Exploring Benefit-Cost Analysis for Earthquake Risk Reduction

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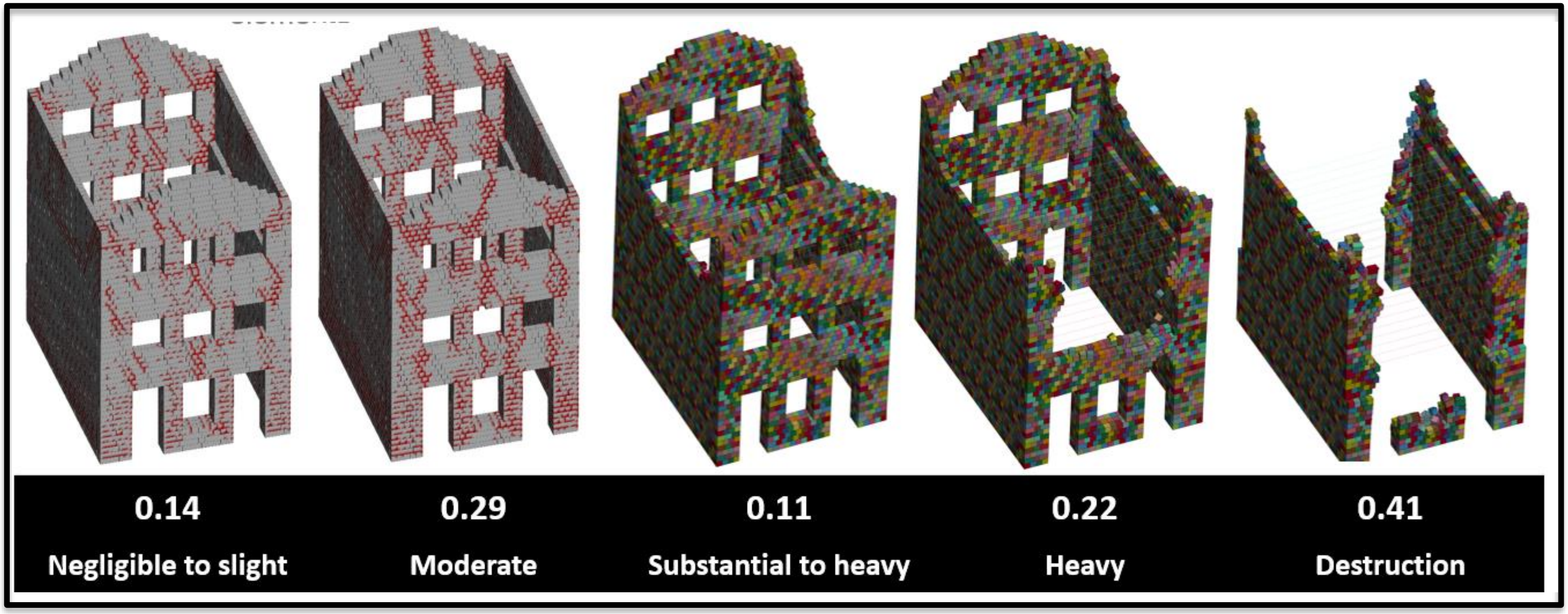
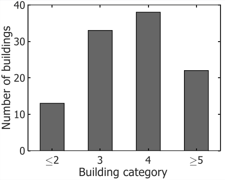
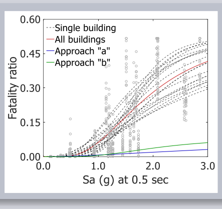
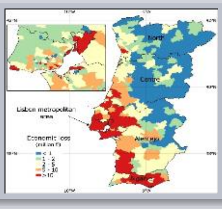


Presentation outline







The challenge

Characterisation of masonry buildings in Portugal

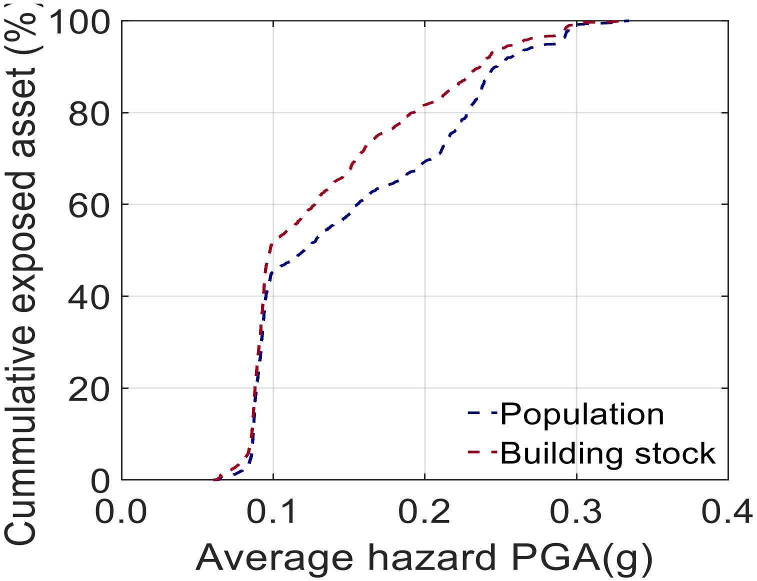
Fatality vulnerability functions

Earthquake scenarios

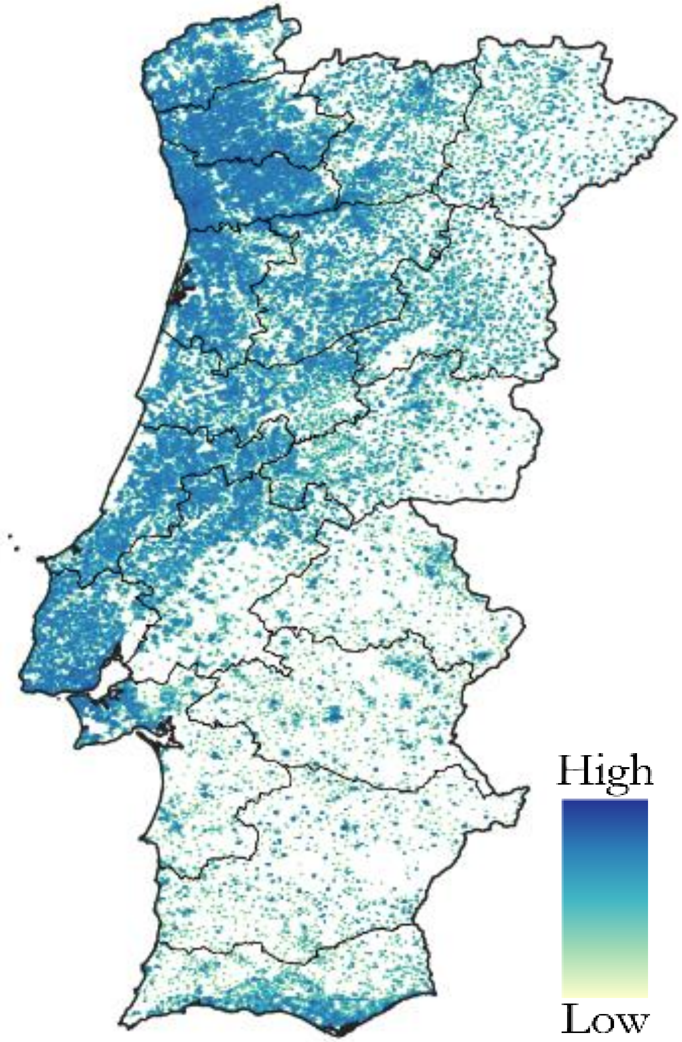
Conclusions

The challenge

Masonry buildings are the most common types of buildings in Portugal (in terms of number), and also the most fragile class.



Percentage of exposed assets to different levels of seismic hazard expressed in terms of PGA (g)

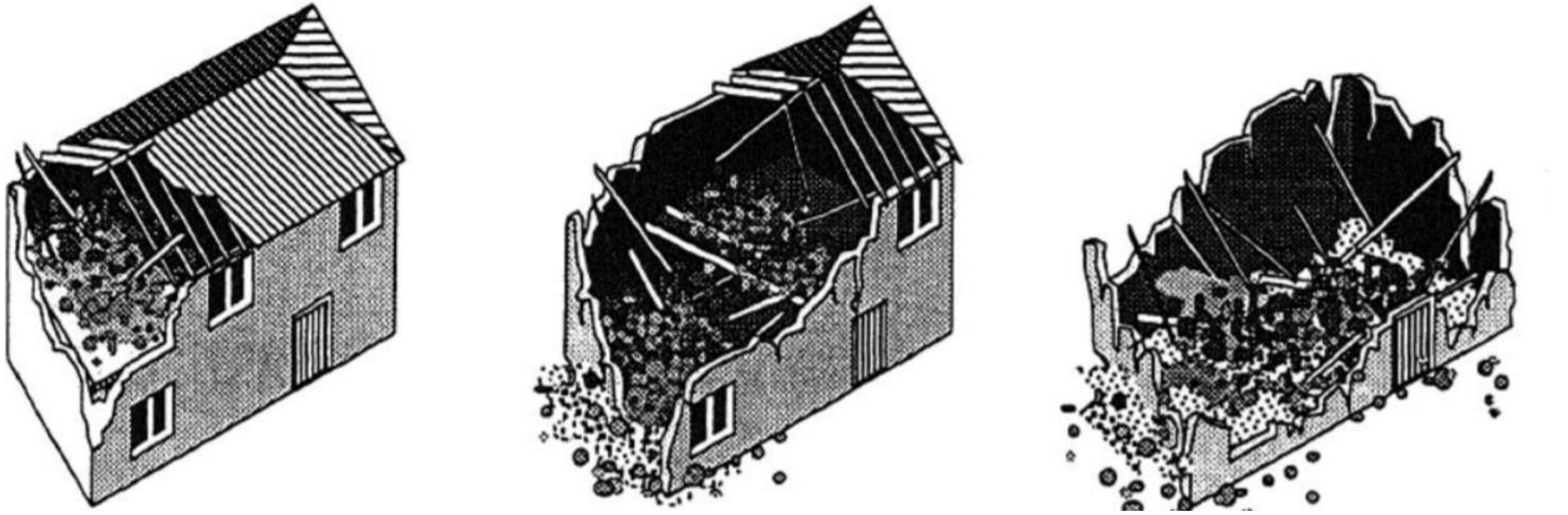


Density map of URM buildings without RC slab

The vast majority of the existing research used simplified models for the assessment of vulnerability of masonry buildings.

Literature focus mainly on economic losses and structural damage, leaving out the estimation of injured and fatalities. It is fundamental to include human losses in order to do not underestimate the risk.

According to Coburn et al [1] human losses are not appropriately predicted by physical damage states, instead volume of debris should be used.

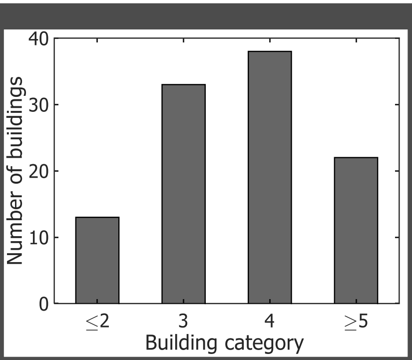


Damage Level: **D5 Collapse**
Extent of Collapse: 10% of Volume

Damage Level: **D5 Collapse**
Extent of Collapse: 50% of Volume

Damage Level: **D5 Collapse**
Extent of Collapse: 100% of Volume

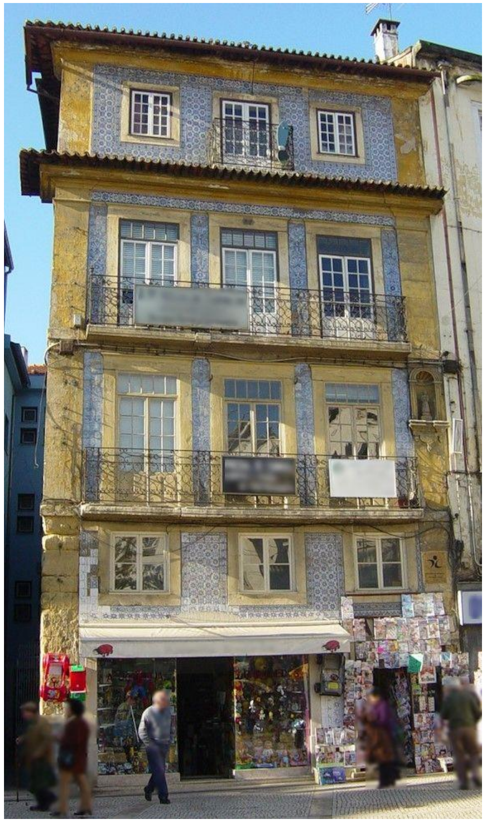
Example of different extents of collapse for damage state 5 in masonry buildings, extracted from [1]

