separate models for each damage level. Additionally, correlations may exist both within the same DS across buildings and between different DSs, further increasing model complexity. This has resulted in a methodology that although conceptually appealing and functional for single building taxonomy types, runs into practical issues when extended to full regional-based assessments.

An alternative approach can be considered by introducing the correlation directly at the EDP level, as have been studied by some authors (e.g., [5], [6]). Since DSs are defined from EDP thresholds, correlating structural demands inherently captures cross-damage-state dependencies. This allows a single correlation model to represent directly structural response dependence, simplifying the modelling process while maintaining theoretical consistency. This approach, however, requires sampling directly the EDP values of each structure, so instead of using FFs for each building taxonomy type, it requires a statistical model for the considered EDPs conditioned on the experienced intensity, which might not always be available. The objective of this study is then to explore the implications of introducing correlation at the EDP level within a scenario-based regional risk assessment. The approach is tested through to a case study to evaluate the influence of structural response correlation on regional damage estimates.

2- METHODOLOGY

In the considered framework, EDPs are sampled first to assign later the resulting DSs by checking the exceedance of the respective thresholds. This requires the definition of demand–intensity models, which describe the statistical relationship between an intensity measure (IM) and the resulting EDP. It is important to note, however, that such models are conditioned on the non-collapse collapse of the structures, so collapse must be treated separately through the respective collapse FF.

To illustrate the approach, a case study was developed considering a single building taxonomy composed of high-ductility reinforced concrete frame buildings representative of modern Turkish construction, *tr_0018_dch* [7]. Using the Built Environment Data Framework for Simulated Design [8], a portfolio of 80 buildings with varying structural characteristics was generated. These models were used to derive both building-specific and taxonomy-level demand-intensity models and collapse FFs through a cloud analysis. The analyses were performed on equivalent non-linear single-degree-of-freedom (SDOF) oscillators representing the buildings by performing a modal transformation based on a linearisation of the pushover curve of the buildings. For the cloud analysis, a suite of 500 ground-motion records was selected using an unconditional record selection strategy using the Djura ground motion record selector [9]. Only shallow crustal earthquakes with moment magnitude larger than 5.0 were considered. To increase the number of observations in the non-linear range, the records were also scaled by factors of 2 and 6.

For each building, a log-linear regression model was fitted relating the selected IM to the resulting PSD. The IM selected for the analysis was the average spectral acceleration, $Sa_{\text{avg}}(T)$, calculated for values between 0.1 and 2.0 times a period of 0.67s, which is the average of the fundamental period of all the considered structures. Collapse cases were excluded from the regression, defined as when PSD > 5%. The individual building models were subsequently combined to obtain a taxonomy-level demand model, accounting for both record-to-record variability and building-to-building variability within the taxonomy, presented on Equation 1, where the variable ε represents the residual of the *EDP* which accounts for the randomness of the variable. Because demand-intensity models are conditioned on non-collapse responses, collapse probabilities must be evaluated separately. Collapse cases observed during the cloud analysis were used to estimate collapse fragility functions using the method proposed by Jalayer et al. [10]. As in the case of the demand-intensity models, individual building collapse fragilities were combined to derive a taxonomy-level collapse fragility, incorporating the variability between buildings within the taxonomy, obtaining that it has a mean in log-space of 0.821 and a standard deviation of 0.322.

$$
\begin{aligned}
&\ln EDP \mid \ln IM = \mu_{tax|IM} + \varepsilon\, \beta_{\text{tot,tax}} \\
&\mu_{tax|IM} = 0.57 + 1.06 \ln\left(Sa_{avg}(\mathrm{T})\right) \\
&\beta_{\text{tot,tax}} = 0.282
\end{aligned} \tag{1}
$$

As for the correlation in the response different models were evaluated, both for the correlation of the collapse damage outcomes and the EDP residuals as presented on Table 1. The proposed models are a function of different parameters, such as the Euclidean distance between the location of the buildings, h, and the absolute difference between the fundamental periods, ΔT, and yield acceleration, ΔSa_y, of the structures. These models are examples of the types of models that could be used for this type of assessment. Specifically, they are valid kernel functions that guarantee the correlation matrix calculated from them to be positive semidefinite, a mathematical property of correlation matrices that guarantees all the resulting variances are non-negative.

