Exploring Benefit-Cost Analysis for Earthquake Risk Reduction

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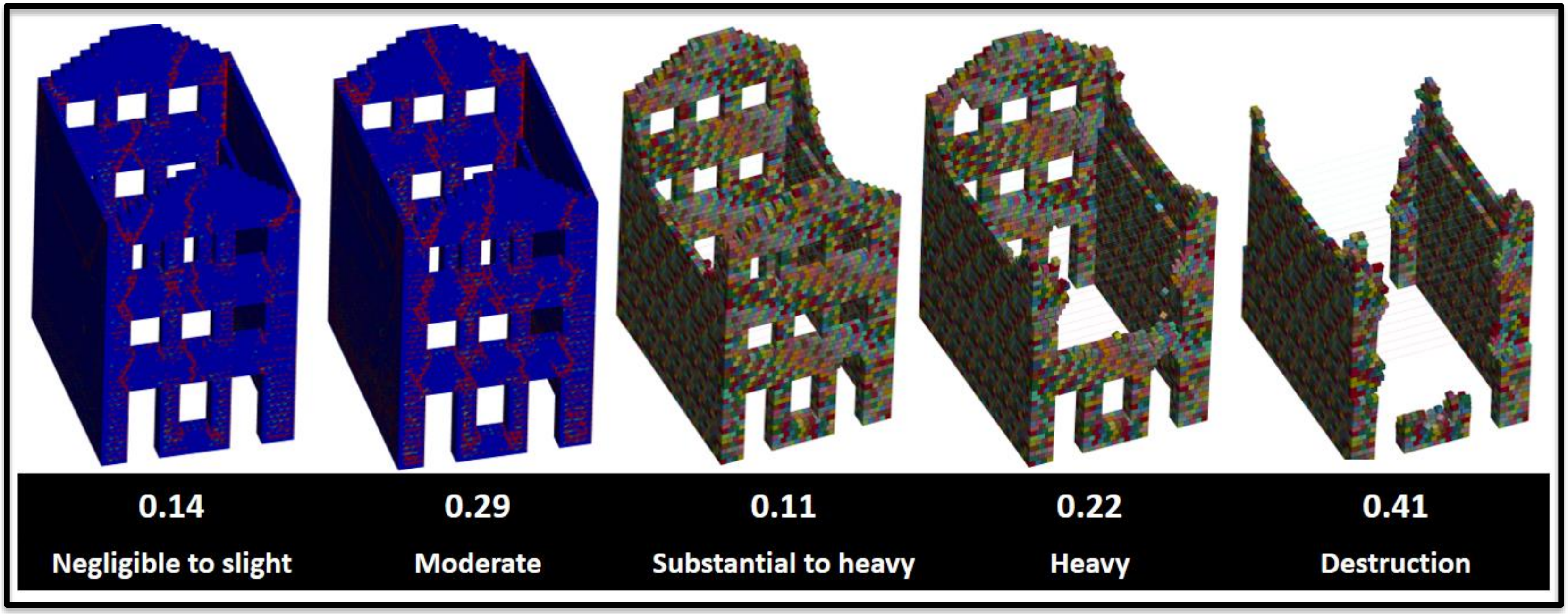
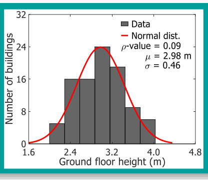
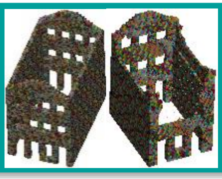


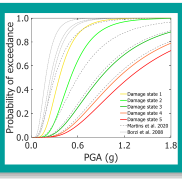
What I will show you today:



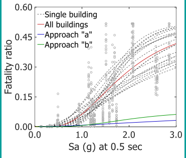
The challenge



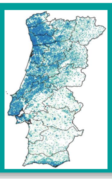
The proposed solution



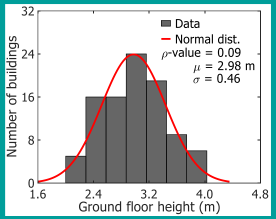
Some results



Current research



Future research



The challenge

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

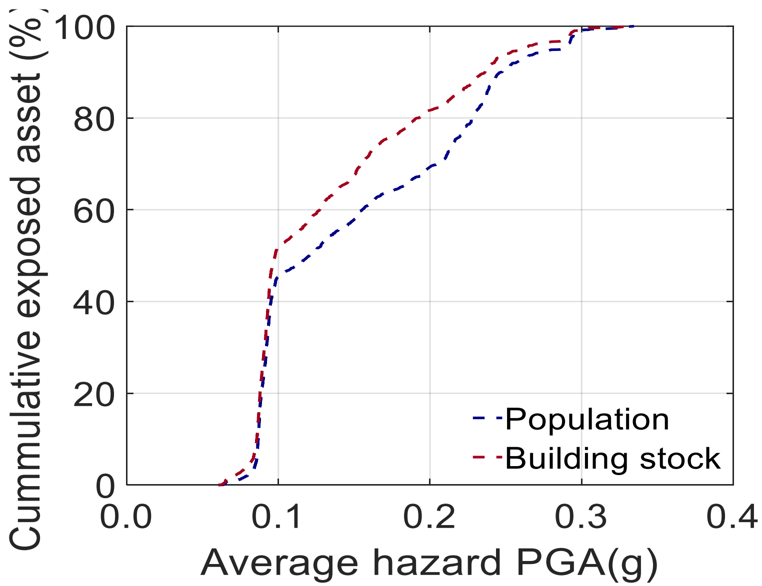


Fig. 1 Percentage of exposed assets to different levels of seismic hazard expressed in terms of PGA (g)

