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THE IMPACTS OF STRUCTURE-TO-STRUCTURE DAMAGE CORRELATION ON REGIONAL SEISMIC RISK ASSESSMENT

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Abstract

Structure-to-structure damage correlation is a key factor in regional seismic risk assessment, yet it is often neglected or treated in an overly simplified manner. While the spatial correlation of ground motion intensities has been extensively studied and incorporated into seismic hazard models, the correlation of structural damage across buildings remains an area of ongoing research. This study examines the influence of structure-to-structure damage correlation on regional seismic risk estimates by deriving it from the results of nonlinear time history (NLTH) analyses performed on equivalent single-degree-of-freedom (SDOF) models of the buildings. A case study in the province of Caserta is presented, focusing on mid-rise concrete buildings. Monte Carlo simulations are used to evaluate the probability distribution of the number of damaged buildings under a scenario-based earthquake analysis. The results indicate that while incorporating structure-to-structure correlation does not significantly alter the mean number of damaged buildings, it has a substantial impact on the standard deviation of the results. These changes directly affect the probability of localized or widespread damage, a critical consideration for governmental agencies planning post-earthquake mitigation and resource allocation strategies. The findings underscore the necessity of integrating structure-to-structure damage correlation into regional seismic risk models to improve the accuracy of disaster response planning.

Keywords: Risk Analysis, Regional Assessment, Structural Damage, Correlation

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1 INTRODUCTION

The quantification of seismic risk has been a key focus in earthquake engineering, driven by the development of performance-based earthquake engineering (PBEE). First introduced in SEAOC's Vision 2000 and later refined by Cornell and Krawinkler [1] and in the FEMA P-58 report [2], PBEE provides a probabilistic framework for assessing and designing structures against seismic hazards, accounting for different sources of variability and uncertainty. At its core, the PBEE methodology integrates probabilistic seismic hazard analysis (PSHA), fragility functions, and consequence estimation to quantify the likelihood of different damage states (DS) for a given structure. This is typically expressed through the risk assessment integral, which evaluates the mean annual frequency of exceeding a specific DS based on the relationship between structural capacity, measured in terms of engineering demand parameters (EDP), and seismic demand, represented by a given intensity measure (IM).

While PBEE has been widely applied to individual structures, a broader perspective is needed to assess the societal impact of seismic events at a regional scale. This has led to the development of regional performance-based earthquake engineering (RPBEE), which adapts the PBEE framework to account for spatially distributed structures and their interdependencies [3]. A fundamental modification in RPBEE is the treatment of seismic hazard, where IMs are modeled as random variables following a multivariate lognormal distribution, incorporating spatial correlation through ground motion models (GMMs). The influence of spatial correlation on seismic risk assessment has been extensively studied, leading to the development of models to characterize it (e.g. [4], [5]).

At a regional scale, fragility assessment relies on taxonomies, that classify structures with similar expected response, enabling the derivation of fragility curves for global DSs such as light, moderate, or severe damage. This approach allows risk estimation to focus on the collective performance of structures rather than individual buildings. Standard fragility-based methods assume that all buildings within a taxonomy share the same probability of exceeding a DS for a given IM, corresponding to the proportion of buildings expected to sustain the corresponding DS. Hence, Monte Carlo simulation from the taxonomy fragility function is utilised to simulate a set of buildings that have exceeded DS and a set of buildings that have not, where the overall percentage of this exceedance is the same as the percentage of the fragility function value at that IM level.

A critical factor in regional risk assessment is structure-to-structure damage correlation, which arises from similarities in construction quality, materials, and design practices within a given region. If an earthquake causes one building to sustain higher damage than expected, neighboring structures with similar characteristics are likely to experience similar effects. Despite its significant impact on regional risk estimation, this correlation is often overlooked or treated in an oversimplified manner. In regional assessments of bridges or transportation networks, this variable is particularly relevant, as highways often feature multiple overpasses with nearly identical structural configurations, likely with a common design and constructed by the same team and standards.

This study, however, focuses on quantifying damage correlation among buildings, conducting a case study to evaluate its effects on regional seismic risk assessment, with an emphasis on residential structures in Italy. Different methodologies for estimating structure-to-structure damage correlation are examined, highlighting their advantages and limitations. A case study in the province of Caserta, Southern Italy, demonstrates how incorporating this correlation refines seismic risk estimates and enhances decision-making for disaster resilience.

