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

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Abstract

One of the main challenges of implementing the performance-based earthquake engineering framework and computing risk and associated consequences on a regional scale is incorporating structure-to-structure damage correlation in the analysis. This correlation relates to the expected damage between different structures in a region, considering they were likely built with similar characteristics, resulting in similar strengths or deficiencies when subjected to seismic shaking. While this type of correlation has been largely neglected in risk analysis to date, it can be estimated analytically from non-linear time history analyses (NLTH) when models of all buildings in the region are available, requiring a computationally demanding and time-consuming method. Some strategies, however, can be implemented to simplify the procedure, such as analysing equivalent single degree of freedom (SDOF) oscillators instead of full 3D models of the buildings, an approach commonly found in the literature for similar applications.

To examine the impact of considering such correlation in a regional seismic risk assessment, a case study was conducted, involving the assessment of mid-rise reinforced concrete frame buildings in the Province of Caserta, southern Italy. The correlation was estimated from the results of Incremental Dynamic Analysis (IDA) performed on equivalent SDOF oscillators. Even though it was found that the incorporation of the correlation in the analysis does not significantly alter the estimates of the mean and median number of damaged buildings from a given earthquake scenario, it affects the probability distribution of the data, increasing the estimated risk of low- or widespread damage. Incorporating this aspect into regional risk analysis leads then to more accurate damage and loss estimates, enabling improved strategies for disaster risk preparedness and mitigation.

Keywords: risk analysis, regional assessment, structural damage, correlation

1. Introduction

The quantification of seismic risk has garnered considerable attention from practitioners and researchers in earthquake engineering over the past few decades. A notable advancement in this area is the performance-based earthquake engineering (PBEE) framework, developed by the Pacific Earthquake Engineering Research Center (PEER). Initially introduced in SEAOC's Vision 2000 and subsequently refined in the FEMA P-58 report [1], PBEE has become the leading methodology for assessing the seismic risk of individual structures worldwide.

The PBEE framework systematically addresses uncertainties and variabilities across its modules: earthquake hazard, structural response, damage assessment, and consequence estimation. It begins with a probabilistic approach to the earthquake hazard, which quantifies ground motion intensity measures (IM) such as spectral acceleration or peak ground acceleration at the building site. The outcome is a hazard curve representing the mean annual rate of exceedance for various IM levels.

In the building response module, engineering demand parameters (EDP) like peak story drift or peak floor acceleration are used to describe the structure's response at different IM levels. These are typically estimated through nonlinear time history analyses, using methods such as incremental dynamic analysis (IDA) [2] or multiple stripe analysis (MSA) [3]. The damage module then uses fragility curves to model the likelihood of reaching specific damage states (DS) for each EDP, while the consequence assessment module translates these damage outcomes into economic losses, casualties, or downtime, known as decision variables (DV). The entire framework integrates these components using the total probability theorem, often solved through Monte Carlo simulation for complex cases.

While PBEE was initially designed for single buildings, extending performance assessment to a regional level is essential for understanding the societal impacts of seismic events. This broader perspective, termed regional performance-based earthquake engineering (RPBEE), requires adjustments to the traditional PBEE methodology, particularly in modelling uncertainties and correlations between variables [4] and the impacts on the broader community. For example, at a regional scale, hazard is treated as a vector representing ground motion intensities at various building sites. These intensities are modelled as random variables following a multivariate lognormal distribution, incorporating a spatial correlation through models such as those developed by Bodenmann et al. [5] and Esposito & Iervolino [6], among others.

The building response module at the regional level often employs taxonomies to group structures with similar characteristics, focusing on overall damage performance rather than individual component behaviour. Fragility curves, that reflect probabilities of observing different global damage states, are used for each taxonomy. Considerable efforts have been made by researchers and organizations to develop fragility curves for commonly used taxonomies worldwide, such as the work of the Global Earthquake Model Foundation (GEM).

Considering regional construction practices, buildings designed and built during similar time periods in a specific geographic area often share structural characteristics, which leads to them having similar strengths or deficiencies during seismic shaking. This results in the fact that damage experienced by one building is likely correlated with damage to nearby, similar structures, a phenomenon known as structure-to-structure damage correlation. Accurately modelling this correlation is crucial, as it significantly influences estimates of large-consequence risks; however, it is either completely neglected or considered in an oversimplified manner by risk modellers in their analysis. A case study in the province of Caserta, Southern Italy, was performed to illustrate the importance of incorporating this correlation in risk analysis, emphasising how its careful estimation is fundamental for a more accurate risk assessment.