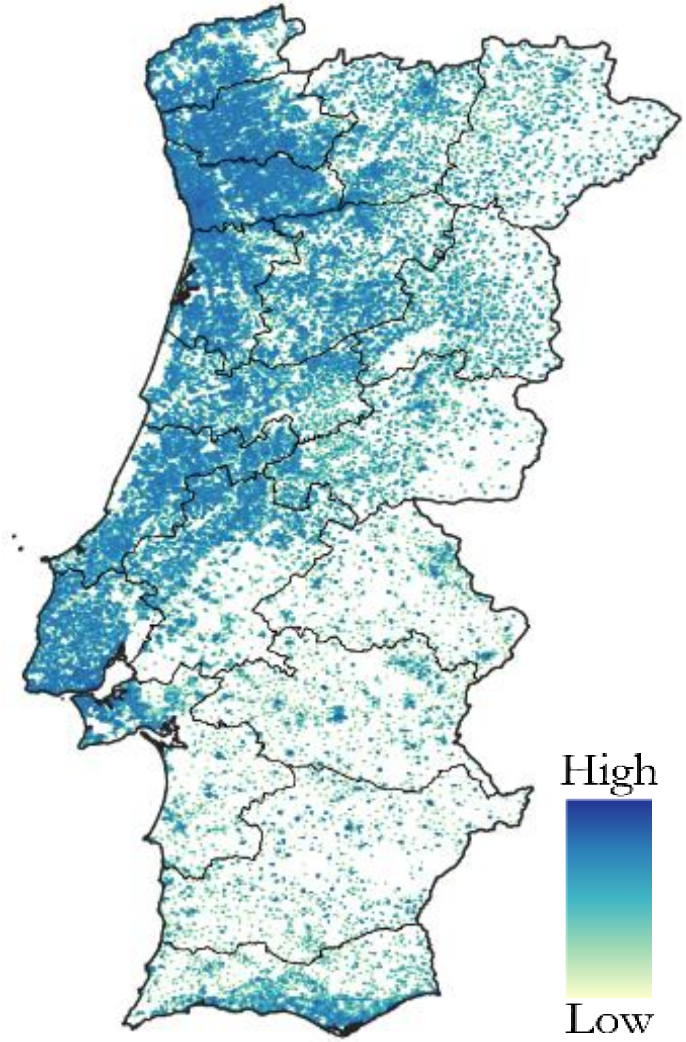


Fig. 2 Density map of URM buildings without RC slab

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.

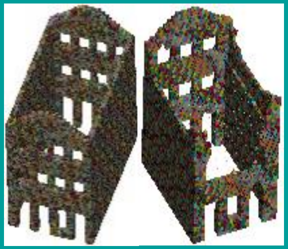
According to Coburn et al [1] human losses are not appropriately predicted by physical damage states, instead volume of debris should be used.

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

Fig. 3 Example of different extents of collapse for damage state 5 in masonry buildings, extracted from [1]



The proposed solution

To perform the detailed numerical modelling, about 200 buildings were analyzed.

NCREP consulting company provided access to its granite building database. Data for limestone masonry buildings was obtained from [2], a total of 185 buildings was gathered.