2 STRUCTURE-TO-STRUCTURE DAMAGE CORRELATION

According to Heresi and Miranda [3], one of the main challenges of assessing seismic risk at a regional scale is incorporating the structure-to-structure damage correlation into the analysis. Unlike the spatial correlation of IMs used in seismic hazard analysis, which has been extensively studied with several mathematical models developed to quantify it, damage correlation has received comparatively less attention. This variable is often either completely neglected in the analyses or treated approximately by assigning a constant value for all structures. Some efforts, however, have been made in the last few years to study and understand the problem and make more accurate regional risk models in terms of considering this variable.

One of the first studies on the topic was conducted by Lee and Kiremidjian [6], who analyzed the effects of considering the structure-to-structure damage correlation on spatially distributed systems, primarily focusing on transportation networks. Specifically, the damage correlation was estimated for bridges within the same network, assuming an equi-correlated scenario, in which a value of one was assumed in the diagonal of the correlation matrix (i.e., the structure's damage state is perfectly correlated with itself) and a constant value between 0 and 1 in all the other cases (i.e., the damage to structure i is correlated to structure j by the same amount that structure m is to structure n). The correlation value was considered to be independent of the ground motion intensity level but not on the damage level and was estimated mathematically as an optimisation problem using a least squares adjustment and considering the marginal probabilities of each bridge as constraints. A sensitivity analysis demonstrated that the variation in total loss increases with the estimated value of the correlation.

Other approaches were developed by Kang et al. [7] and Xiang et al. [8]. The first study proposed a model to estimate the correlation between EDPs using the results of IDA's performed on several structures, which in concept, has the same effect as considering the structure-to-structure damage correlation. In the second study, a model was developed to derive the structure-to-structure correlation analytically based on the dynamic properties and the spatial distance of the structures, using equivalent SDOF models subjected to consistent and spatially varying white noise.

Heresi and Miranda [9] approached the problem considering that the random variable damage of the structure can be represented by a Bernoulli trial. The correlation between two Bernoulli trials can be derived from their marginal probabilities and the joint probability of both buildings experiencing damage. The authors modelled the joint distribution with a Gaussian Copula, a bivariate normal distribution with a mean vector equal to zero and a given covariance matrix. However, selecting an appropriate correlation factor for the copula remains challenging. The authors proposed an equation inversely proportional to the distance between structures and the difference in their construction years. Although this equation was not validated, it illustrated how different values of structure-to-structure correlation can significantly affect regional risk assessment outcomes.

Among the methods previously discussed, the approach proposed by Heresi and Miranda is the most suitable for the regional seismic risk assessment methodology typically used. It not only allows the use of fragility curves widely accepted in the literature, like the ones derived by GEM [10], but also acknowledges that the correlation value should not be uniform across all buildings, given their varying characteristics. Additionally, the challenge of selecting the correlation for the Gaussian Copulas can be addressed by developing mathematical models performing regressions with data from real historical events or derived from simulated scenarios. Having this in mind, an extension of this approach was used in the case study to estimate the damage correlation.

2.1 Correlation between Bernoulli trials

A Bernoulli trial is an experiment whose outcome is random but has one of only two possible outcomes: success or failure [11]. The probability of success is typically denoted as p. In the context of seismic events, a structure experiencing a certain damage state can be visualised as a Bernoulli trial, where a successful outcome corresponds to the structure being damaged, and a failure corresponds to the structure remaining undamaged. This probability can be obtained by the fragility curve for a given IM value. Following this assumption, it is possible then to estimate the structure-to-structure damage correlation of two buildings from the equation of the correlation (ρ) between two Bernoulli trials as follows:

$$\rho_{i,j} = \frac{P[D_i=1,D_j=1]-p_i p_j}{\sqrt{p_i(1-p_i)p_j(1-p_j)}} \tag{1}$$

where p_i and p_j correspond to the marginal probability of buildings i and j experiencing a given damage state, and $P[D_i=1,D_j=1]$ is the joint probability of both buildings experiencing damage simultaneously.