2. Structure-to-structure damage correlation

According to Heresi and Miranda [4], 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 [7], 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. [8] and Xiang et al. [9]. 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 [10] 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, 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:

$$\rho_{1,2} = \frac{P[D_1=1,D_2=1,]-p_1p_2}{\sqrt{p_1(1-p_1)p_2(1-p_2)}} \quad (1)$$

where p_1 and p_2 correspond to the marginal probability of buildings 1 and 2 experiencing a given damage state, and $P[D_1=1,D_2=1]$ 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 [10] 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 IDA or 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 [2]. The MSA, proposed by Jalayer [3], 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. If the same set of records is used for all structures, the probability of two buildings reaching certain damage state can be estimated by counting the records for which the corresponding limit EDP was exceeded for both buildings simultaneously and dividing by the total number of records. 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 the joint probability by counting the records exceeding the damage threshold for both buildings from the results of IDAs, as presented on Figure 1.

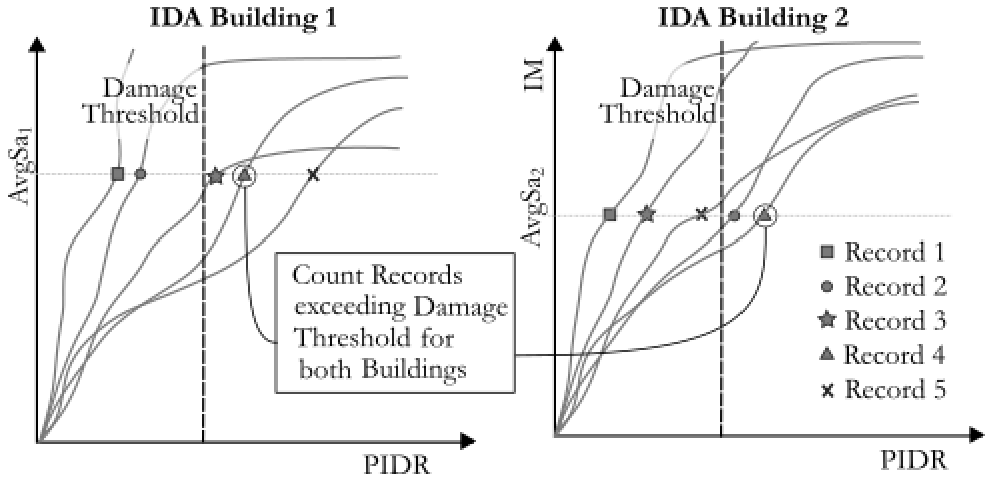

Figure 1. Estimation of joined probability distribution from IDA results

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. (2) and (3), 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.

$$p_1 = \frac{z_1}{n} \tag{2}$$

$$p_2 = \frac{z_2}{n} \tag{3}$$

where z_i is the number of observations of a given damage state 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 [15] and Nafeh et al. [16]. 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. [17]. 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 [18], 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 [19]. 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). This model in particular [20] 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 [21]. 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 [22]. The spatially disaggregated location of the assets adopted for this study is presented on Figure 2. 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.