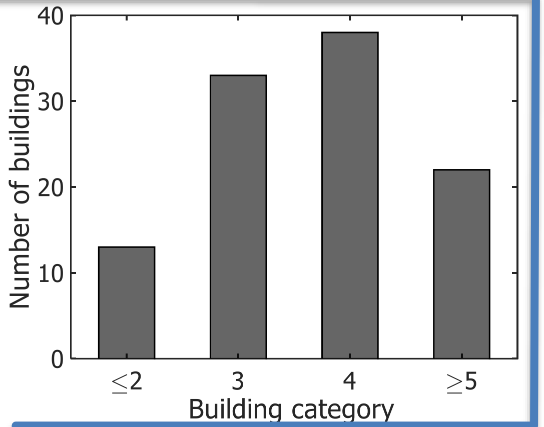


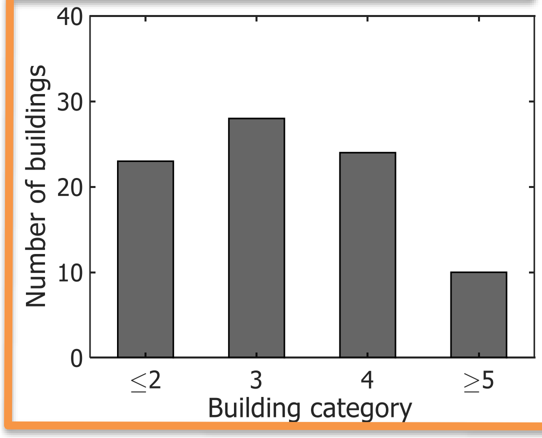
Characterisation of masonry buildings in Portugal

About 200 buildings were analyzed between limestone and granite masonry

NCREP consulting company provided access to its granite building database. Limestone database was constructed with basis in data from past studies [2]. A total of 185 buildings was gathered.



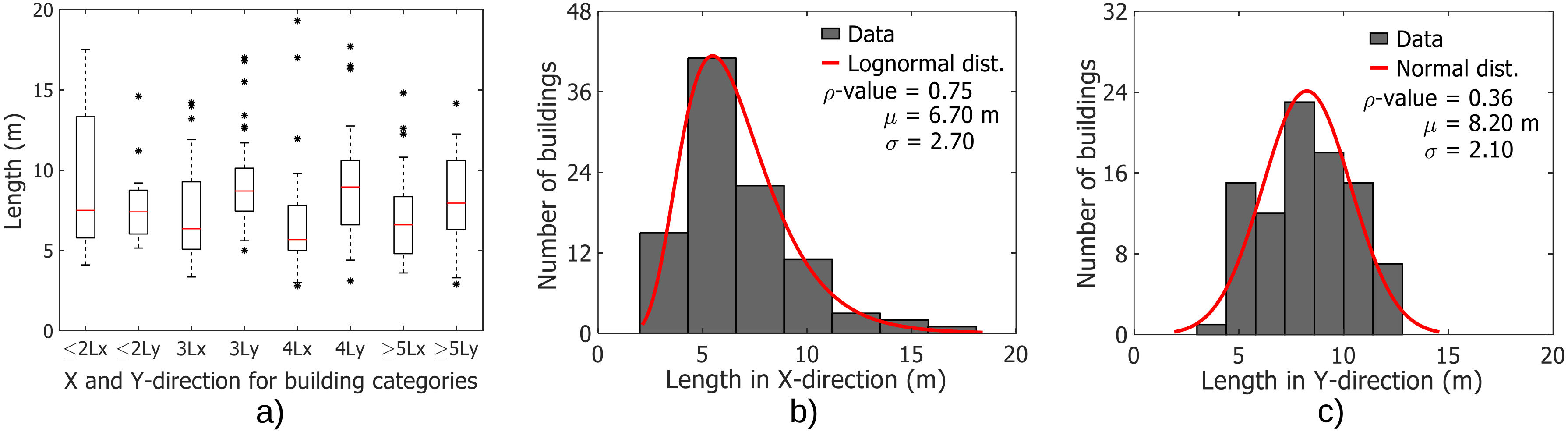




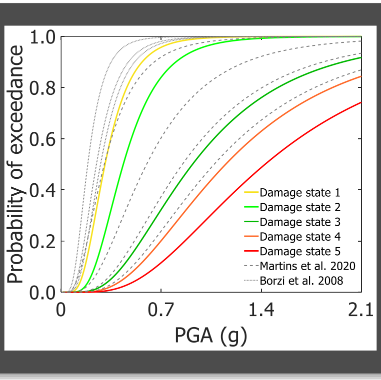
Schemes and number of Limestone and granite buildings analyzed

Data was used to develop statistical models for 10 structural features.

A set of probability density functions were tested for each structural feature and. The identification of most common archetypes was also part of the process

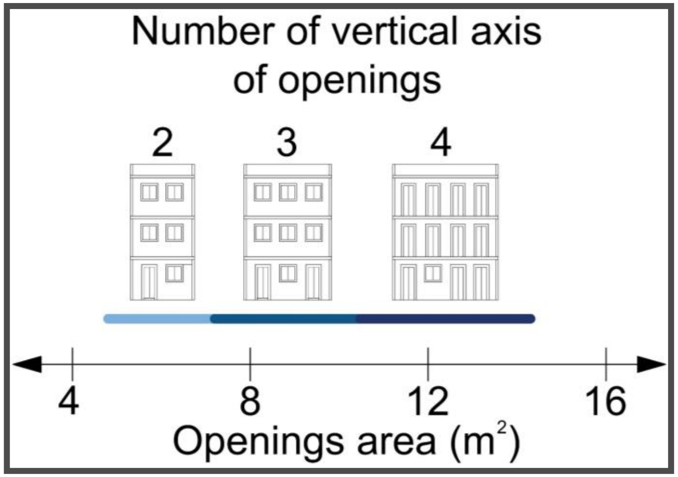


a) Dispersion, b) Histogram, fitted distribution and goodness-of-fit results for the length in façade (X) and c) orthogonal (Y) direction in Limestone masonry buildings

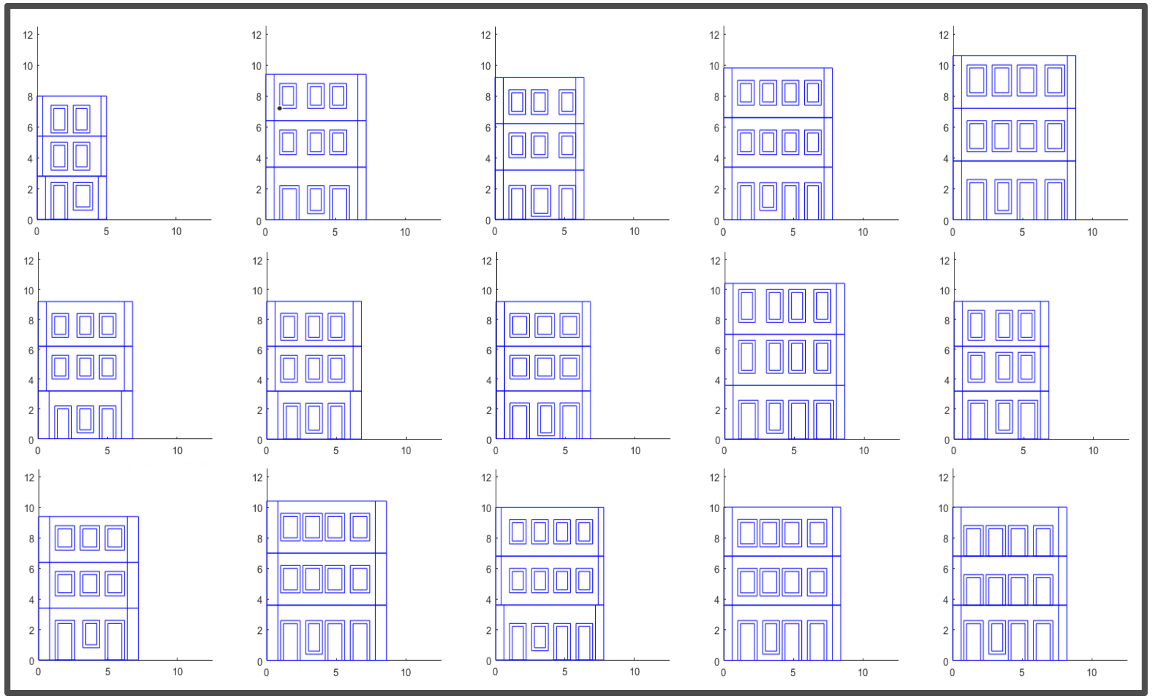


Development of fragility functions

A probabilistic framework was developed to randomly generate families of buildings of the same typological class.



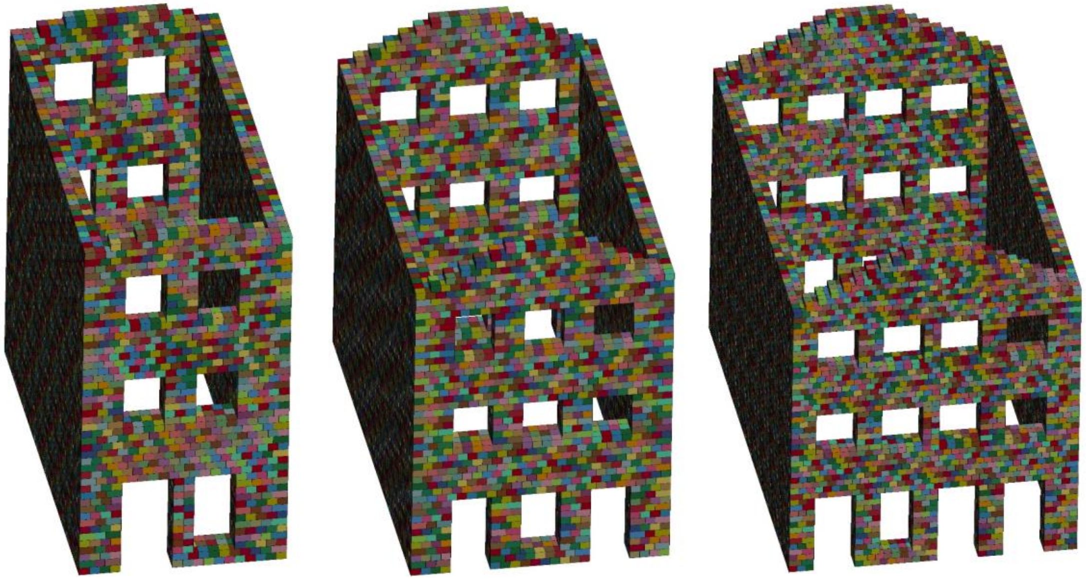
Archetypes and corresponding opening ratios



Sample of 15 3-storey buildings randomly generated. Lengths in meters (m)

A routine was programmed to export randomly sampled buildings into LS-Dyna software

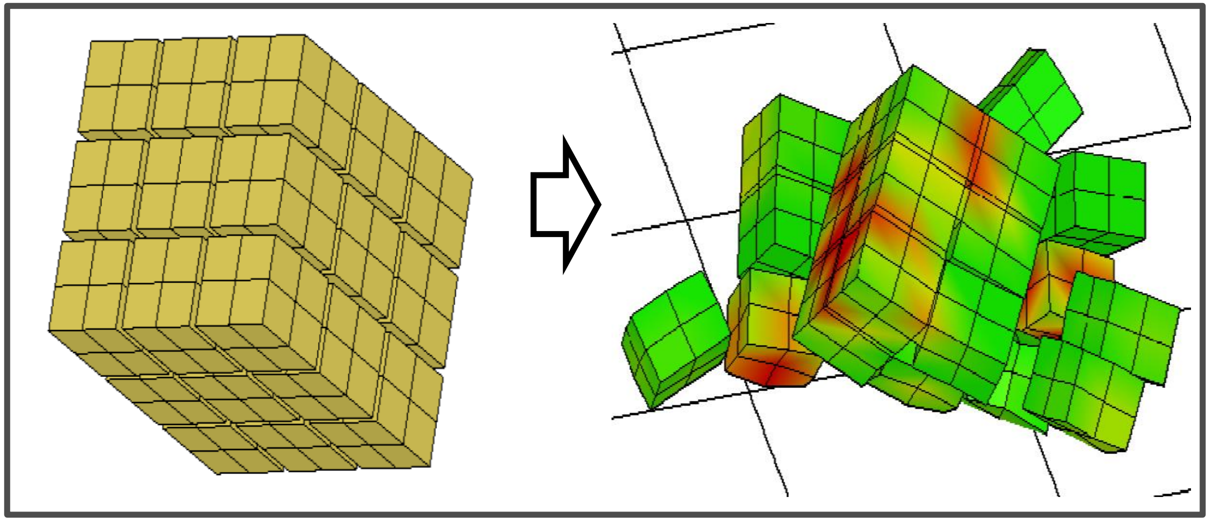
- Compression links to represent inter-storey timber joists
- Automatic deletion of elements that falls below the ground level
- Interlocking between walls
- Previous calibration of Pushover and Eigen-analysis
- Hourglass formulation