Even though the marginal probabilities can be easily obtained from the fragility curve of each building, there needs to be more information to estimate the joint probability of damage to the buildings, which is why Heresi and Miranda [9] suggested the use of the Gaussian Copulas. However, in a hypothetical case where sufficient data would exist to perform nonlinear time history analyses on all buildings of the region, it could be possible to determine the joint distribution, and consequently, the structure-to-structure damage correlation for that set of buildings, with a similar procedure to the one used to determine analytical fragility functions.

2.2 Analytical determination of joint probability distribution

The most common approach to estimate fragility functions of buildings is the analytical method [12], in which damage probability distributions are simulated based on statistical results obtained from structural analysis on computational models. The most accurate results are obtained when nonlinear time history analyses are performed, using methods like the Incremental Dynamic Analysis (IDA) or Multiple Stripe Analysis (MSA) to estimate the seismic response of the building. The IDA, introduced by Vamvatsikos and Cornell [13], involves performing nonlinear time history analyses on a set of ground motion records scaling them incrementally until structural collapse is observed. By using the same records across all IM levels, IDA generates curves that relate EDP to IM values, doing a linear interpolation to estimate the values for unperformed analysis points.

However, the method has some limitations, particularly regarding the selection of ground motion records, which can significantly impact the results [14]. Additionally, scaling records heavily may introduce bias, as low and high-intensity motions differ in characteristics, potentially leading to unrealistic outcomes [15]. The MSA, proposed by Jalayer [16], addresses these limitations by using hazard-consistent ground motion records at each IM level (or stripe), thereby minimising the need for extensive scaling and reducing bias. Consequently, MSA is commonly preferred in performance-based earthquake engineering. Although MSA is based on the same underlying principles as IDA, it does not allow for the creation of continuous IM-EDP curves, since different records are used at each stripe.

In the context of the calculation of the structure-to-structure damage correlation, the joint probability distribution can be then determined analytically from the results of either an IDA or MSA of both buildings, in case than some special considerations are accounted for during the analysis, considering the following equation:

$$P\left[D_i = 1, D_j = 1\right] = \frac{z_{i\,\&\,j}}{n} \tag{2}$$

Where $z_{i\,\&\,j}$ is the number of observations in which both structure i and j result in a given DS and n is the total number of records used for the analysis. If the same set of records is used for all structures, the value of $z_{i\,\&\,j}$ can be estimated by the results of IDA or MSA by counting the records for which the corresponding limit EDP was exceeded for both buildings simultaneously. It should be noted that the value of the joint probability, and consequently, the correlation factor, is conditioned on the value of the IM experienced by the buildings, since the records are counted for the specific level of the IM experienced by each structure.

Given the limitations of IDA discussed earlier, the ideal approach would involve using the results of MSA on all buildings. However, the impossibility of interpolating the EDP results for IM values other than those corresponding to the one for which the records were selected means that MSA can only be used in a hypothetical scenario where all buildings experience a constant level of ground motion, with an IM corresponding to that of a particular stripe. Considering that the previous case doesn't correspond to a realistic scenario, since each building experiences a different level of intensity, although with some spatial correlation between each site, the only viable alternative is estimating $z_{i\&j}$ by counting the records exceeding the damage threshold for both buildings from the results of IDAs, as presented on Figure 1.