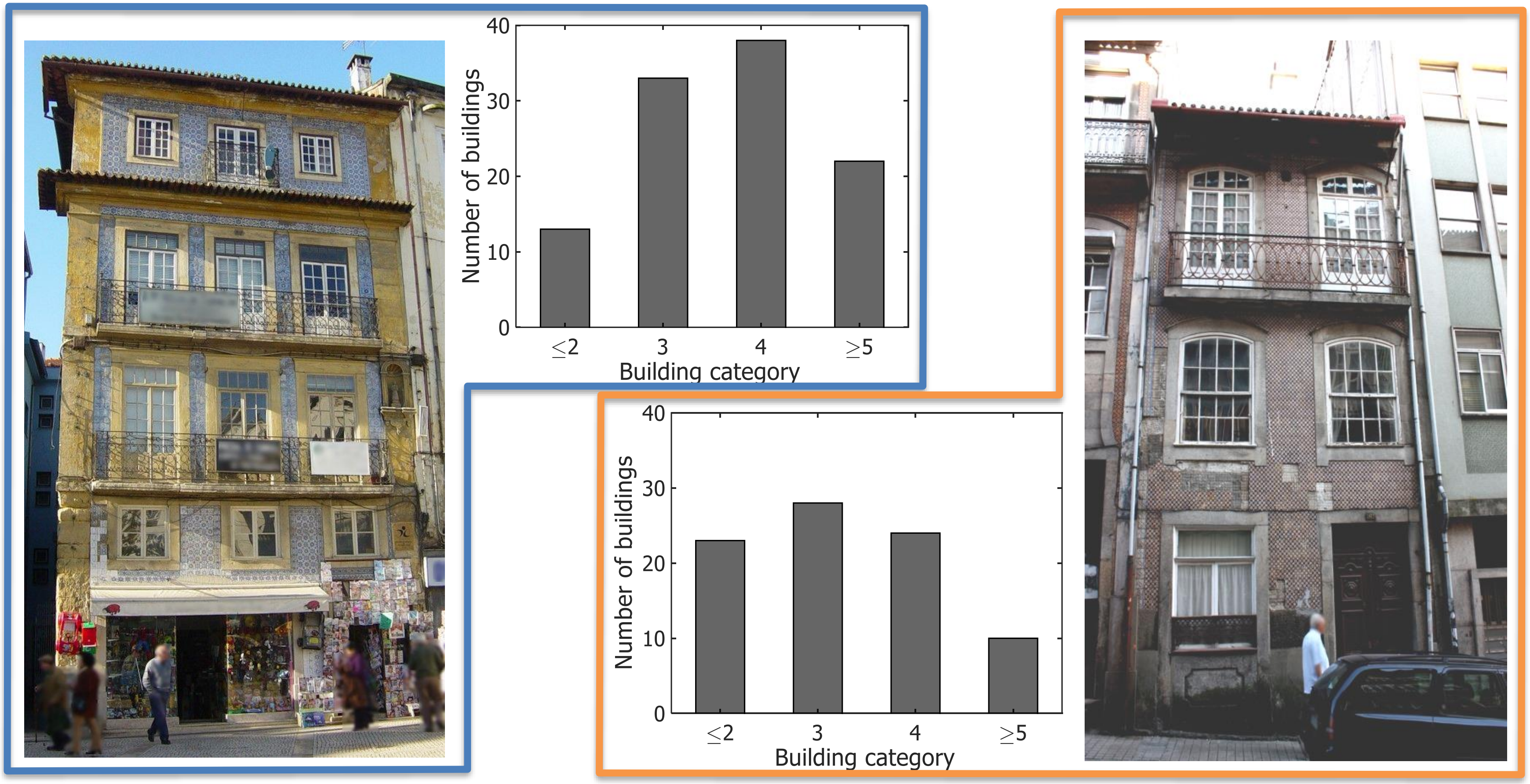


Fig. 4 Schemes and number of Limestone and granite buildings analyzed

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

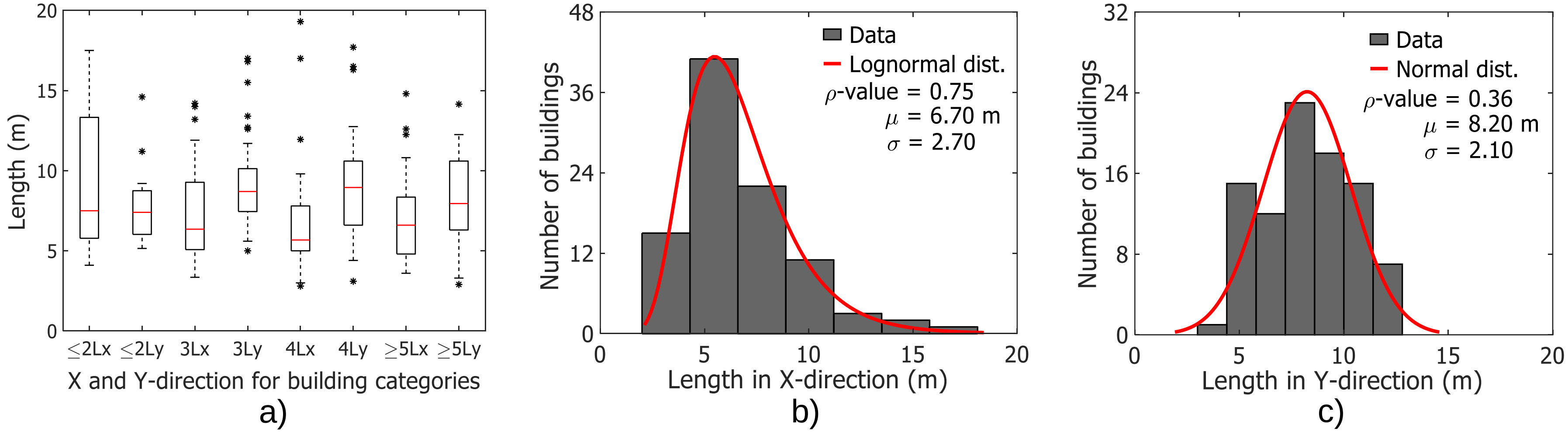


Fig. 5 a) Dispersion, b) Histogram, fitted distribution and goodness-of-fit results for the length in façade (X) and c) orthogonal (Y) direction in Limestone masonry buildings

The results are published in:

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.