Example of LS-Dyna models randomly generated

The modelling strategy consist in creating elastic blocks which are joined by cohesive elements

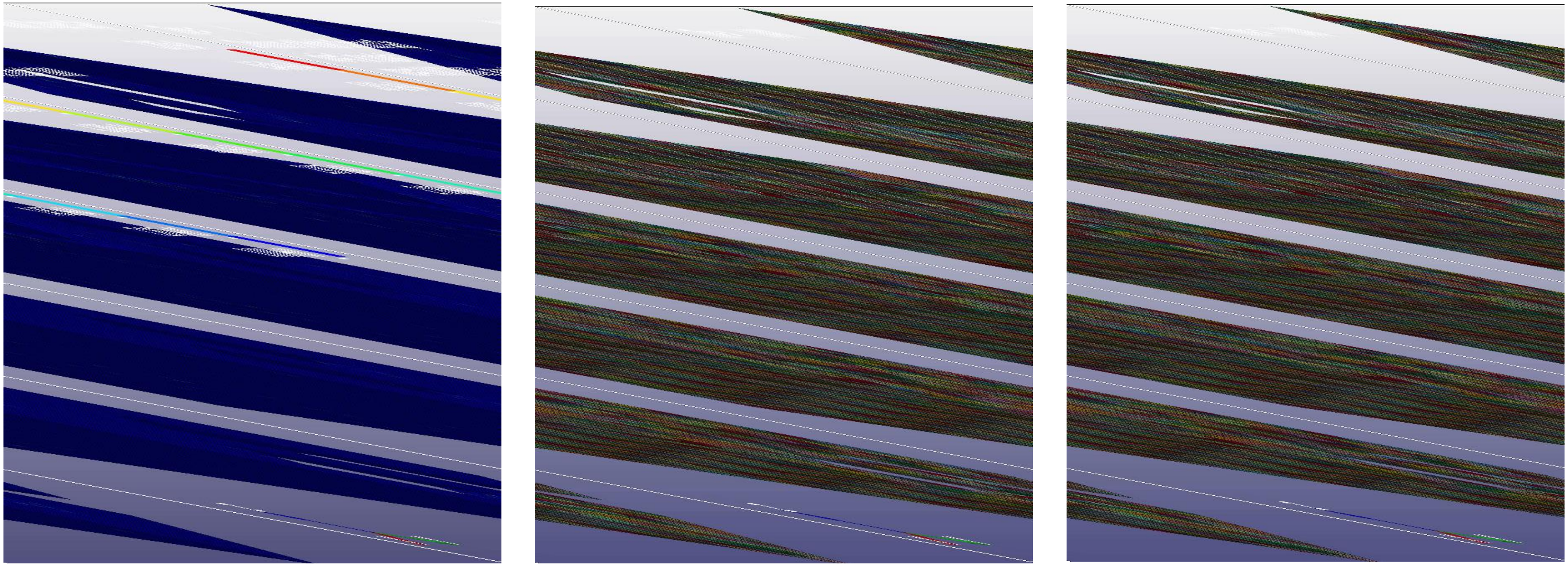
The cohesive elements are deleted as the load increases, and elastic elements are released. After release, contact between parts in modelled using the penalty stiffness approach.



Scheme of modelling strategy, adapted from Baker [4]

This strategy has been used in past studies (e.g [4-6]) for calibration of monotonic and shaking table test of masonry assemblies.

Each numerical model was tested against the 30 ground motion record.



Each numerical model was tested against the 30 ground motion record.

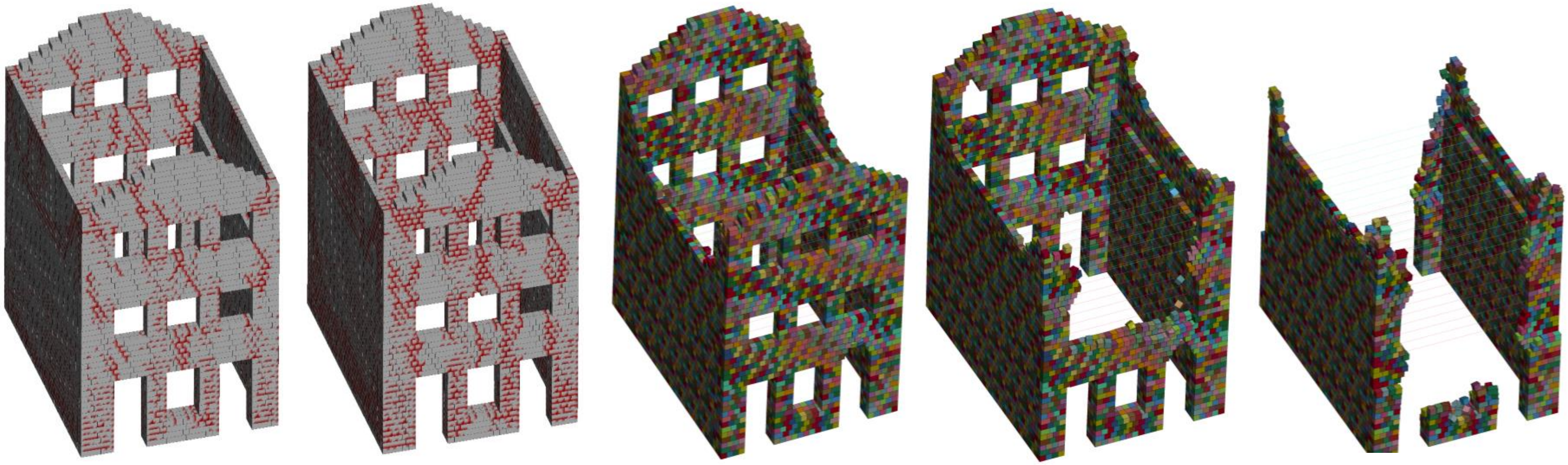
One of the current shortcomings in the existing literature is that some EDPs have a poor correlation with damage, particularly for URM. This is the reason because two novel EDPs are herein proposed with closer correlation with the actual damage

Cracked wall ratio

It is defined as the ratio between the collapsed and the total number of cohesive elements

Volume loss ratio

It is defined as the ratio between the volume of the damaged and the original building

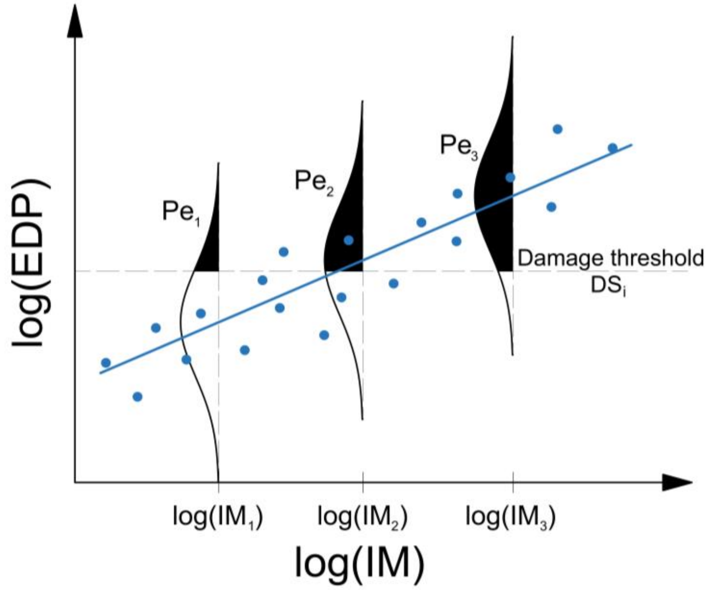


0.14	**0.29**	**0.11**	**0.22**	**0.41**
Negligible to slight	**Moderate**	**Substantial to heavy**	**Heavy**	**Destruction**

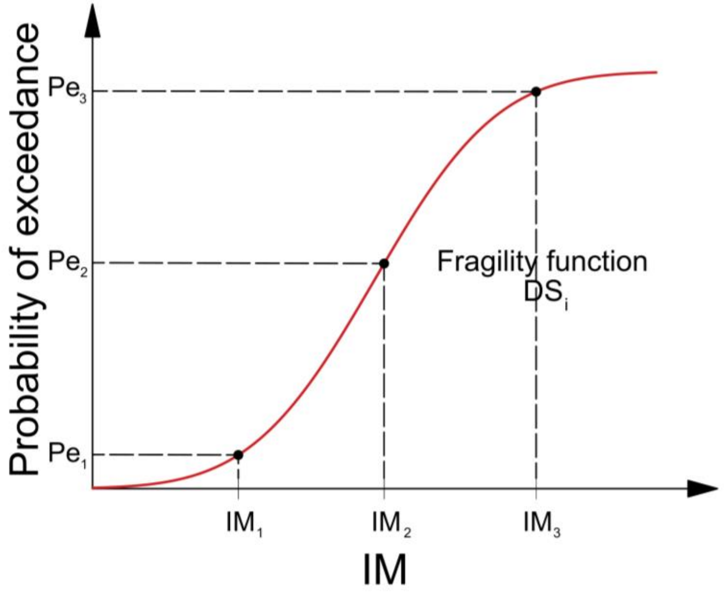
Fig. 10 Example of damage levels and corresponding EDPs and IMs

Structural analysis results were used to derive fragility functions for each building class using cloud analysis.

The approach consist in fitting EDP-IM to a line in log space, homoscedasticity is assumed. This approach has been widely tested for fragility assessment (e.g. Jalayer et al. [9], Jalayer et al. [10], Martins & Silva [11], and others)



$$\begin{cases} E\left[\log\left(EDP|IM\right)\right]=\log\left(a\right)+b\cdot\log\left(IM\right) \\ \sigma_{\log\left(EDP|IM\right)}=\sqrt{\dfrac{\sum_{i=1}^{n}\left(\log\left(EDP_i\right)-E\left[\log\left(EDP_i|IM_i\right)\right]\right)^2}{n-2}} \end{cases}$$



$$P\left[EDP\geq ds_i|IM\right]=1-\Phi\left(\frac{\log\left(EDP_{dsi}\right)-E\left[\log\left(EDP|IM\right)\right]}{\sigma_{\log\left(EDP\right)|IM}}\right)$$

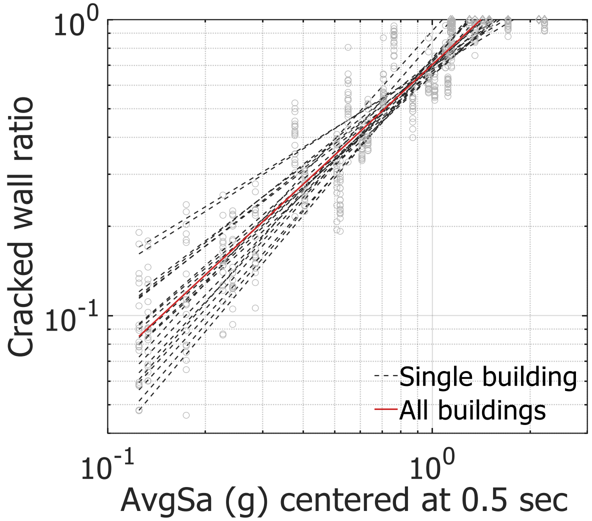
Building-to-building variability was found to have a larger impact than record-to-record variability for extreme damage states.