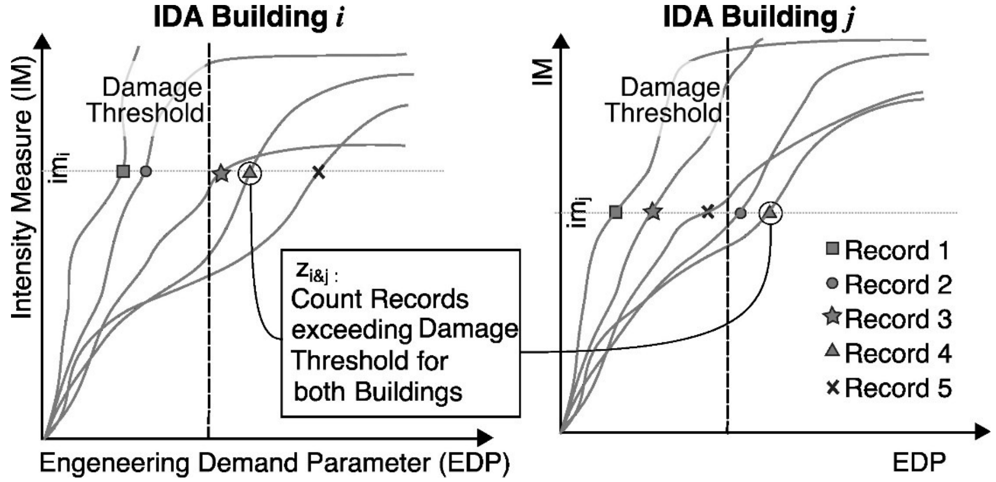

Figure 1: Estimation of joined probability distribution from IDA results

For the marginal probabilities used to estimate the correlation in Eq. (1), it is preferable to derive them directly from the results of the IDA, as shown in Eq. (3) and (4), rather than relying on probabilities from fragility curves, preventing unrealistic mathematical probability distributions. Marginal probabilities from fragility curves are often based on fitted lognormal distributions of the data, which could result in smaller values than the joint probability distribution, leading to inaccurate correlation estimates. Calculating the marginal probability by counting the records where the damage threshold is exceeded and dividing by the total number of records ensures consistency with the method used to calculate the joint probability distribution and presented in Eq. (2).

$$p_i = \frac{z_i}{n} \tag{3}$$

$$p_j = \frac{z_j}{n} \tag{4}$$

where z is the number of observations of a given damage state in either building i or j and n is the number of ground motions utilised.

It is important to note, however, that the application of the proposed method is very computationally demanding, as it requires running several records at various IM levels on all buildings of the region under assessment. It is possible, however, to apply in this specific context different approaches commonly used to simplify the process of generating fragility curves, such as using SDOF nonlinear oscillators to approximate the behaviour of a multiple degree of freedom building. This simplification has been previously done in the works of Martins and Silva [10] and Nafeh et al. [17]. The properties of the equivalent oscillator can be estimated considering that the response of the building is dominated by the first mode and based on a linearisation of the pushover curve of the building. This approach was used in the case study to estimate structure-to-structure damage correlation, allowing for an assessment of the impacts of including this variable in a regional seismic risk assessment.

3 DEFINITION OF CASE STUDY

This case study involves a regional seismic risk assessment of mid-rise residential concrete frame structures, using a portfolio generated with the Built Environment Data (BED)'s Design service (https://design.builtenvdata.eu/). This tool simulates building characteristics using Monte Carlo simulation, estimating structural features based on their observed regional proportions. Each building is then designed using the equivalent lateral force method, following European standards and using the lateral force coefficient (β) classification described by Crowley et al. [18]. The resulting building models are compatible with OpenSees, allowing nonlinear time history analyses to be performed in order to estimate specific fragility curves for each of the buildings as well as the structure-to-structure damage correlation with the proposed methodology.

To ensure the simulated buildings reflect realistic conditions, their characteristics were estimated based on real-world data from a study by Corlito and De Matteis [19], in which detailed structural properties of reinforced concrete (RC) buildings across eight municipalities were collected for the Caserta province, Italy. It was decided to focus on three municipalities, Castello del Matese, Gioia Sannitica, and Piedimonte Matese, that share a similar high seismic hazard classification according to the Italian building code, NTC18 [20]. The number and locations of buildings in the analysis were derived from an accurate exposure model, discussed in the next section, reflecting the actual portfolio of buildings of the selected typologies in the studied municipalities.

3.1 Exposure model

The exposure model used for the analysis was the one considered for the European Seismic Risk Model (ESMR20) [21]. This model in particular was developed as part of the SERA project for 44 European countries, using publicly available information. It divides the buildings into residential, commercial and industrial use, and categorises them according to the GEM Building Taxonomy v3.1. For the analysis, only the residential buildings with more than four storeys were considered, including all code levels and design lateral force coefficients found in the area. In total there are 62 buildings located in the studied municipalities, distributed into the following taxonomies:

- CR/LFINF+CDL+LFC:0.0/HBET:4-: Low code RC infilled frames with more than four storeys designed for a load factor of 0% (41 Buildings).
- CR/LFINF+CDL+LFC:7.0/HBET:4-: Low code RC infilled frames with more than four storeys designed for a load factor of 7.0% (15 Buildings).

- CR/LFINF+CDM+LFC:7.0/HBET:4-: Moderate code RC infilled frames with more than four storeys designed for a load factor of 7.0% (6 Buildings).