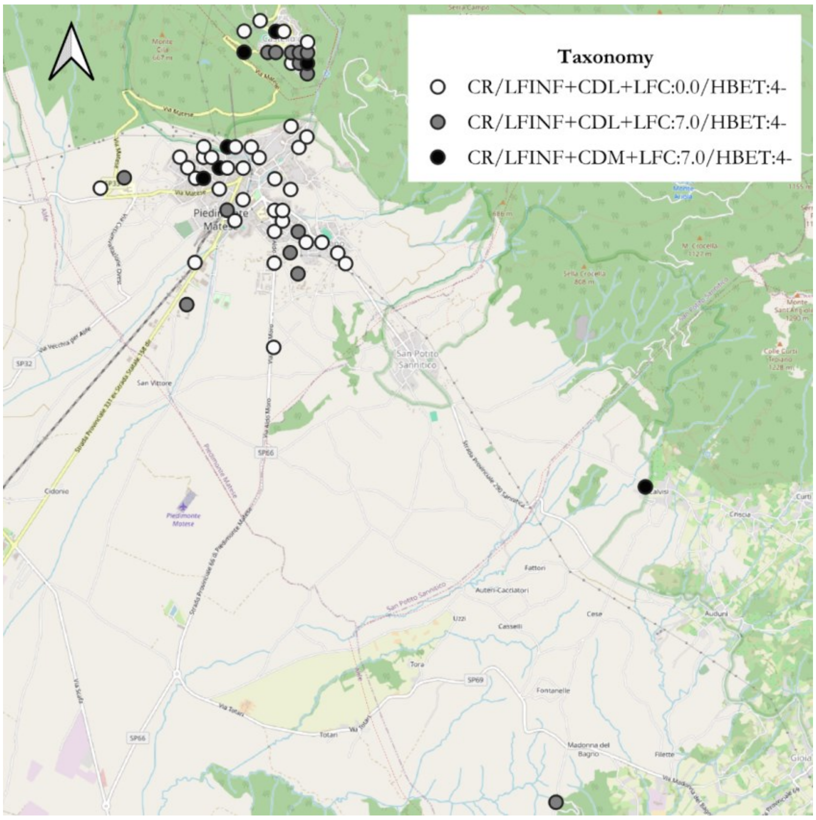

Figure 2 Geographical location of assets

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 [18] 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 [23]. The ground motion model (GMM) considered was the one developed by Boore et al. [24], assuming a firm soil to account for the local site effects, $V_{s,30}$=480 m/s, and considering the spatial correlation model from Jayaram and Baker [25]. The IM selected for the analysis was the average spectral acceleration over a period range, $Sa_{avg}(T)$, 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. [26], 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.

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

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

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. [27]. 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 [27].

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 $Sa_{avg}(T)$ 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. [28]. 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 $Sa_{avg}(T)$ (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 $Sa_{avg}(T)$ are observed at close locations.

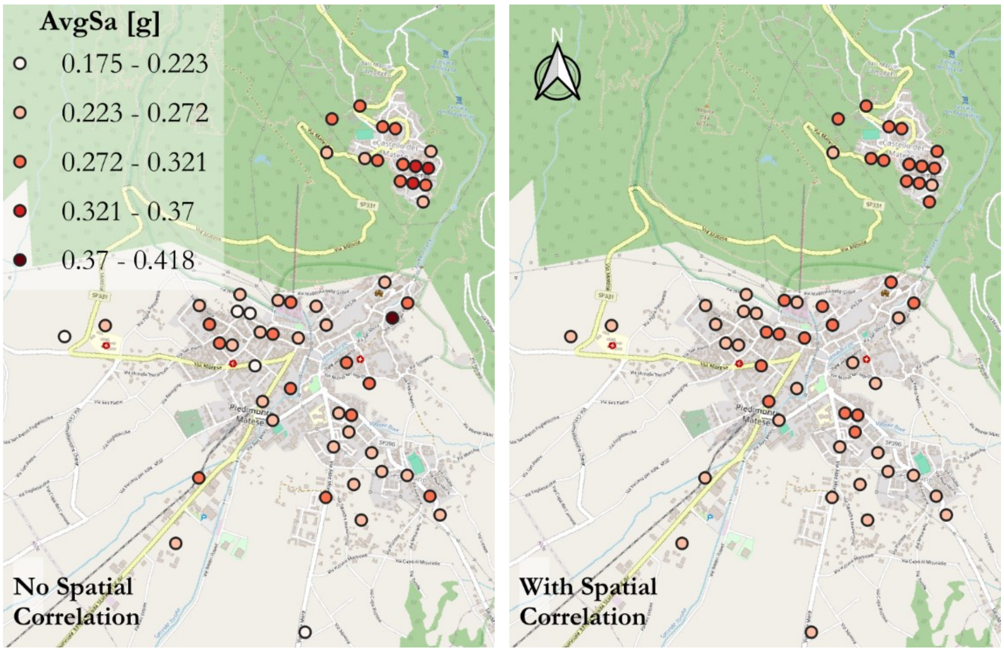

Figure 3 Modelled $Sa_{avg}(T)$ with (left) and without (right) spatial correlation for one realization

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.

Table 2. Considered Cases for Damage Estimation

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,

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 4. 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 4.