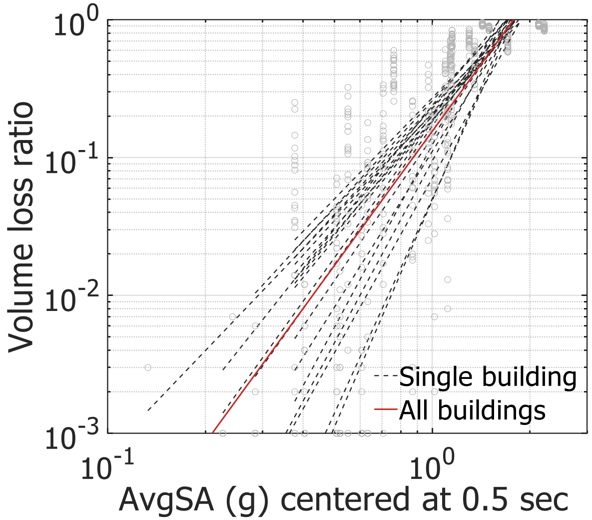
A set of 3-storey limestone masonry buildings were sampled and analyzed in LS-Dyna to assess the uncertainty associated to building-to-building and record-to-record variability

The total variability is expressed as:

$$\sigma_{\log(EDP|IM)} = \sqrt{\sigma_{btb}^2 + \sigma_{rtr}^2}$$

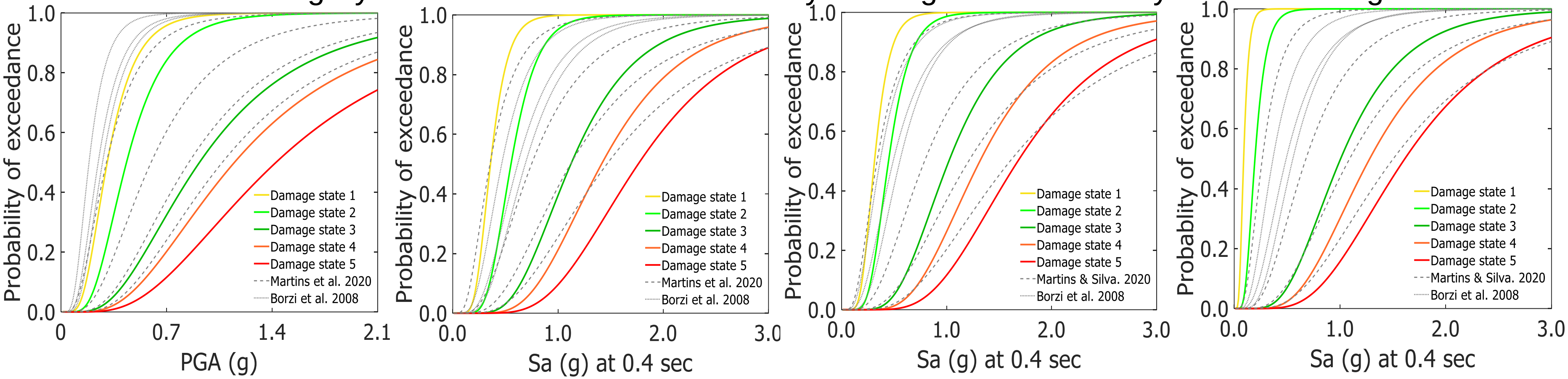
Where $\sigma_{\log(EDP)|IM}$ is the total variability, σ_{rtr} and σ_{btb} are the record-to-record and building-to-building variability.



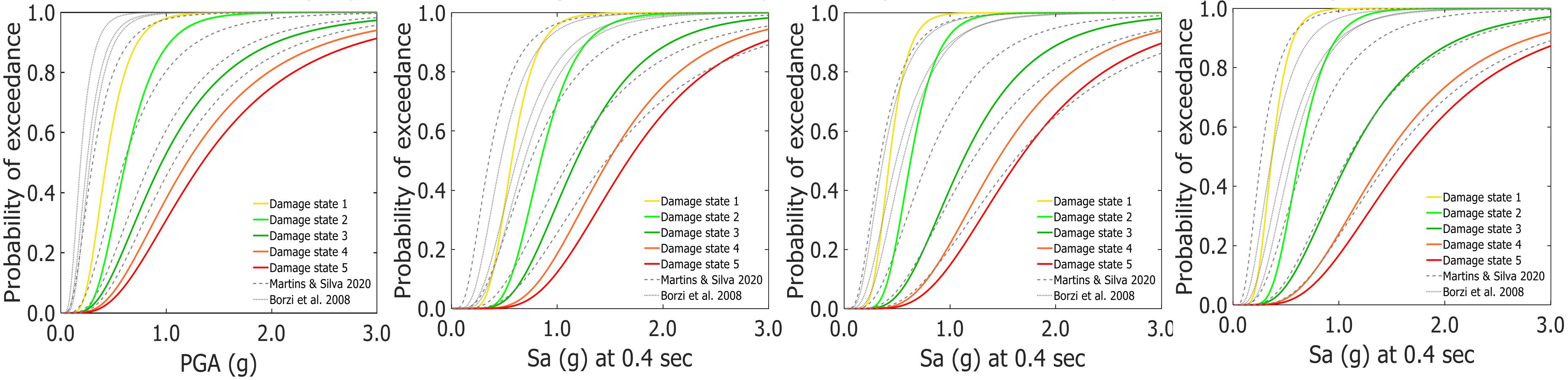


Fragility analysis was carried for other building classes.

Fragility functions for limestone masonry buildings of 1 to 4 storeys from left to right

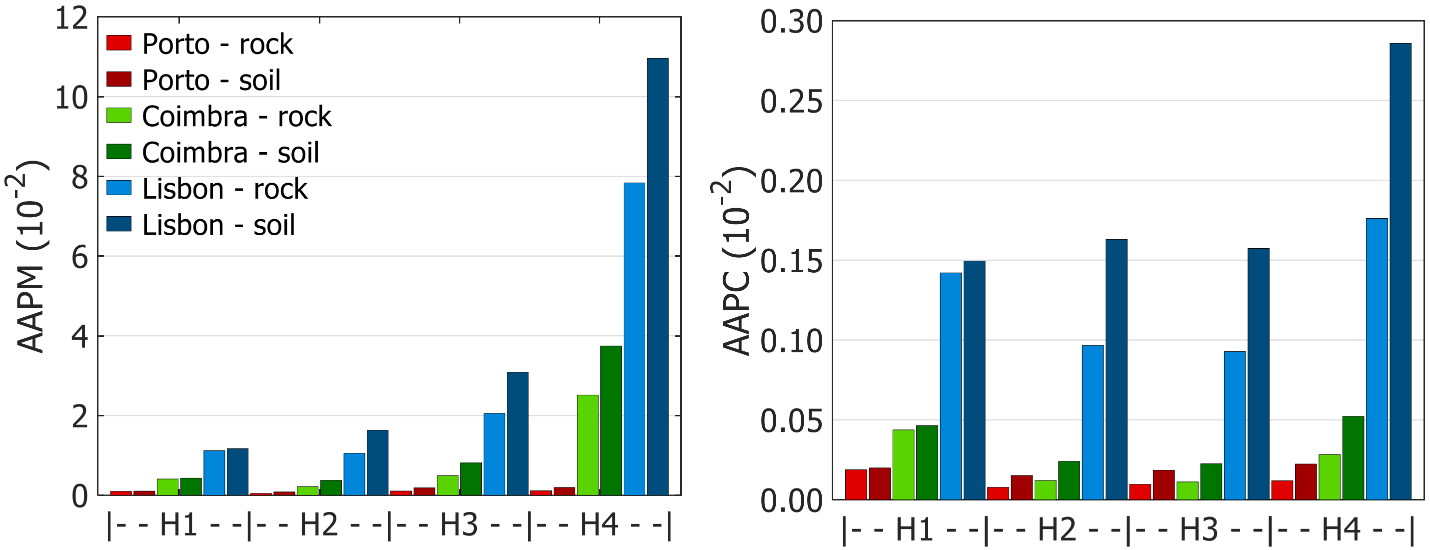


Fragility functions for granite masonry buildings of 1 to 4 storeys from left to right

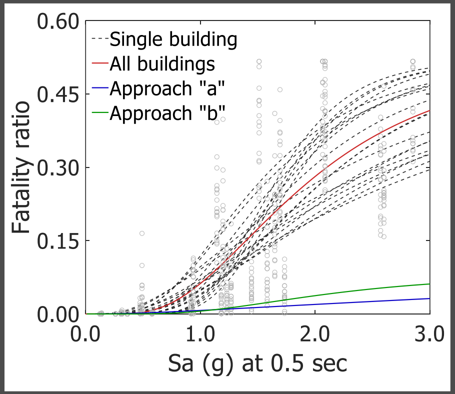


Average annual probability of achieving moderate damage and collapse was also calculated for Porto, Coimbra and Lisbon.

AAPD ranges from 10^{-2} to 10^{-1}, while literature proposes values from 10^{-3} to 10^{-4} for code-compliant reinforced concrete buildings. The difference is reasonable, it might be because masonry buildings do not have any seismic provision (non-engineeered) revealing a brittle behaviour.



Average annual probability of moderate damage and collapse probability from left to right

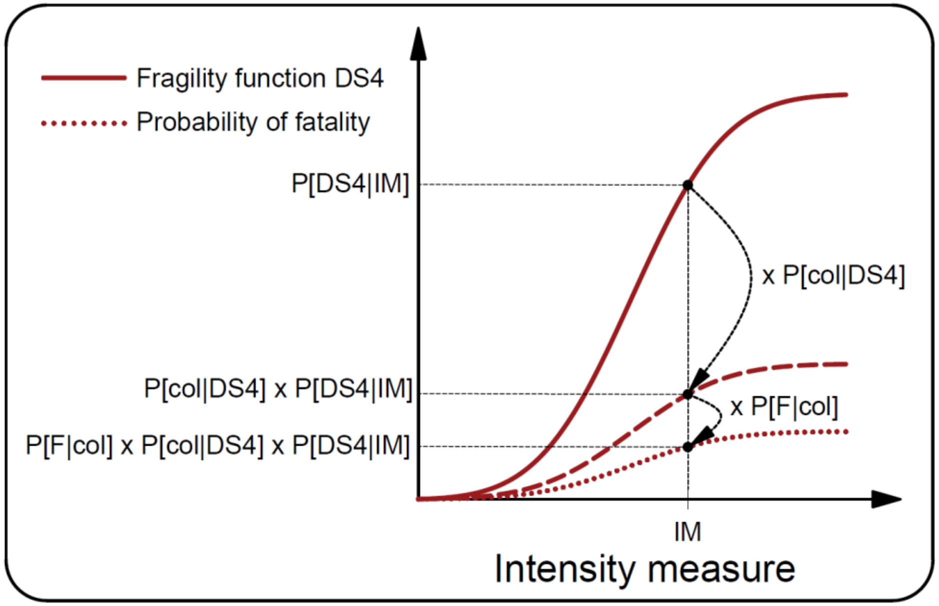


Fatality vulnerability functions

Current literature suggest to assess fatality ratios by multiplying the probability of collapse by a fatality rate.

However, this procedure is extremely simple and do not capture well the increase in mortality ratio with the increase in ground shaking, since fatality and collapse rates are not constant for all IMs.

Illustration of state-of-practice procedure for fatality vulnerability assessment

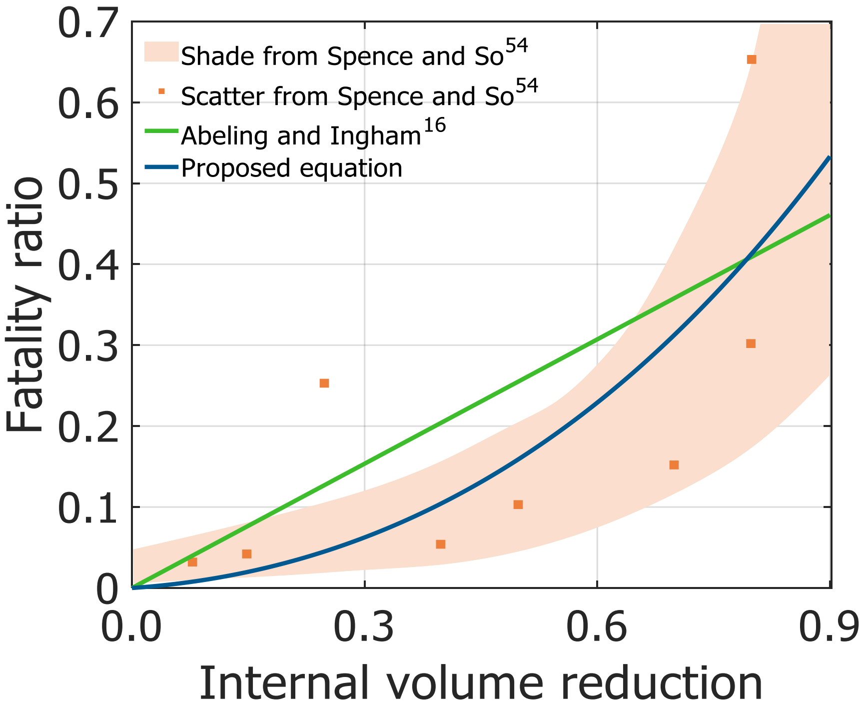


$$E\left[F\middle|IM\right]=P\left[F\middle|col\right]\times E\left[col\middle|DS4\right]\times E\left[DS4\middle|IM\right]$$

Volume loss has been found to be a better predictor of fatality rates with basis in post-earthquake data (Spence & So [12])

A equation was proposed to link the fatality ratio and the internal volume reduction according to the shade proposed by Spence & So [12].