Since the considered exposure model has all buildings in each municipality lumped in one point, the buildings were spatially disaggregated according to the population distribution within the region. The Python scripts developed by GEM to perform this analysis were used, which can be found in their spatial disaggregation repository available on GitHub [22]. The data on the distribution of the population used for the analysis was obtained from the WorldPop data of Italy for the year 2020, with a resolution of 100m [23]. The spatially disaggregated location of the assets adopted for this study is presented on Figure 1. While these do not necessarily correspond to the actual locations of these typologies, it not envisaged to have any impact on the overall conclusions of the work.

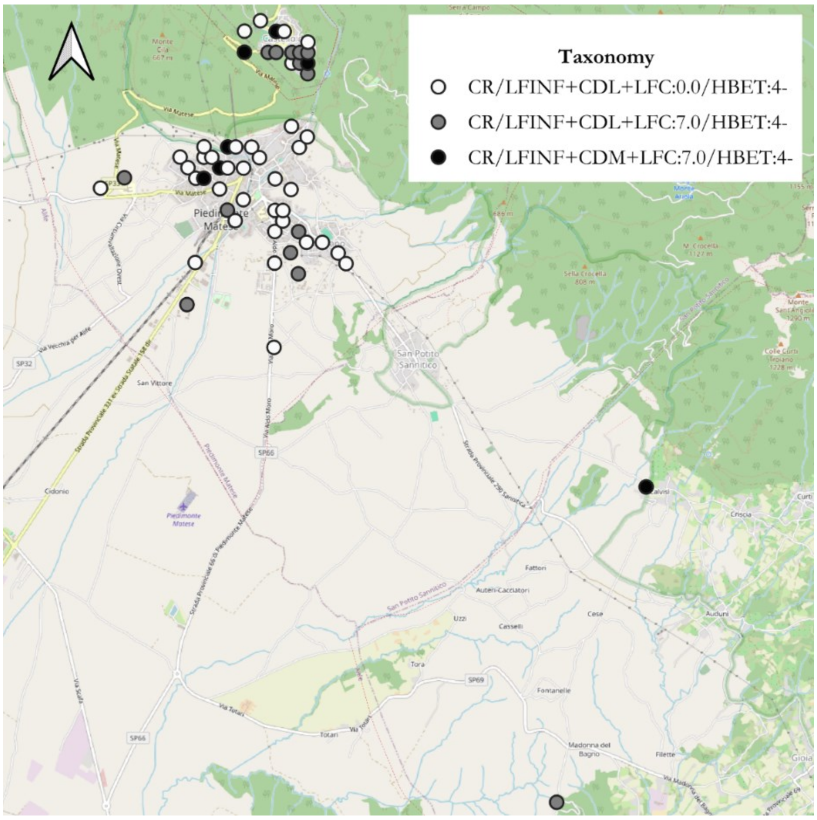

Figure 1 Geographical location of assets

3.2 Modelling of buildings

The portfolio of the 62 buildings found in the exposure model was simulated with the Built Environment Data's Design service based on observed regional proportions of given characteristics, such as slab type, column geometry, number of stories and construction quality. The structural attributes were obtained from a study by Corlito and De Matteis [19] who analysed RC buildings in the province investigated here. Each of the buildings was then designed to its vertical loads and the corresponding lateral force factor, following the design standards in Europe for the desired level of the design code and using the equivalent lateral force coefficient method.

The resulting structural models were developed in OpenSeesPy. Each building was modelled with elastic elements for beams and columns, while zero-length elements were used to simulate nonlinear behaviour, capturing plastic deformations under seismic activity. Pushover analyses and modal characteristics were calculated to transform the calculate the properties of the equivalent nonlinear SDOF oscillator. The buildings were distributed geographically across the area, assigning them a random location from the spatially disaggregated exposure model.

3.3 Seismic hazard

The seismic hazard for the case study was quantified performing a probabilistic seismic hazard analysis (PSHA) at the mean coordinates of all the buildings considered in the region. For the analysis the source model developed in the frame of the 2013 European Seismic Hazard Model (ESHM13) was used [24]. The ground motion model (GMM) considered was the one developed by Boore et al. [25], assuming a firm soil to account for the local site effects, Vs,30=480 m/s, and considering the spatial correlation model from Jayaram and Baker [26]. The IM selected for the analysis was the average spectral acceleration over a period range, Saavg(T), since it not only accounts for the period lengthening of each individual structure when they start to behave inelastically, but also for the variability of the periods of the different structures analysed. Having that in mind, the period of the range for the analysis was defined based on the limits proposed by Eads et al. [27], considering the average period of both directions of all the 62 buildings under analysis (i.e., 0.12s-1.82s). The $Sa_{avg}(T)$ intensity levels for different return periods is presented in Table 1.