Table 1- Correlation models considered for analysis

Model	Independent variables	Equation
Collapse Cases		
HT	h, ΔT	(2)
Non-collapse cases		
HTS	h, ΔT, ΔSa_y	(3)
HT	h, ΔT	(4)
TS	ΔT, ΔSa_y	(5)

$$\delta^{C}_{a,b}(\mathrm{h},\Delta\mathrm{T}) = e^{\left(-\frac{h}{129\,km}\right)^{0.39}} \cdot e^{\left(-\frac{\Delta\mathrm{T}}{0.73\,s}\right)} \quad (2)$$

$$\delta^{EDP}_{a,b}(\mathrm{h},\Delta\mathrm{T},\Delta Sa_y) = e^{\left(-\frac{h}{3.22\,km}\right)^{0.12}} \left(0.93\, e^{\left(-\frac{\Delta\mathrm{T}}{0.15\,s}\right)} + 0.07\ cos(12.56\,\Delta Sa_y)\right) \quad (3)$$

$$\delta^{EDP}_{a,b}(\mathrm{h},\Delta\mathrm{T}) = e^{\left(-\frac{h}{4.67\,km}\right)^{0.13}} \cdot e^{\left(-\frac{\Delta\mathrm{T}}{0.15\,s}\right)} \quad (4)$$

$$\delta^{EDP}_{a,b}(\Delta\mathrm{T},\Delta Sa_y) = 0.92\, e^{\left(-\frac{\Delta\mathrm{T}}{0.15\,s}\right)} + 0.08\ cos(12.55\,\Delta Sa_y) \quad (5)$$

3- RESULTS

The proposed framework was applied to a scenario-based assessment of the 1999 Chi-Chi earthquake. The EDP were sampled from the taxonomy's demand-intensity model assuming a random building out of the 80 considered before to be located on top of each of the stations that recorded the event. This means the sampling was done considering the actual recorded IM at the site in which the building was assumed to be located. A single DS was considered, defined as when PSD > 0.5%, so the probability distributions of the number of damaged buildings were obtained based on the sampled EDPs using correlated realisations and comparing with the results obtained for independent structural responses. It is also possible to perform a non-linear time history analysis using the specific building model assigned to each of the stations to use as a reference value for the real number of damaged buildings in this scenario and evaluate the obtained results. The results are presented in Figure 1.

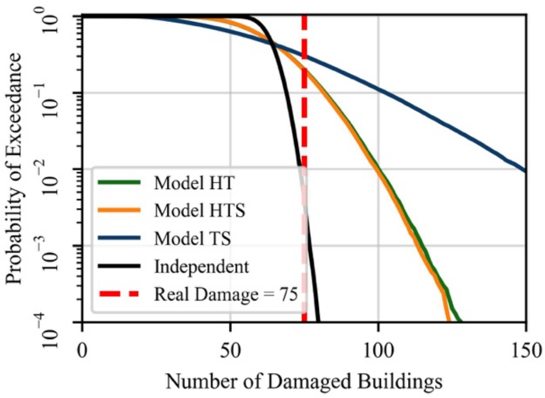

Figure 1- Probability distribution of the number of damaged buildings for the 1999 Chi-Chi earthquake scenario under independent and correlated structural response assumptions

The figure shows that neglecting structural response correlation significantly alters the results. Simulations that assume independence tend to underestimate the probability of widespread damage, which was actually observed. When the correlation is incorporated, the simulations produce more spatially consistent damage patterns, reflecting the common ground-motion and structural characteristics affecting nearby buildings. As a result, the probability of observing the real damage simulated for the reference scenario goes from 0.45% if response is assumed to be independent to around 20% if correlation models HT and HTS are considered (20.1% and 19.7% respectively) and 30.2% for Model TS. 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. The incorporation of the response correlation in the analysis allows then to have better estimation of highly impacting damage and losses and as a consequence, efforts should be made to obtain models like the ones used in this study to quantify it.