Relationship between fatality rates and Internal volume reduction [10].



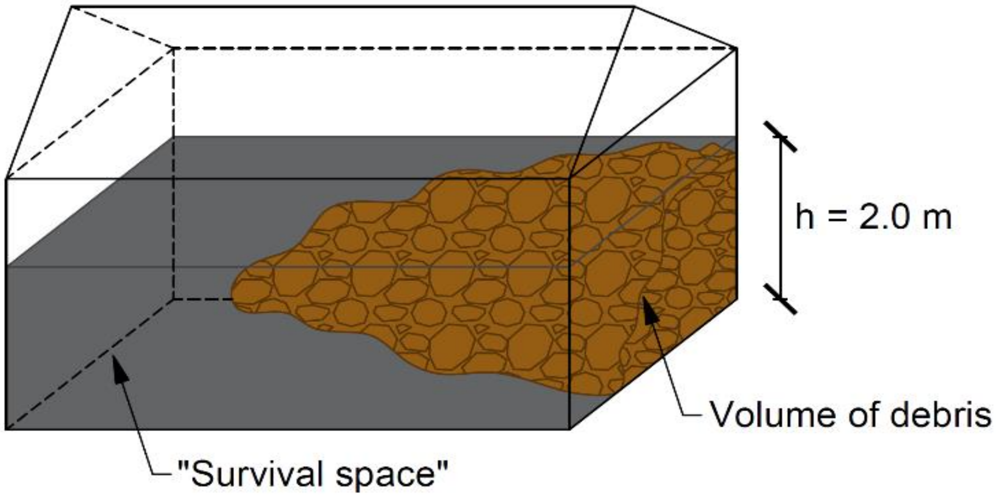
$$FR = e^{0.932 \cdot IVR} - 0.867 \cdot IVR - 1$$

Approach	Estimation of IVR or probability of collapse	Estimation of fatality rates
A	IVR computed based on the nonlinear time-history analysis in LS-Dyna within this study.	Fatality rates estimated using the IVR-FR model proposed by Abeling and Ingham [13]
B		Fatality rates estimated using Equation 4, which was derived using the data from Spence and So [12].
C	Probability of collapse provided directly by the fragility functions herein derived	Fatality rates estimated using rates proposed by HAZUS (i.e., 10%).
D	Probability of collapse estimated using the complete damage fragility functions herein derived, and the collapse rate given complete damage proposed by HAZUS (i.e., 15%)	

Internal volume reduction is defined as the reduction of the survival space inside a building. It is the plan area in the 2 first meters.

Advanced numerical modelling allows the estimation of internal volume reduction. Hence permitting the development of fatality vulnerability functions. This is particularly useful due to the lack of post-earthquake field data for countries with low recurrence of earthquakes.

Illustration of the “Survival space” (Adapted from [11])



Out-of-plane and "Zero" collapse mechanisms were identified as the most common types in the L'Aquila earthquake (Indirli et al. [14])

Advanced numerical modelling allows the estimation of internal volume reduction. Hence permitting the development of fatality vulnerability functions. This is particularly useful due to the lack of post-earthquake field data for countries with low recurrence of earthquakes.

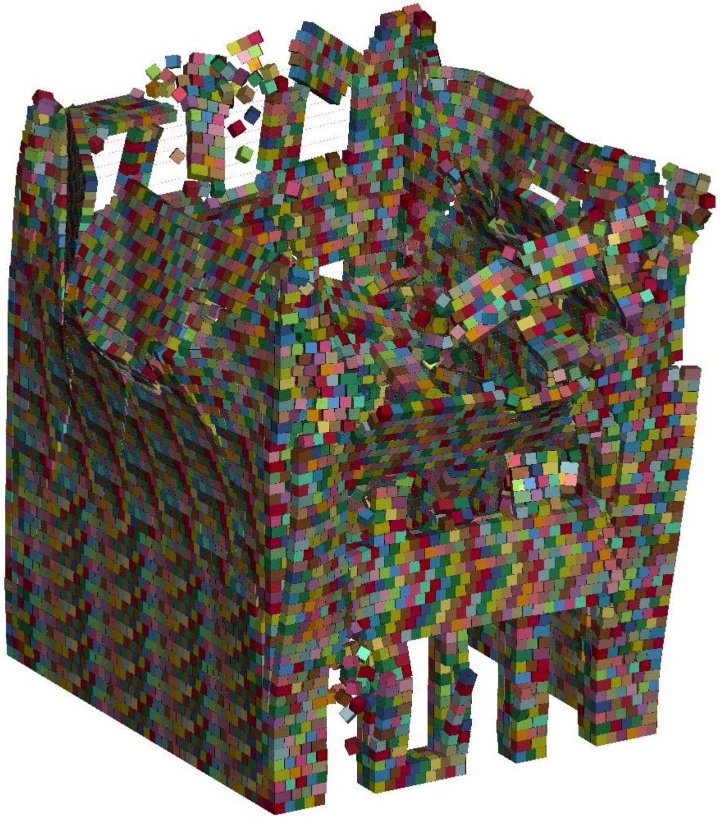
Examples of the two most common collapse mechanisms observed during the Mw 6.9 L'Aquila earthquake

"Zero" collapse mechanism

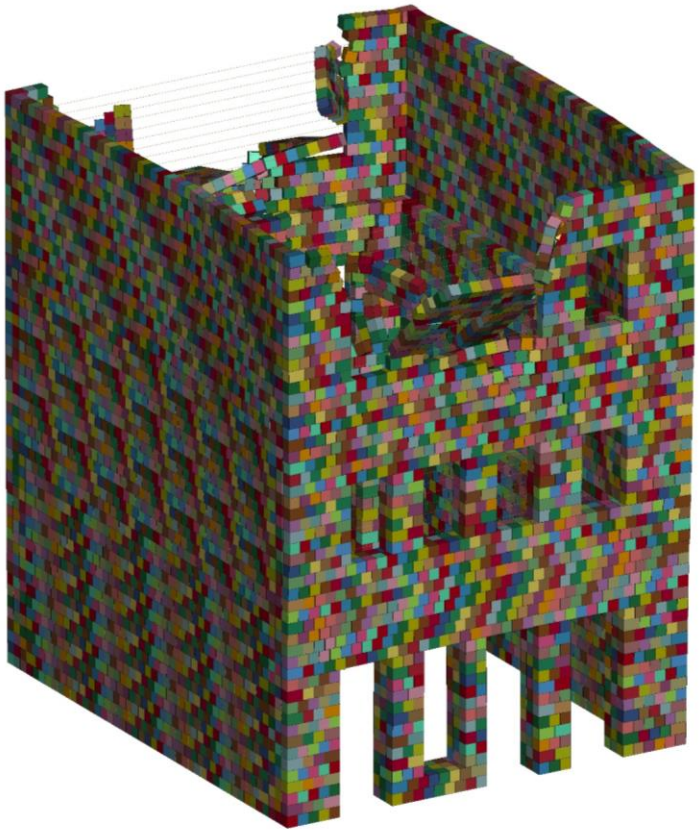
Out-of-plane failure mechanism

Collapse mechanisms compatible to “Zero”, and out-of-plane failures were identified along the structural analysis.

Examples of the two collapse mechanisms obtained by structural analysis.



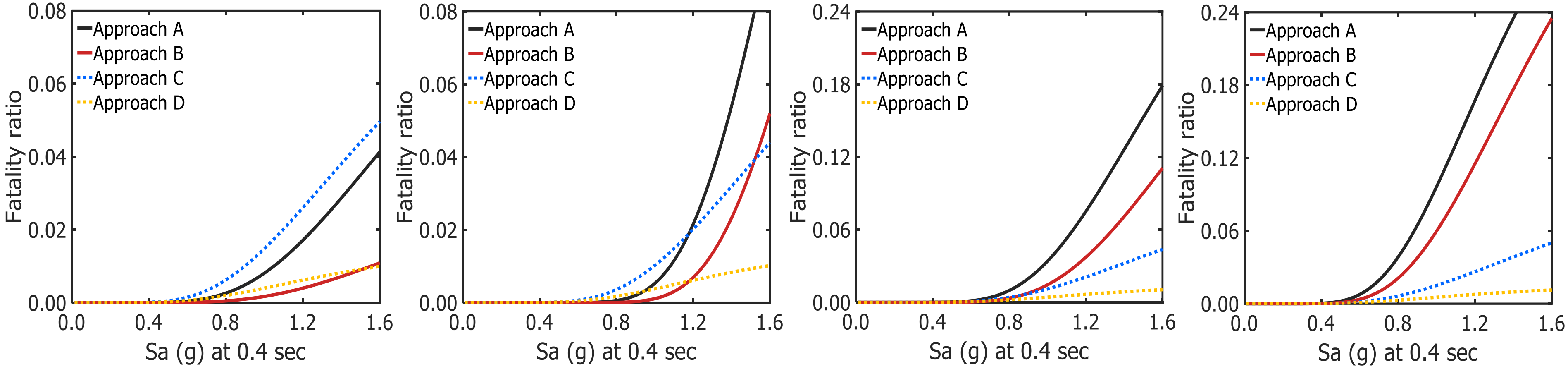
“Zero” collapse mechanism



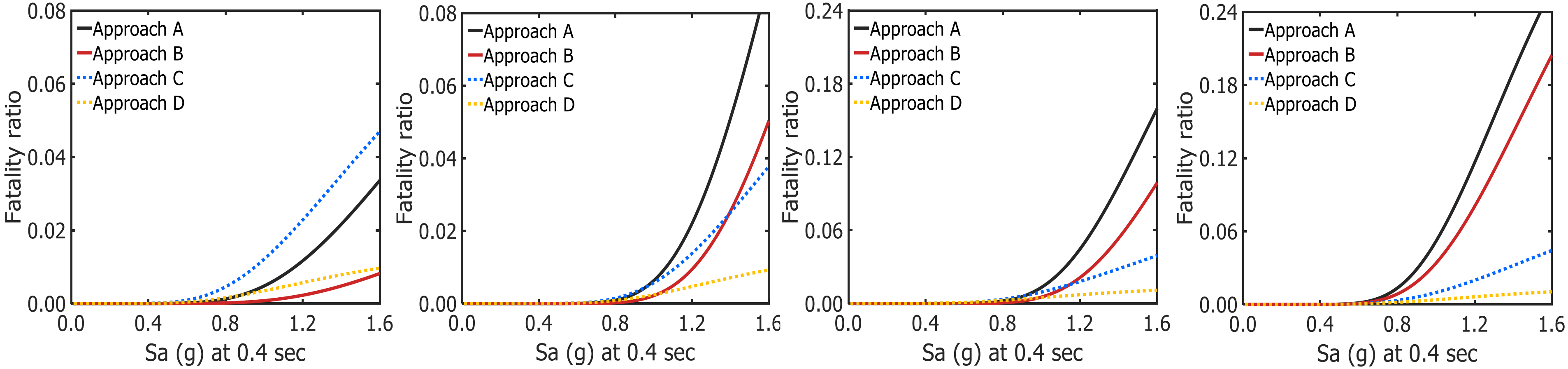
Out-of-plane failure mechanism

Fatality vulnerability functions were developed and compared

Fatality vulnerability functions for 1 to 4 limestone masonry buildings from left to right

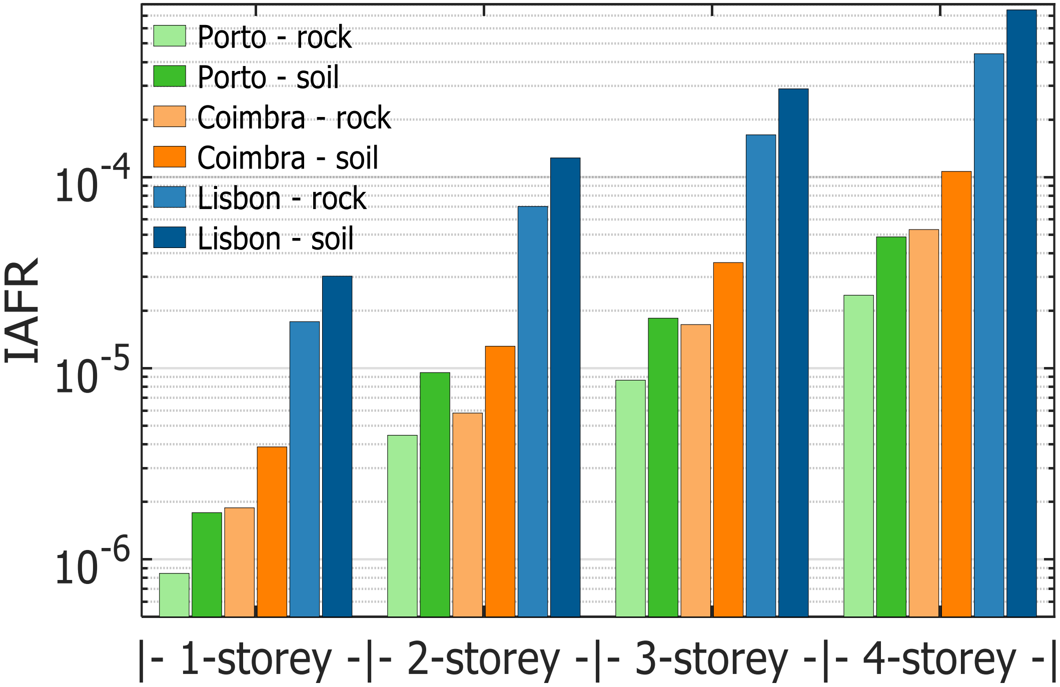


Fatality vulnerability functions for 1 to 4 granite masonry buildings from left to right