Experimental results and existing literature were reviewed.

Geometric and numerical properties were used to develop numerical models

Table 2. Existing studies that addressed the mechanical properties of limestone masonry in Portugal

Source	Elasticity modulus (GPa)	Compressive strength (MPa)	Shear strength (MPa)	Type of test	Masonry description
Pagaimo (2004)	0.30	1.00	-	In-situ flat-jack test	Irregular limestone masonry. Clay and lime mortar.
Pinho (2007)	0.31	0.43	-	Laboratory compression test	Irregular limestone masonry. Lime and sand mortar
Vicente (2008)	1.71	0.76	-	In-situ flat-jack test	Irregular limestone masonry. Lime, sand, pebble and clay mortar
Milosevic et al. (2013)	1.64	8.01	0.45	Laboratory uniaxial compression, and triplet shear test	Irregular limestone masonry. Hydraulic lime and sand mortar
	0.56	7.41	0.22		Irregular limestone masonry. Air lime and sand mortar
Moreira (2014)	1.02	1.70	0.29	Laboratory uniaxial, and diagonal compression test	Irregular limestone masonry. Hydraulic lime, sand, clay-rich sand and cement mortar
Simões (2016)	2.00	1.89	0.19	In-situ flat-jack test	Irregular limestone masonry. Air lime mortar – Pombalino Building.
	0.39	0.63	0.13		Irregular limestone masonry. Air lime mortar – Gaioleiro Building.

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

The process consist on sampling a ratio of openings. After, a façade configuration is selected based on a predefined range of application. The final step consist on selecting the opening sizes that better match the ratio of openings. Very low residuals were found during the process.

Type	Configuration					
1	D	W				
2	D	W	D			
3	D	W	D	D		

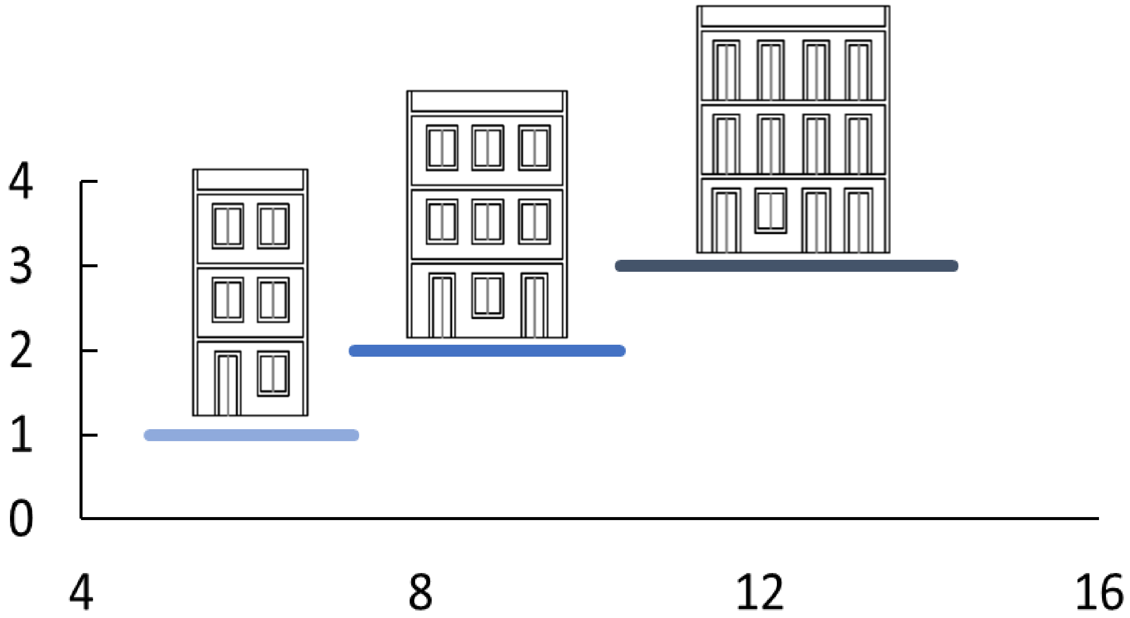


Fig. 6 Archetypes and opening ratios

The procedure was implemented in MatLab software. A sample of 15 randomly sampled buildings is shown.