Table 3. Statistics of results for considered cases

Statistic	Case 1	Case 2	Case 3	Case 4
Mean	30.66	30.56	31.09	30.96
Median	31.00	30.00	32.00	32.00
Standard Deviation	5.72	10.01	17.87	20.04

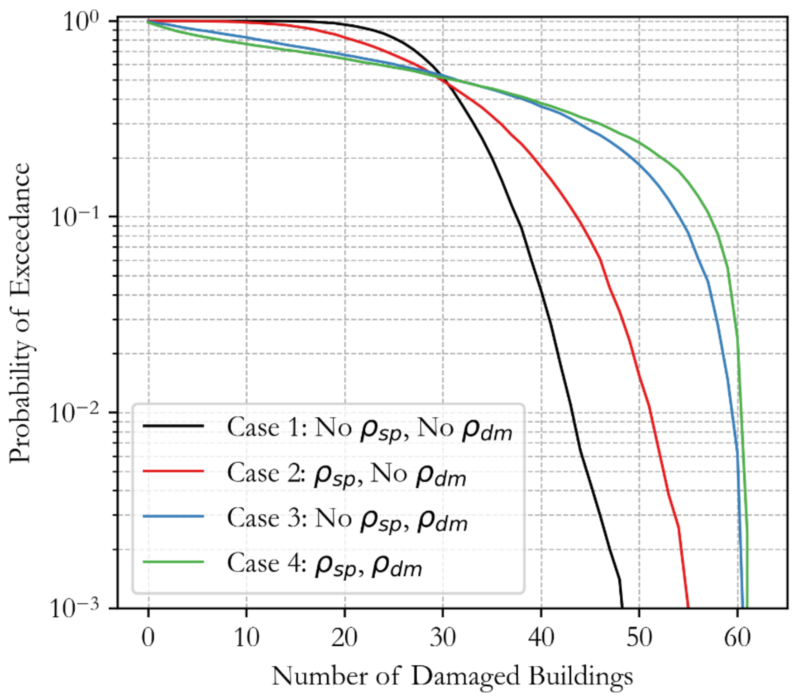

Figure 4 Comparison of probability of exceeding a given number of damaged buildings for the rupture scenario analysed

It can be seen that when considering only spatial or damage correlation, the latter has a more significant impact on the results. It can be deduced then that considering the structure-to-structure damage correlation can be as important as considering the spatial correlation on regional seismic risk assessment, at least for the case study under examination here. On the other hand, the use or not of the spatial correlation also impacts the calculation of the damage correlation itself, since it depends on the values of the simulated ground motion intensities that are derived based on that variable. To observe the results of the figure on a more comparable way the probability of exceeding a range of buildings between 35 and 45 is presented on Table 4.

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

Number of buildings	Case 1	Case 2	Case 3	Case 4
35	20%	33%	45%	45%
40	4%	18%	37%	38%
45	0.4%	8%	28%	31%

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 45 damaged buildings increases from 8% to 31%, resulting in a difference of around 300% 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 5% 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 47 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 59 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

In this study, it was demonstrated how significantly the results of a regional seismic risk assessment can differ when the structure-to-structure damage correlation is either considered or neglected. Using a case study where the probability distribution of the total number of damaged buildings was estimated, it was shown that even if this parameter doesn't affect the average estimates, it does heavily influence the standard deviation and shape of distribution. These parameters heavily impact the probability of exceeding a large number of buildings, which can be a variable of particular interest to government for planning mitigation strategies.

For example, in a hypothetical scenario in the Caserta Province case where the government plans resources based on the number of buildings with a 5% probability of exceeding damage from the earthquake scenario presented here, they would require 21% more resources for building repairs if both damage and spatial correlations are considered. This finding emphasises the importance for decision-makers to incorporate both correlations in risk modelling to ensure accurate resource estimation and efficient allocation of funds for recovery during disaster planning.

It is still important, however, to determine how good are the estimations of the correlation obtained by using the simplification of the equivalent SDOF nonlinear oscillators. A future application of this study could imply comparing the results with the case in which the IDA was performed on full 3D models of the buildings. It would also be ideal to validate the estimations with information from actual events, to assess whether the analytical approach proposed here can be used to develop mathematical models of correlation as a function of different building characteristics that influence their vulnerability. However, doing this validation might be difficult, given that the available data may be sparse and challenging to interpret.

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