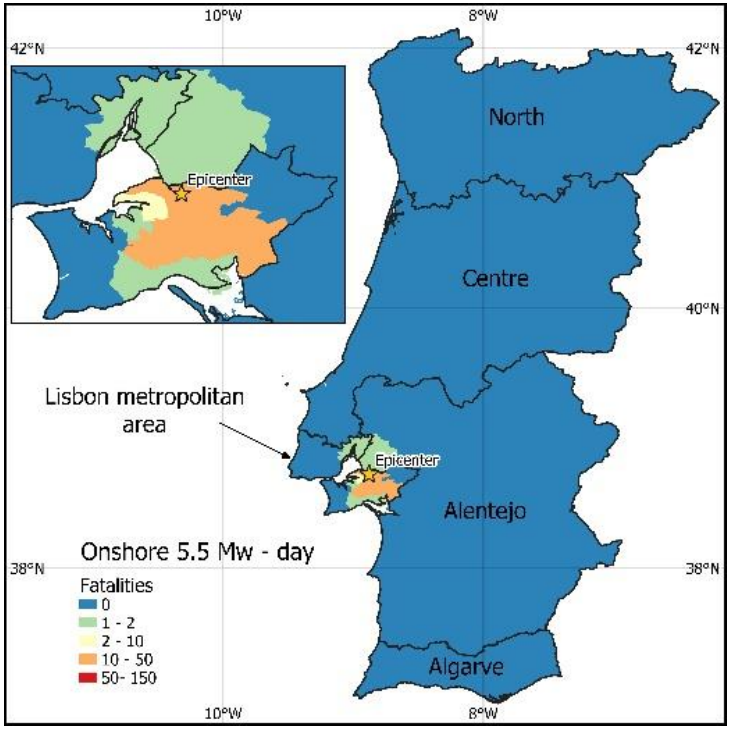
Average annual probability of life loss was calculated using the hazard functions developed in Vilanova & Fonseca [15].

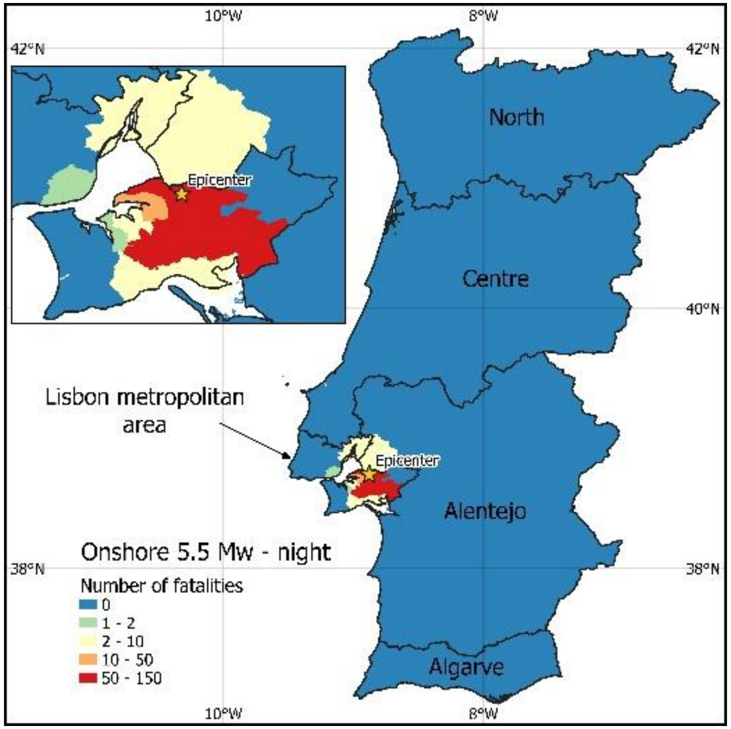
Individual annual fatality risk (IAFR) is a common risk measure that indicates the probability of loss of life a single unprotected person being permanently a given location. Diamantidis et al. [16] proposes an acceptable IAFR of 1·10-5 for structures subjected to geohazards.



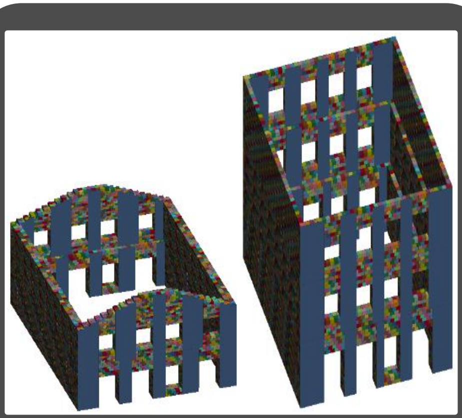
Average annual probability of loss of life (AALL) for 1 to 4-storey masonry

Earthquake Scenarios were developed to estimate human losses caused for Portugal



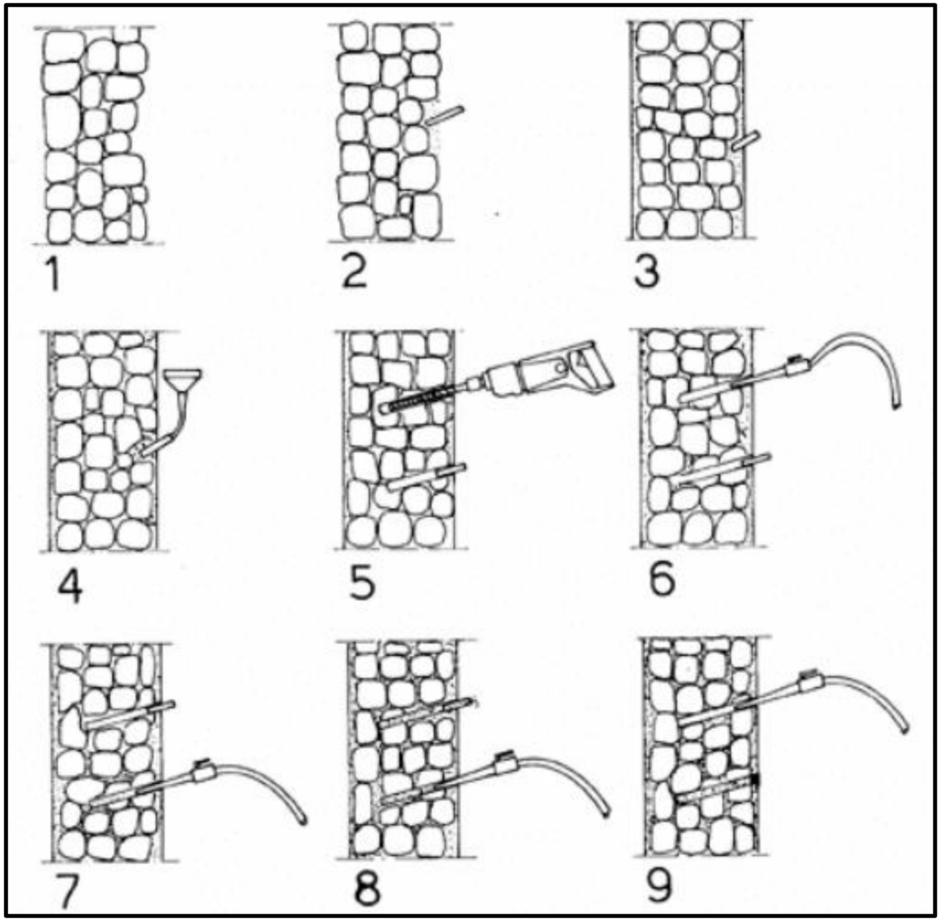


Approach	Onshore 5.5 Mw			
	Day		Night	
	Mean	Std	Mean	Std
A	106	88	488	404
B	61	57	208	264
C	132	47	609	218
D	28	8	131	37

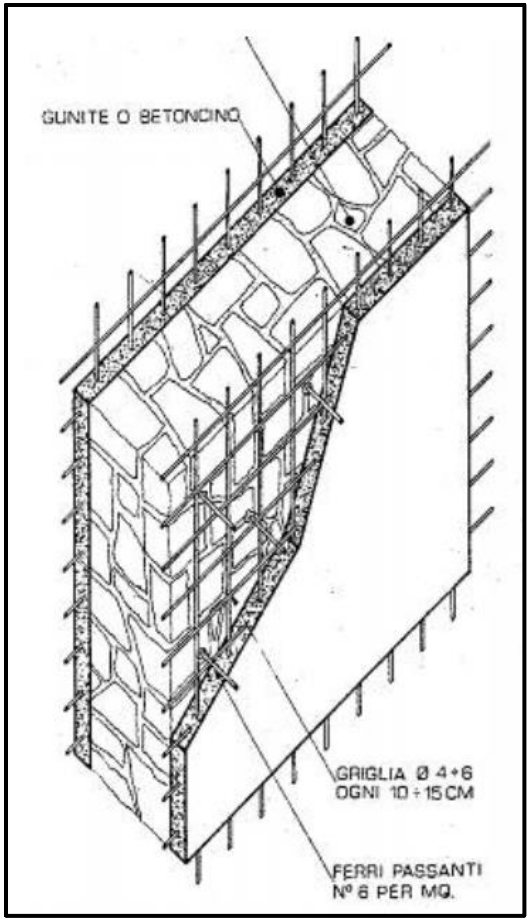


Vulnerability assessment of retrofitted masonry buildings

Two retrofitting techniques were considered and modelled:



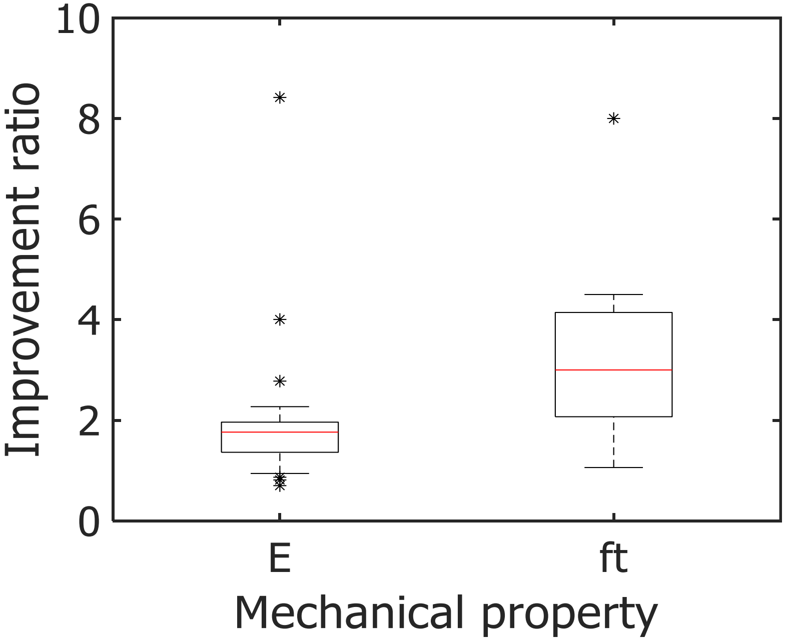
Wall grouting



Wall coating

A database of experimental tests was created to calculate the improvement ratio associated to grouting technique of masonry walls.

The database gathers 28 tests on elasticity modulus and 18 tests on tensile strength values. Peer reviewed data is still scarce for the grouting technique. Average values were considered for updating mechanical properties of retrofitted buildings models.