Return Period [years]	22	42	72	140	224	475	975	2475	4975	9975
PoE in 50 years	0.897	0.696	0.501	0.300	0.200	0.100	0.050	0.020	0.010	0.005
$Sa_{avg}(T)$ [g]	0.021	0.044	0.072	0.123	0.166	0.268	0.383	0.577	0.746	0.945

Table 1. $Sa_{avg}(T)$ for different return periods

3.4 Fragility estimation

Fragility curves were derived for each of the buildings by performing a MSA on each of the full 3D models of the buildings for a defined DS. The analysis was performed considering the return periods presented on Table 1, selecting 40 records using the conditional spectrum method described by Lin et al. [28]. The resulting ground motions were therefore hazard consistent with the Sa(T) values at different vibration periods. Then, a lognormal distribution was fitted to the results obtained from the MSA using the maximum likelihood method, as outlined by Baker [29].

3.5 Quantifying structure-to-structure damage correlation

The structure-to-structure damage correlation was estimated with the method previously described by performing IDA on the equivalent nonlinear SDOF oscillators. Since the considered earthquake rupture scenario was selected according to the disaggregation of the 475-year return period, it is expected that the simulated ground motion fields will be centred around the $Sa_{avg}(T)$ value estimated in the PSHA for that intensity. Then, to prevent bias from excessive record scaling in the IDA results, the analysis used the 40 ground motions previously selected for consistency with that hazard level, which were also used to derive fragility functions. For the linearization of the buildings pushover curves required to define the nonlinear SDOF oscillators, maintaining the maximum strength of the buildings over the area beneath both curves was prioritized, as this was considered a more representative parameter of their mechanical behaviour.

4 SCENARIO ANALYSIS

4.1 Estimation of ShakeMap

The total number of damaged buildings was estimated for a given earthquake rupture scenario, corresponding to an event of magnitude 6.25 at 5 km from the point of mean coordinates between all the considered buildings in the study region. The scenario was selected based on the results of the disaggregation of the 475-year return period. The intensity of shaking at each building location was simulated for the specified earthquake rupture scenario, using the same GMM and spatial correlation model previously defined for quantifying seismic hazard in the region. Since Saavg(T) was used for the analysis, and the selected GMM and spatial correlation model estimate spectral ordinates for specific periods, the ground motion fields were calculated indirectly by obtaining spectral acceleration values across different periods, following the method proposed by Kohrangi et al. [30]. This allowed Monte Carlo simulations of multiple earthquake scenario realisations to be performed, both including and neglecting the spatial correlation.

An example for two of the realisations is presented in Figure 3, one using the spatial correlation (left), which is the more realistic case, and another neglecting it (right), which is less realistic and more randomised. It can be seen that, even if both realisations have very similar mean values of $Sa_{\mathrm{avg}}(T)$ (0.266g for the spatially uncorrelated model and of 0.260 g for the spatially correlated one), the spatially uncorrelated model presents a larger variation of the data, containing the points with both the largest and lowest estimations at random locations. The spatially correlated model, on the other hand, presents a more reasonable estimation of the ground motion intensity, capturing the variability of the results but maintaining a realistic geographical distribution of the data in which similar $Sa_{\mathrm{avg}}(T)$ are observed at close locations.