4- Conclusions

The study investigated the incorporation of structural response correlation in scenario-based regional seismic risk assessment using an EDP-based framework. A case study was performed to evaluate the impact of incorporating the variable into the analysis. The results highlight several important findings:

- Introducing correlation directly at the EDP level provides a consistent way to capture structural dependence across buildings. Unlike DS-based approaches, the method requires only a single correlation model, avoiding the need to define separate correlations for different damage states within a single building taxonomy type.
- Collapse must be evaluated separately through dedicated collapse fragility functions, since demand models are conditioned on non-collapse behaviour.
- Neglecting response correlation can significantly underestimate the probability of widespread damage in regional assessments.
- When correlation is included, simulated damage patterns are more consistent with the observed consequences.
- The proposed models to quantify the correlation can only capture sources of dependency between the buildings that can be represented by analytical models of the buildings. The impact of other variables that contribute to the correlation, such as design or constructive errors should be considered separately and can only be estimated from real observations of instrumented buildings.

Overall, the proposed framework demonstrates that EDP-based formulations offer a practical and theoretically consistent approach for incorporating structural response correlation in regional seismic risk assessments.

5- Acknowledgements

The ground motion record selections described here were performed using an academic licence of the Djura online ground motion record selector (www.djura.it).

6- References

[1] Heresi, P.; Miranda, E.; RPBEE: Performance-based earthquake engineering on a regional scale, Earthquake Spectra, Volume 39, 2023, 1328–1351, ISSN 8755-2930, https://doi.org/10.1177/87552930231179491
[2] Lee, R.; Kiremidjian, A.S.; Uncertainty and Correlation for Loss Assessment of Spatially Distributed Systems, Earthquake Spectra, Volume 23, 2007, 753–770, ISSN 8755-2930, https://doi.org/10.1193/1.2791001
[3] Heresi, P.; Miranda, E.; Structure-to-structure damage correlation for scenario-based regional seismic risk assessment, Structural Safety, Volume 95, 2022, 102155, ISSN 01674730, https://doi.org/10.1016/j.strusafe.2021.102155
[4] Mejia, T.; O'Reilly, G.J.; Quantifying the Impacts of Incorporating Damage Correlation on Scenario-Based Regional Seismic Assessment, Earthquake Engineering & Structural Dynamics, 2025, ISSN 0098-8847, https://doi.org/10.1002/eqe.70069
[5] DeBock, D.J.; Garrison, J.W.; Kim, K.Y.; Liel, A.B.; Incorporation of Spatial Correlations between Building Response Parameters in Regional Seismic Loss Assessment, Bulletin of the Seismological Society of America, Volume 104, 2014, 214–228, ISSN 0037-1106, https://doi.org/10.1785/0120130137
[6] Kang, C.; Kwon, O.-S.; Song, J.; Evaluation of correlation between engineering demand parameters of structures for seismic system reliability analysis, Structural Safety, Volume 93, 2021, 102133, ISSN 01674730, https://doi.org/10.1016/j.strusafe.2021.102133
[7] Hasanoğlu, S.; Ozsarac, V.; O'Reilly, G.J.; A model for the simulated design of Turkish RC frame buildings in seismic vulnerability analysis, Bulletin of Earthquake Engineering, 2025, ISSN 1570-761X, https://doi.org/10.1007/s10518-025-02301-y
[8] Ozsarac, V.; Pereira, N.; Mohamed, H.; Romão, X.; O'Reilly, G.J.; The Built Environment Data Framework for Simulated Design and Vulnerability Modelling in Earthquake Engineering, Earthquake Engineering & Structural Dynamics, 2025, https://doi.org/https://doi.org/10.1002/eqe.4378
[9] Shahnazaryan, D.; Ozsarac, V.; O'Reilly, G.J.; DJURA GROUND MOTION RECORD SELECTOR: A SOFTWARE SOLUTION FOR EARTHQUAKE ENGINEERING, 2025, 740–757, https://doi.org/10.7712/120125.12444.25126

[10] Jalayer, F.; Ebrahimian, H.; Miano, A.; Manfredi, G.; Sezen, H.; Analytical fragility assessment using unscaled ground motion records, Earthquake Engineering & Structural Dynamics, Volume 46, 2017, 2639–2663, ISSN 0098-8847, https://doi.org/10.1002/eqe.2922