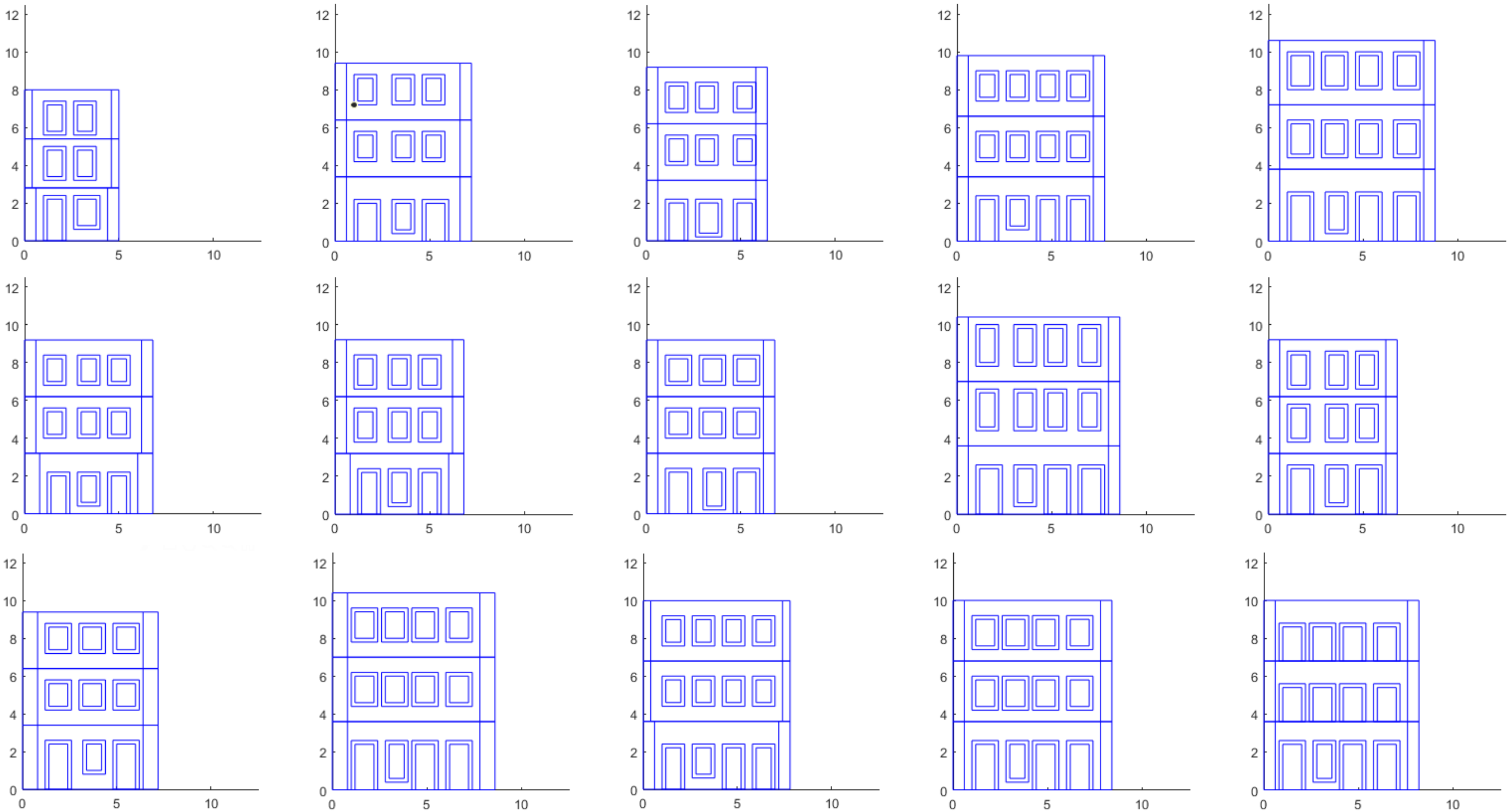


Fig. 7 Sample of 15 3-storey buildings randomly generated. Lengths in meters (m)