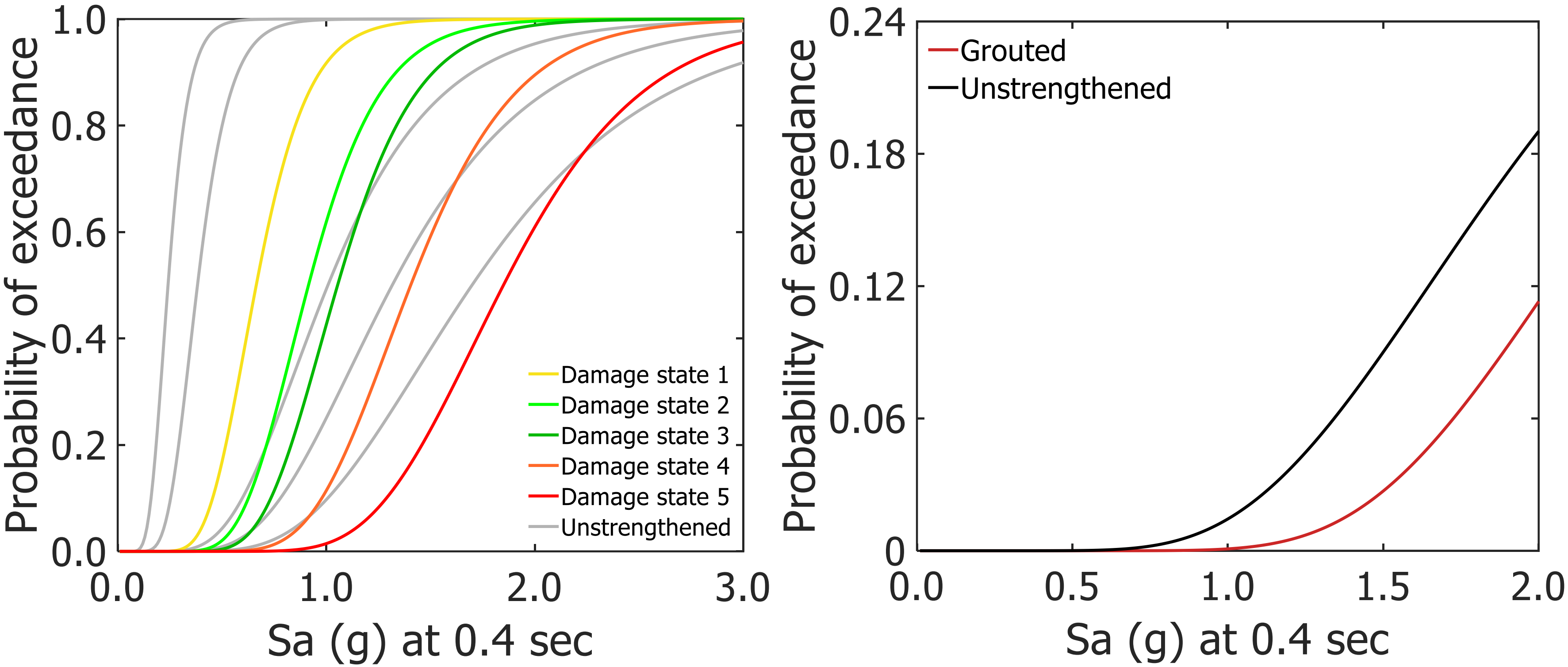


Dispersion on the elasticity modulus and tensile strength

Mechanical properties from the original model were updated using the improvement ratio obtained from the database.

Element	Description	Unit	Unstrengthen		Strengthen	
			Limestone	Granite	Limestone	Granite
Bricks (solid elements)	Elasticity modulus	GPa	0.78	0.93	1.34	1.60
	Poison ratio	-	0.30		0.30	
	Static coefficient of friction	-	0.80		0.80	
	Dynamic coefficient of friction	-	0.60		0.60	
	Penalty stiffness factor	-	1.00		1.00	
Mortar (cohesive elements)	Normal failure stress	MPa	0.12	0.15	0.34	0.42
	Shear failure stress	MPa	0.12	0.15	0.34	0.42
	Normal energy release rate	N/m	30.00	36.00	84.00	100.80
	Shear energy release rate	N/m	30.00	36.00	84.00	100.80
	Normal stiffness	GPa	0.78	0.93	1.34	1.60
	Tangential stiffness	GPa	0.78	0.93	1.34	1.60

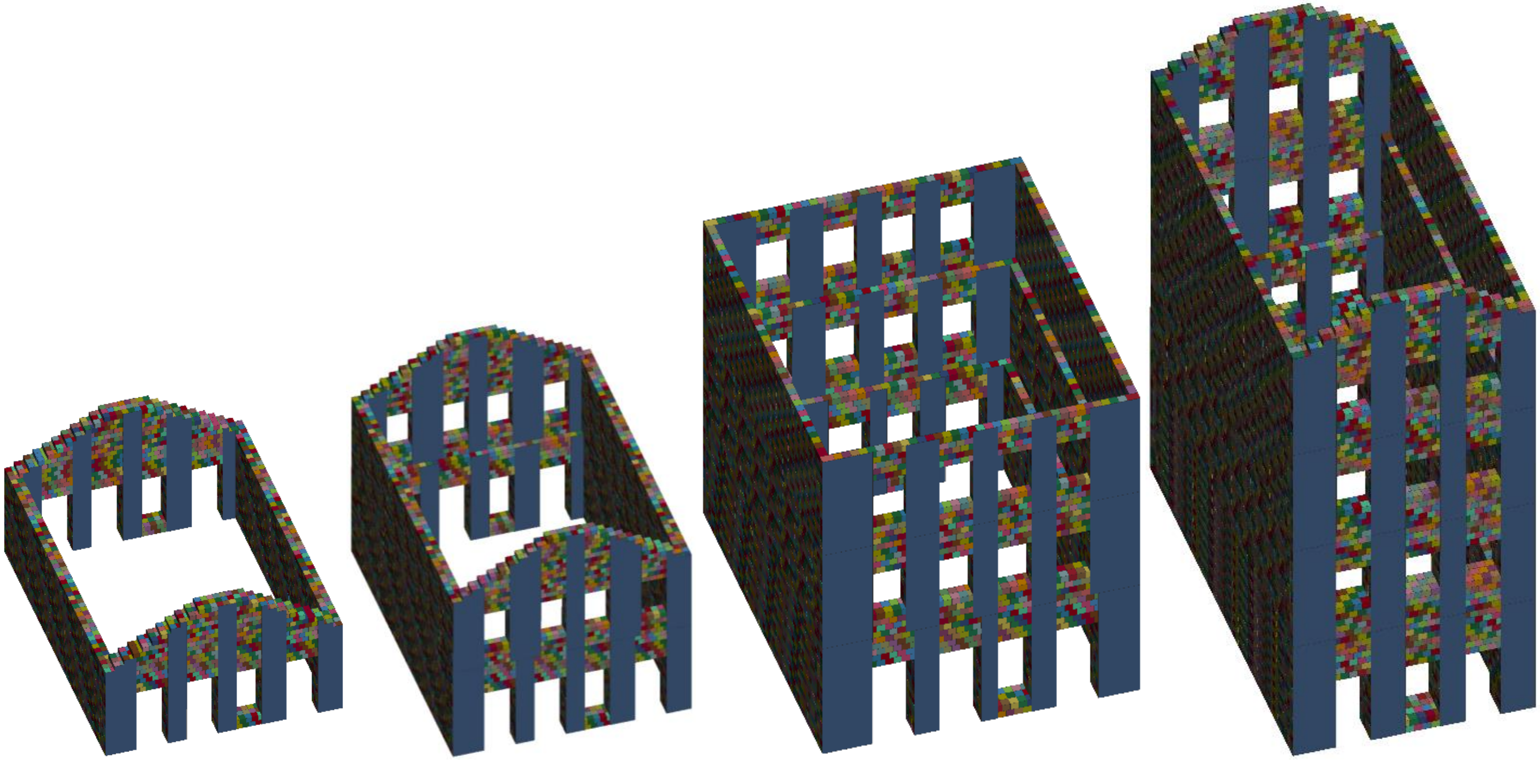
Fragility and vulnerability functions were calculated for a building archetype using the updated properties.



Fragility and vulnerability functions for an archetype 3-storey limestone masonry building retrofitted by grouting

Steel fibber reinforced polymer (SFRP) was selected as walls coating alternative

SFRP layers were modelled by means of shell elements attached to the blocks.



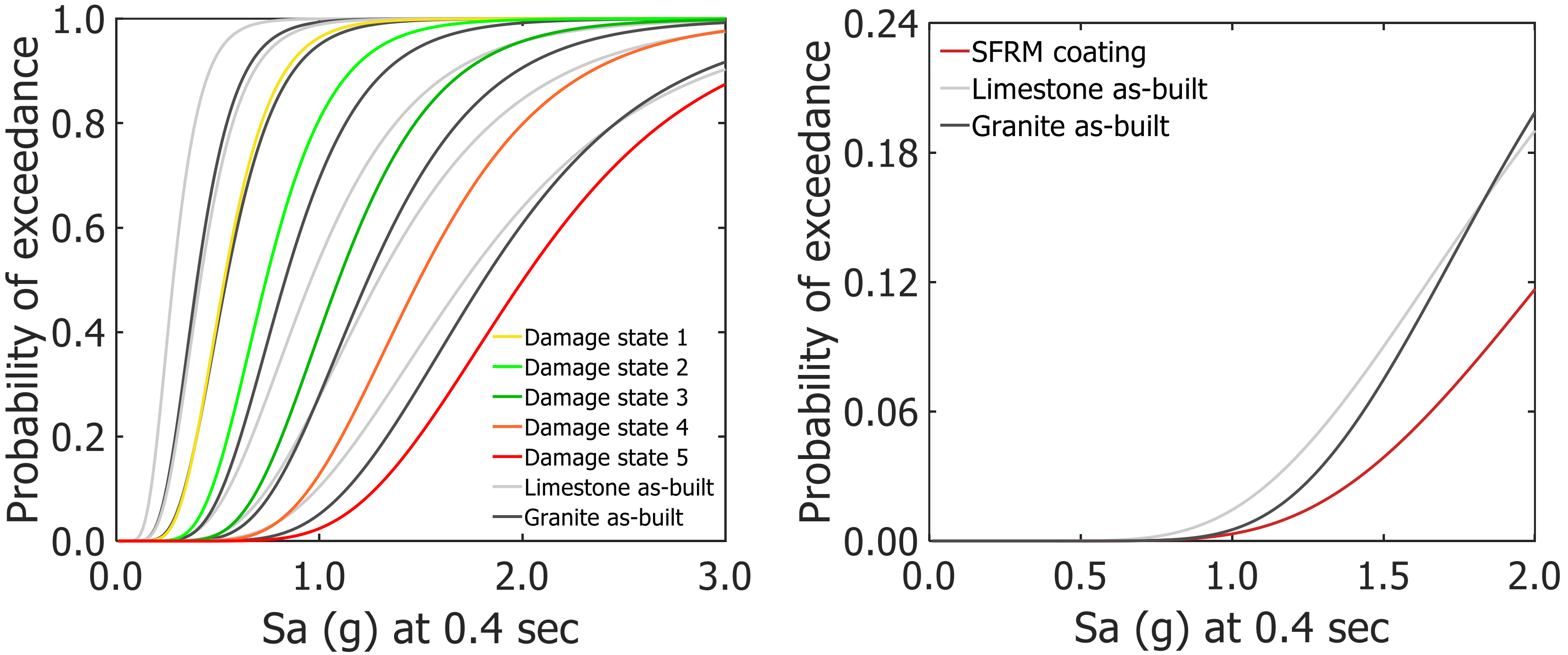
Archetypes of granite masonry buildings retrofitted by walls SFRP coating

SFRP layers were modelled using shell elements. Mechanical properties were defined according to Luchini et al. [18]

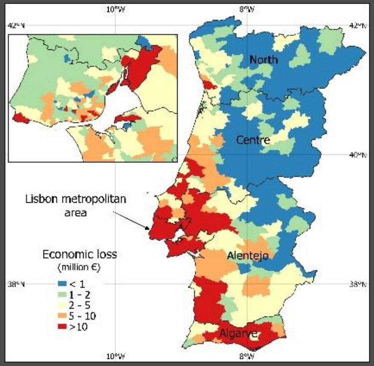
SFRP coating was selected because of its low cost and easy application. However, literature is still scarce about mechanical properties of SFRP.