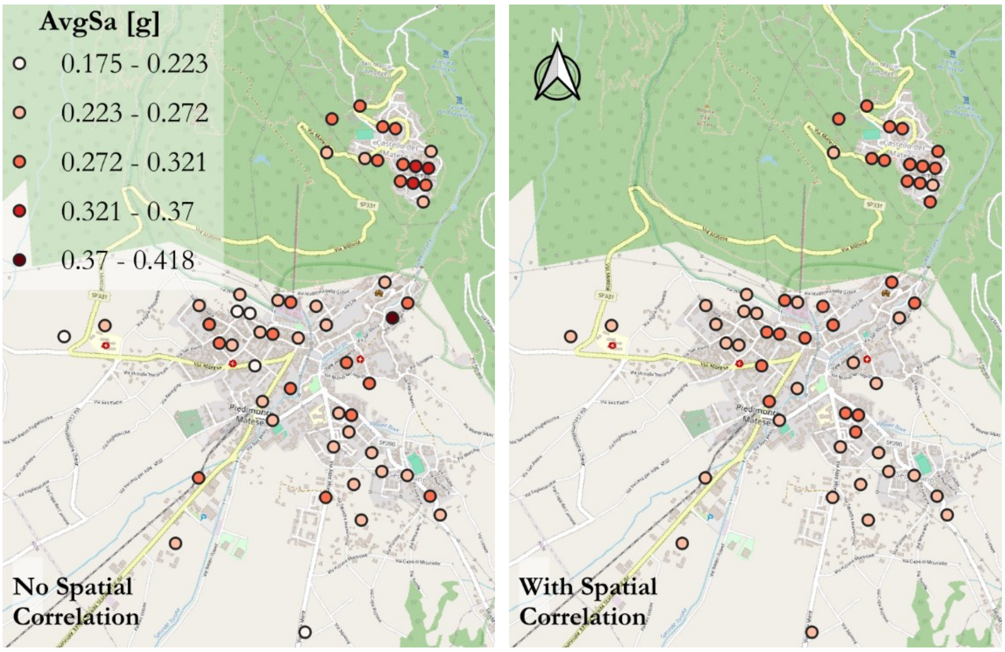

Figure 2 Modelled $Sa_{\mathrm{avg}}(T)$ with (left) and without (right) spatial correlation for one realization

4.2 Estimation of building damage scenarios

A DS of light damage was defined as the case in which the peak storey drift (PSD) in any of the two directions of the buildings exceeds a value of 1.0%. Monte Carlo simulation was used to evaluate the impacts of considering or neglecting both the spatial correlation and the structure-to-structure damage correlation in the analysis. Different cases were analysed to see the impact in the results of considering and neglecting both the spatial correlation and the structure-to-structure damage correlation in the model. A summary of the considered cases is presented in Table 2.

Case	Spatial correlation, ρ_{sp}	Damage correlation, ρ_{dm}
1	Not Considered	Not Considered
2	Considered	Not Considered
3	Not Considered	Considered
4	Considered	Considered,

Table 2. Considered Cases for Damage Estimation

After running 5000 realisations, it was determined that there is not a significant variation of the estimated mean and median number of damaged buildings, as presented on Table 3 and shown in Figure 3. However, there is a substantial difference in the standard deviation, which affects the tails of the distribution and the probability of exceeding a certain number of damaged buildings, as presented in Figure 3.

Statistic	Case 1	Case 2	Case 3	Case 4
Mean	30.52	30.42	30.70	30.44
Median	30.00	31.00	31.00	30.00
Standard Deviation	9.47	20.02	13.08	22.78