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

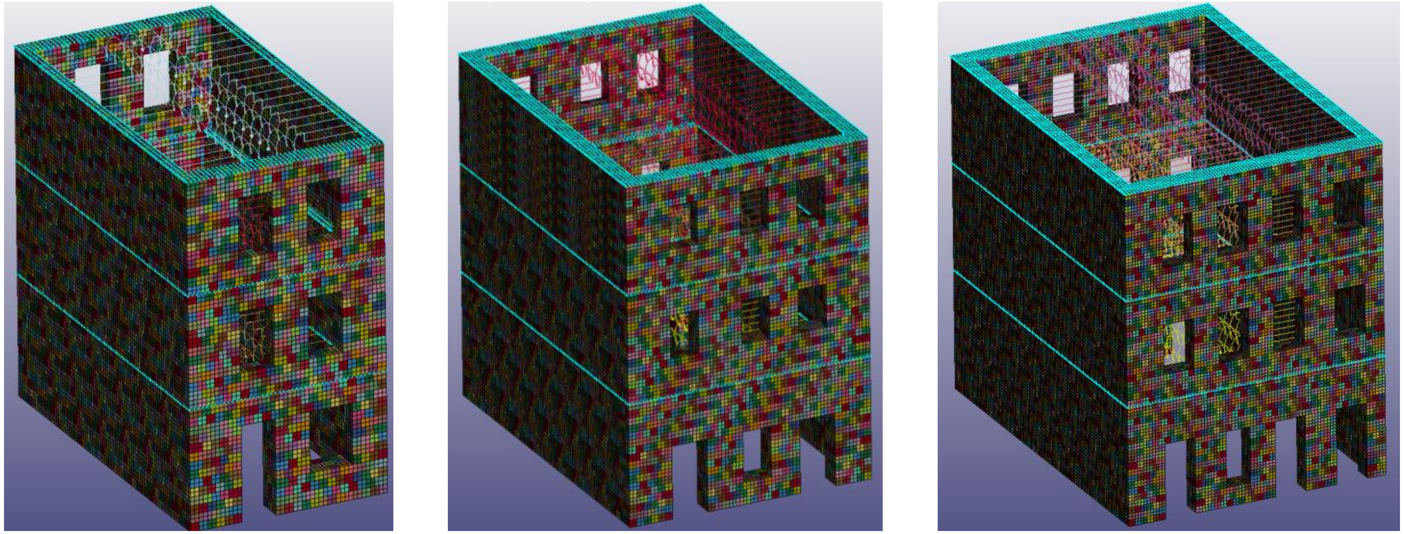


Fig. 8 Example of LS-Dyna models randomly generated

A set of 30 ground motion records were selected based on seismic disaggregation for Portugal and CSM method.

The records are uniformly distributed according its PGA between 0.2 to 1.2 each 0.2 (i.e. 6 records per bin). The records were cut at 5% of the PGA in the beginning and in the end, the latter to reduce the computational effort.

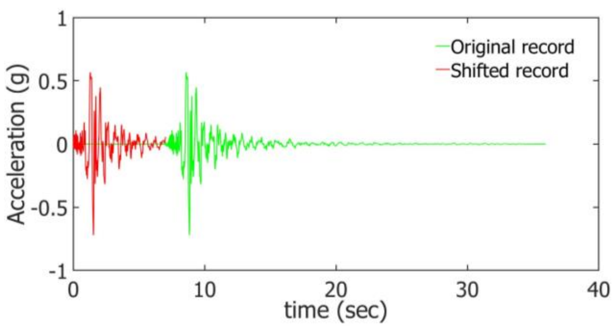
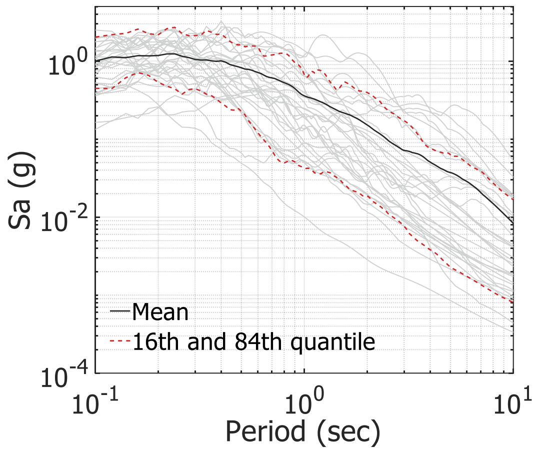


Fig. 9 Scheme of records cut



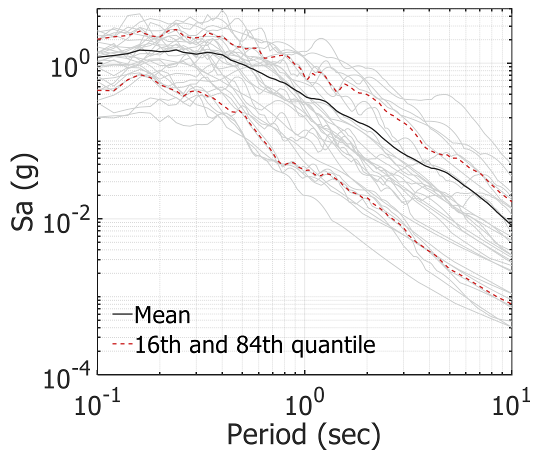
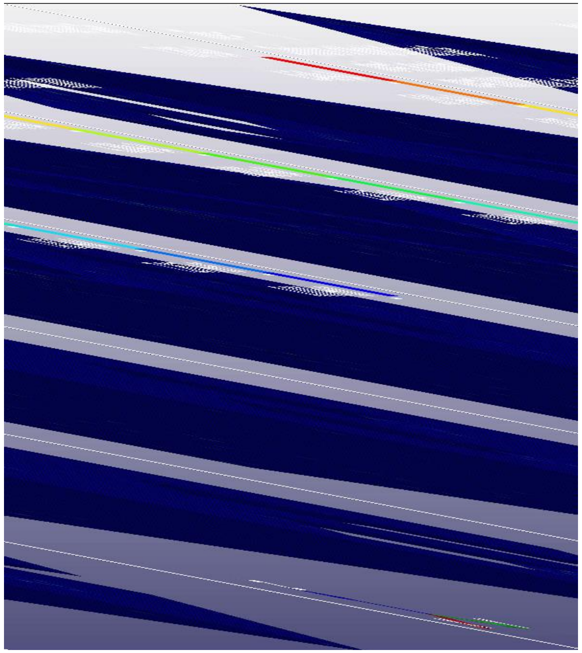
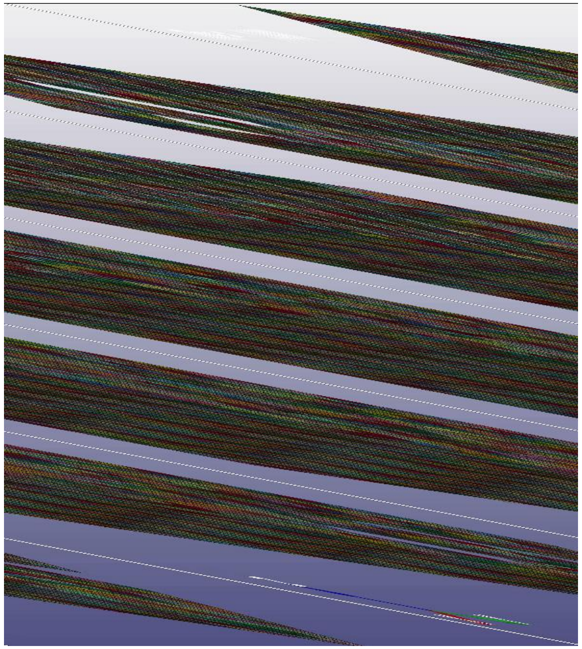
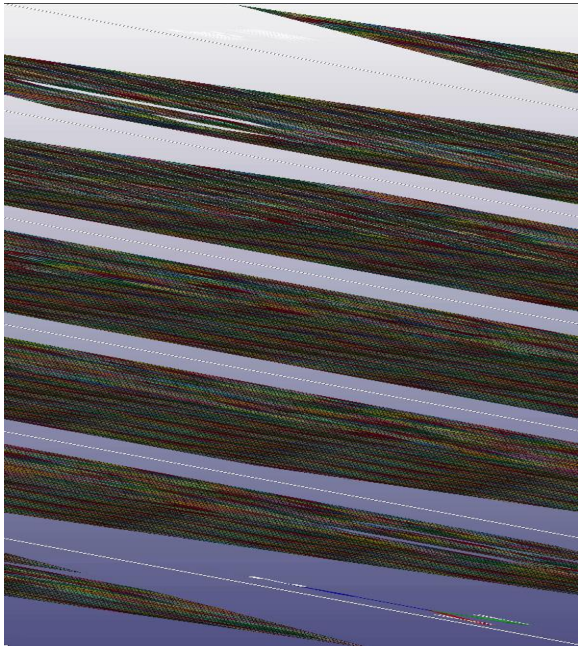