Description	Unit	Value	Study
Elasticity modulus	GPa	20.40	Lucchini et al. [18]
Compressive strength	MPa	30.20	
Tensile strength	MPa	3.60	
Poisson coefficient	-	0.20	
Compressive maximum strain	-	0.010	Herein derived
Tensile maximum strain	-	0.0025	Herein derived

Fragility and Vulnerability functions were calculated employing the retrofitted models

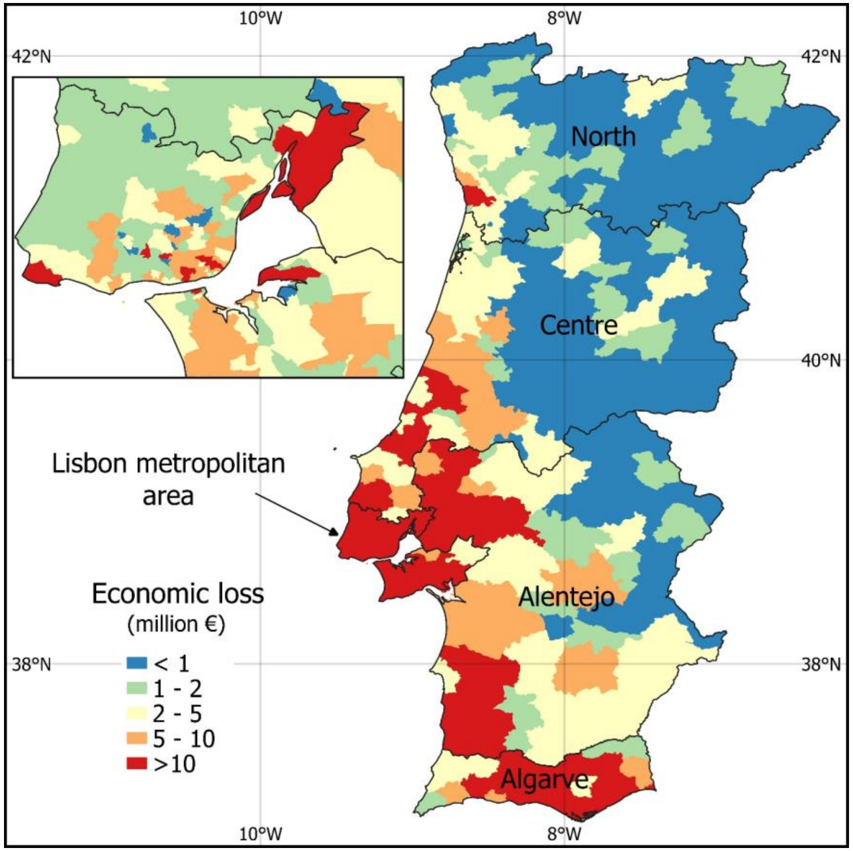


Fragility and vulnerability functions for an archetype 3-storey limestone masonry building retrofitted by SFRP coating.

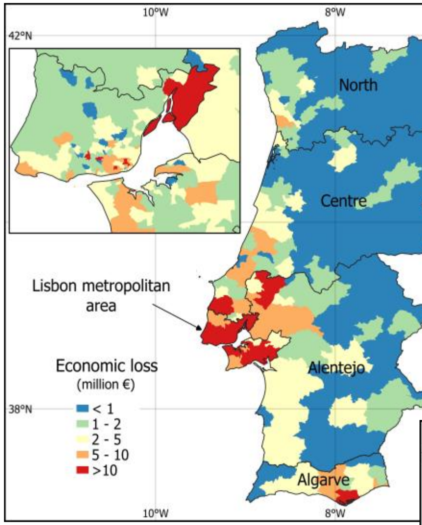


Seismic risk evaluation at national scale

Economic losses were computed for the 475-year return period. 16th and 84th percentile maps are shown together with average.

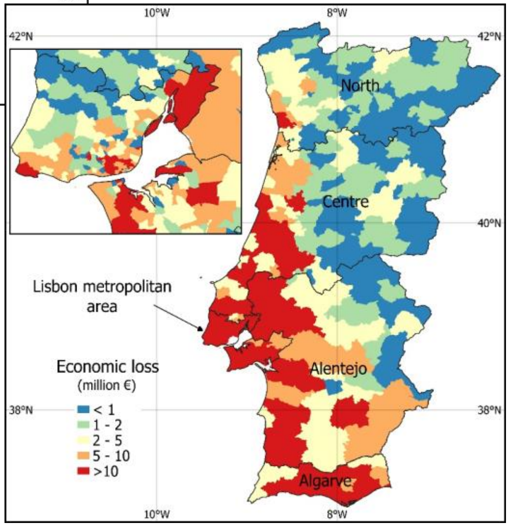


Average economic loss for a probability of exceedance of 10 % in 50 years.



16thquantile

84th quantiles



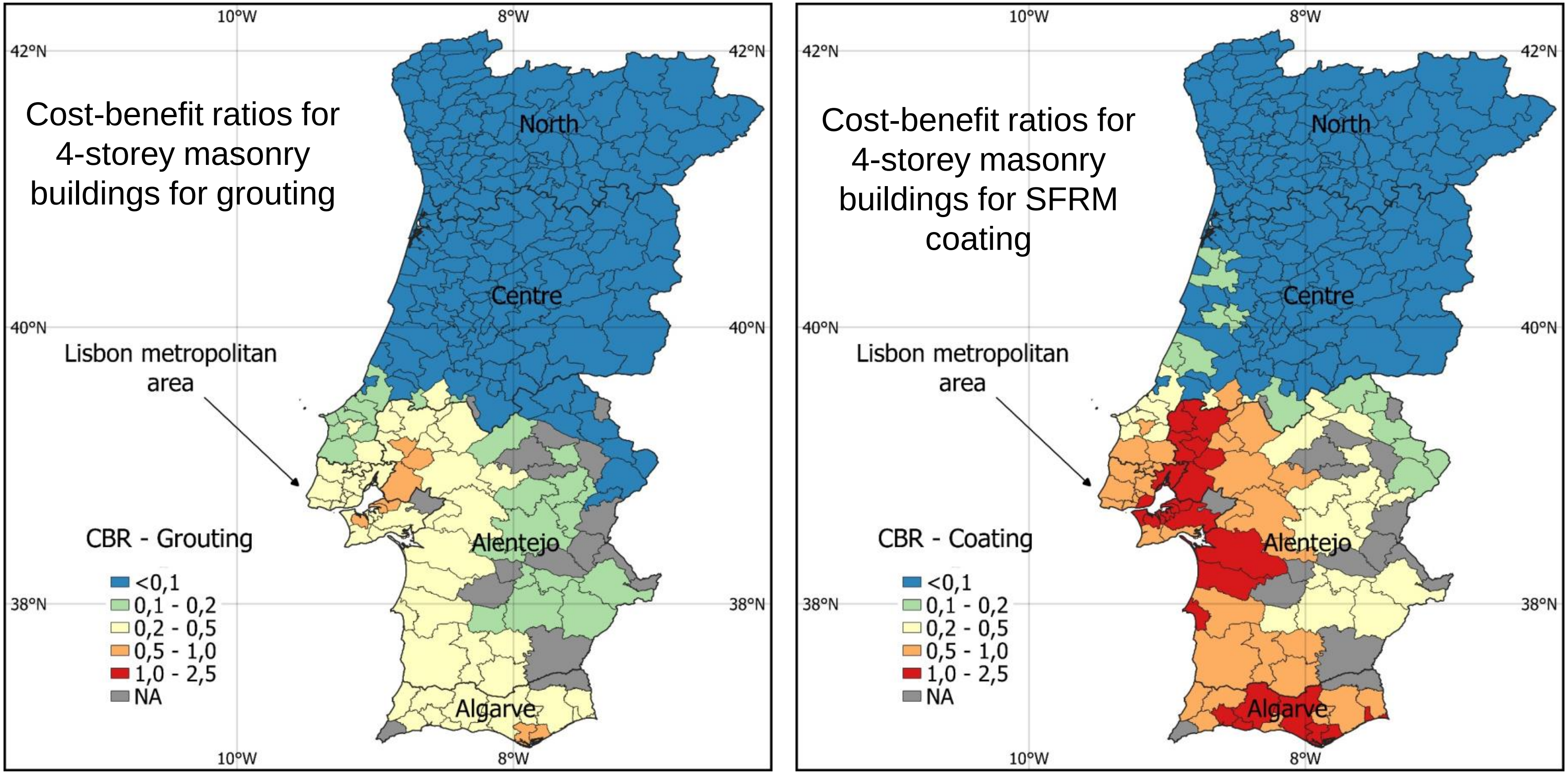
Cost-benefit analysis was performed for the retrofitting techniques previously studied.

Retrofitting technique	Building class	Retrofitting cost (€)	Replacement cost (€)	Ratio retrofitting/replacement
Grouting	**1**	13872	63773	0.22
	2	23047	127545	0.18
	3	27410	168810	0.16
	4	41679	191647	0.22
SFRP Coating	**1**	4269	63773	0.08
	2	7805	127545	0.08
	3	9818	168810	0.07
	4	10078	191647	0.07

$$CBR = \frac{\left(\sum_{t=1}^{T} \frac{L - L_{ret}}{\left(1+r\right)^{t}} \right)}{C_{ret}}$$

CBR is the cost-benefit ratio,
T is the lifespan under analysis,
L_{ret} is the average annual loss of the retrofitted assets,
r is the rate of return (assumed as 2%), C_{ret} is the cost of the intervention

Cost-benefit ratios were calculated for a national level. SFRM coating seems to be the more effective.



Cost-benefit ratios for 4-storey masonry buildings for grouting

Cost-benefit ratios for 4-storey masonry buildings for SFRM coating

Cost-benefit ratios at municipality level for two retrofitting alternatives applied on masonry buildings

Conclusions

Conclusions

- ☐ An extensive characterization of the Portuguese masonry building stock was performed. Uncertainty in geometric properties was modelled using probability density functions and a database from mechanical properties was created.

- ☐ Detailed numerical modelling was performed for limestone and granite masonry buildings. Two novel EDPs are proposed for a better damage assessment. Numerical models are capable to predict a gradual degradation of the building and most common collapse mechanisms are replicated.

- ☐ Building-to-building and record-to-record was calculated by sampling building archetypes. According to results obtained, it seems that including more than 20 buildings can ensure the inclusion of building-to-building variability.

Conclusions

- ☐ Fragility functions were developed according to the EMS-98 scale. It includes the assessment of the collapse probability useful for fatality assessment. Also other risk metrics were calculated. This study provides a comprehensive and unified fragility model for masonry buildings that can be used for risk assessment at national scale.
- ☐ Fatality vulnerability functions were developed with basis on the extend of collapse. These do not saturate as fast as damage-based fatality vulnerability functions. Also fatality risk metrics were calculated.
- ☐ Two retrofitting techniques were explored for masonry buildings. According to the cost-benefit analysis, SFRP is more profitable than grouting. Grouting does not result profitable in any area of the country, while SFRP is profitable in the zones near the MAL, and the south of the country.

Future research

- ☐ Further experimental tests are necessary in order to fully characterize the masonry buildings in Portugal. Also, a study can devote effort to study the influence of the number of leaves at fragility and vulnerability level.
- ☐ It has been evidenced by some seismic events that heavy roofs can increase the deaths. Hence, some effort should be made to model that kind of covering.
- ☐ Due to the limitation of computational effort, it was not possible to propagate the uncertainty associated to mechanical properties. It can be object of study of future research. Also the models are capable to model the pounding and contact with other buildings. However, the buildings were isolated for analysis since considering more structures and the uncertainty on adjacent buildings can increase the computational effort to impractical levels.
- ☐ More retrofitting techniques can be explored in the search for economic efficiency. Modern materials such as polymers and fiber-reinforced meshes can lead to improved results.
- ☐ The cost-benefit analysis indicates that retrofitting might not be attractive in most parts of the country. However, retrofitting can improve the performance when facing other hazards like tsunamis and landslides. Including the risk of those events can become retrofitting more attractive.

Journal articles

- ❑ Lovon H, Silva V, Vicente R, Ferreira T, Costa A (2020). Characterization of the Masonry Building Stock in Portugal for Earthquake Risk Assessment. Engineering Structures
- ❑ Momim S, Lovon H, Silva V, Vicente R, Ferreira T (2021). Seismic Vulnerability Assessment of Portuguese Adobe Buildings. Buildings 11(5), 200.
- ❑ Lovon H, Silva V, Vicente R, Ferreira T (2022). Seismic Vulnerability Assessment of Portuguese Masonry Buildings. (ready for submission).
- ❑ Lovon H, Silva V, Vicente R, Ferreira T (2022). Analytical vulnerability functions for the assessment of fatalities in masonry buildings. (ready for submission).

Conference articles

- ❑ Lovon H, Silva V, Vicente R, Ferreira T, Costa A (2021). Incorporating Epistemic and Aleatory uncertainties in Fragility modelling of Masonry Structures in Portugal. 17th World Conference in Earthquake Engineering. Sendai, Japan.
- ❑ Momim S, Lovon H, Silva V, Vicente R, Ferreira T (2021). Seismic vulnerability assessment of the Portuguese adobe building stock. 17th World Conference in Earthquake Engineering. Sendai, Japan.
- ❑ Lovon H, Silva V, Vicente R, Ferreira T (2021). Development of analytical fatality vulnerability functions for limestone masonry buildings in Portugal. 3rd European Conference on Earthquake Engineering & Seismology. Bucharest, Romania.

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Thanks for your attention

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