Table 3. Statistics of results for considered cases

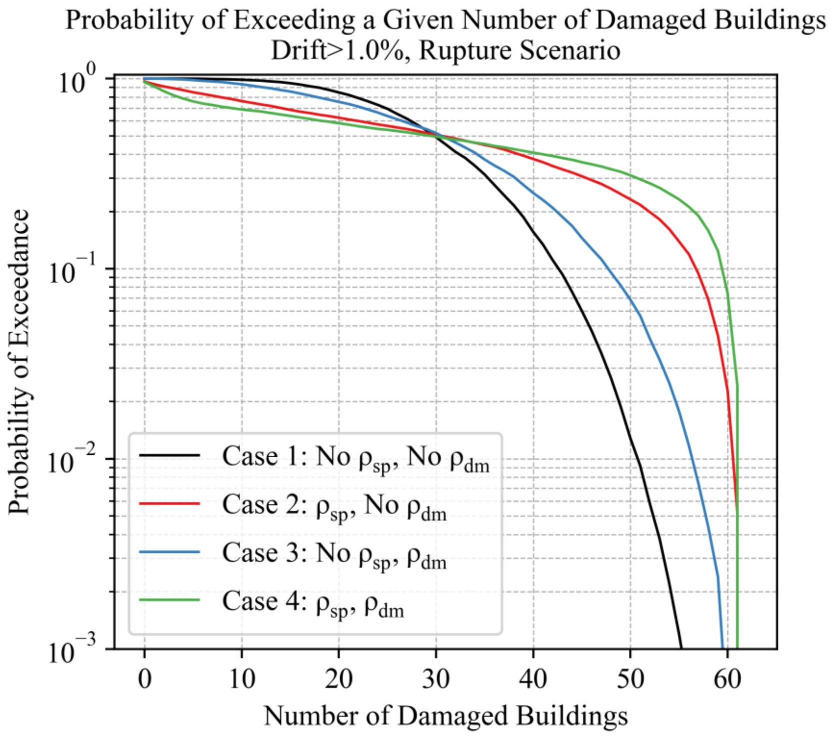

Figure 3 Comparison of probability of exceeding a given number of damaged buildings for the rupture scenario

It can be observed that accounting for damage correlation has a significant impact on the results, at least for the considered case study, particularly in the scenario where spatial correlation is not taken into account. This indicates that the effects of damage correlation are not implicitly captured by incorporating spatial correlation, as some might assume. Moreover, the inclusion or exclusion of spatial correlation also influences the calculation of damage correlation itself, given that it depends on the values of the simulated ground motion intensities, which are derived based on that variable.

At first glance, it might seem that including damage correlation does not lead to significant differences in the results when spatial correlation is also considered. However, this is primarily due to the fact that the maximum possible number of damaged buildings (62) is relatively close to the median value (30). If the results were not truncated at this maximum, the difference between the probabilities of a larger number of damaged buildings would continue to increase significantly. To present the results in a more comparable manner the probability of exceeding a range of buildings between 35 and 50 is presented on Table 4.

Number of buildings	Case 1	Case 2	Case 3	Case 4
35	31%	45%	38%	45%
40	16%	38%	25%	40%
45	6%	31%	15%	36%
50	1%	23%	7%	31%

Table 4 Probability of exceeding a number of damaged buildings for the rupture scenario investigated

Once again, it can be observed that the differences between the cases increase with the number of damaged buildings. Given that the use of spatial correlation is widely adopted and will likely always be used for this type of analysis, the results were compared using Case 2 as the reference. For instance, focusing on Case 4, which considers both spatial and damage correlation, the probability of exceeding more than 50 damaged buildings increases from 23% to 31%, resulting in a difference of around 35% between the two estimations.

To better understand the real-world implications of this difference, consider a hypothetical scenario in which the local government of the Caserta province plans strategies to finance the reconstruction of the three municipalities analysed in this study in the event of an earthquake. Assuming the earthquake scenario presented here is viewed as a "worst-case scenario," the government might decide to secure funds to repair the number of buildings with a 20% probability of being damaged by such an event. If the analyst only considers spatial correlation in the risk assessment, the government would plan to repair 52 buildings. However, if structure-to-structure damage correlation is also considered, as done in this study, the government would need to finance the repair of 57 buildings, resulting in an increase in the required resources. Obviously, these numbers are case study specific and further studies could be conducted to examine the impacts in other regions, but the fundamental issue is clear.

5 SUMMARY AND CONCLUSIONS

This study demonstrated the substantial impact that structure-to-structure damage correlation can have on regional seismic risk assessments when either included or neglected. Through a case study estimating the probability distribution of the total number of damaged buildings, it was shown that while this parameter does not influence the mean estimates, it significantly affects the standard deviation and overall distribution shape. These factors play a crucial role in determining the likelihood of exceeding high damage thresholds, a key variable for government agencies planning mitigation strategies.

For instance, in a hypothetical scenario for the Caserta Province case study, if authorities allocate resources based on the number of buildings with a 20% probability of exceeding a given damage threshold, they would need 10% more resources for building repairs when both damage and spatial correlations are accounted for. This finding underscores the importance of incorporating these correlations into risk models to enhance the accuracy of resource estimation and optimize disaster recovery planning.

Nevertheless, further investigation is needed to assess the accuracy of correlation estimates derived from the simplified equivalent SDOF nonlinear oscillators. A potential extension of this work could involve comparing these results with those obtained from IDA conducted on full 3D building models. Additionally, validating these estimates using data from real seismic events would be ideal, as it would help determine whether the analytical approach presented here can be used to develop mathematical models that express correlation as a function of key building characteristics influencing vulnerability. However, such validation poses challenges due to the limited availability and complexity of observational data.

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