Fig. 10 a) Response spectrum for selected records b) scheme of records cut

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

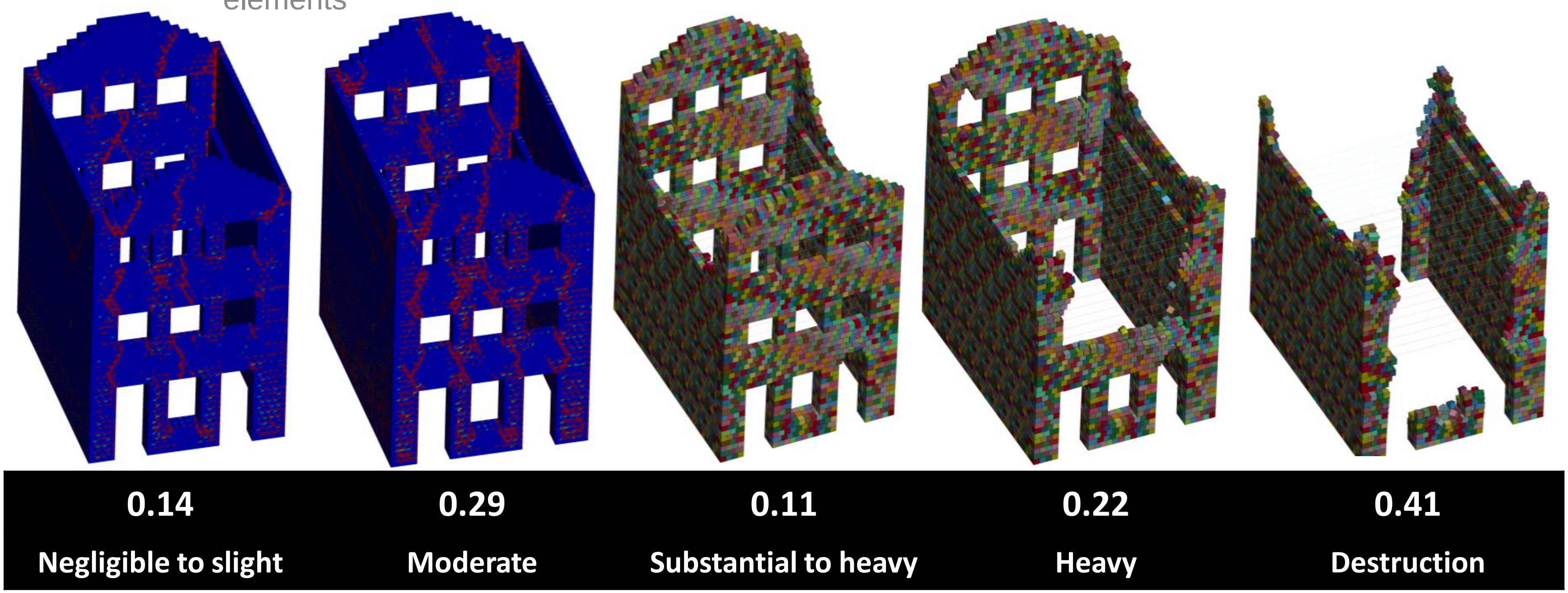


Fig. 10 Example of damage levels and corresponding EDPs and IMs

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

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

The probability of exceedance is calculated as:

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

Building-to-building and record-to-record variability are propagated for all building classes:

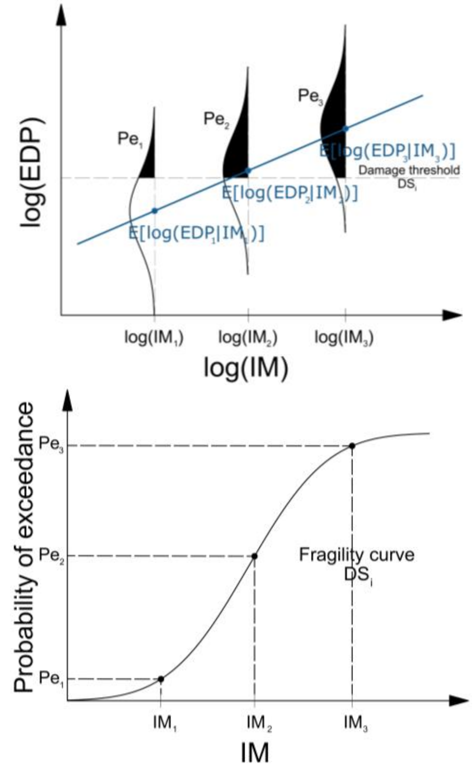


Fig. 9 Illustration of fragility functions derivation process

A similar framework was performed for adobe buildings, results are published in:

Monim S, Lovon H, Silva V, Vicente R, Ferreira T (2021). Seismic Vulnerability Assessment of Portuguese Adobe Buildings. Buildings 11(5), 200.

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

1. Record-to-record variability σ_{rtr} was calculated for each single building.

2. Total variability $\sigma_{\log(EDP)|IM}$ was assessed by applying cloud analysis to all building set.

3. Building-to-building variability σ_{btb} was calculated as indicated in Eq. 3

Table 4 – σ values for 3-storey building class

EDP	σ_{rtr}	σ_{btb}	σ_{total}
Cracked wall ratio	0.26	0.16	0.31
Volume loss ratio	1.28	0.74	1.48

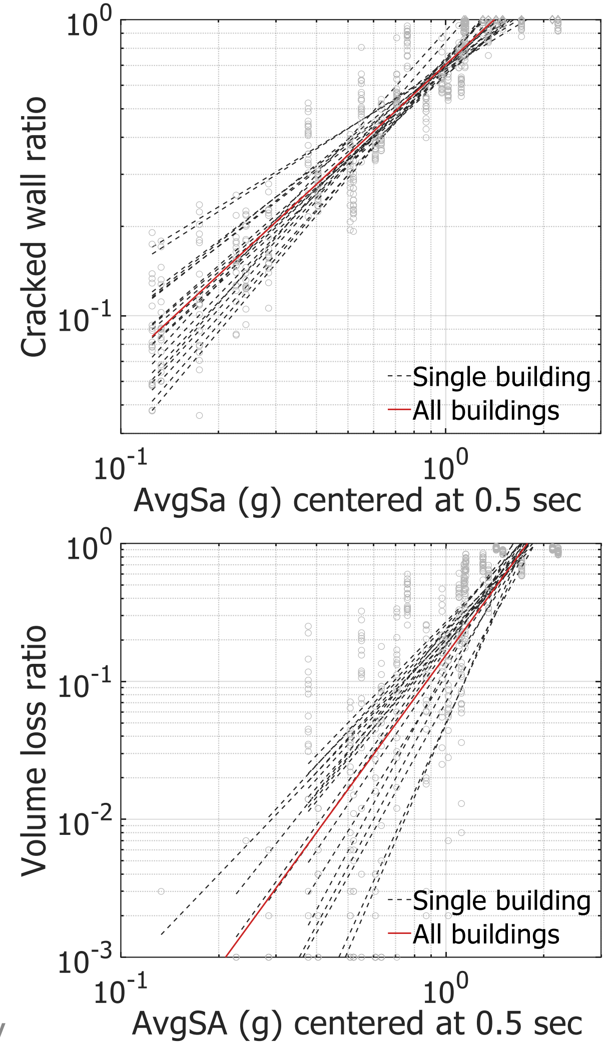
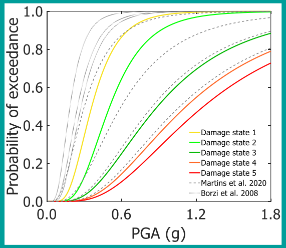


Fig. 12 Dispersion of EDP – IM measures

Results are documented in a conference article:

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.



Some results

Fragility functions were compared with other studies, indicating a reasonable agreement with similar structures.

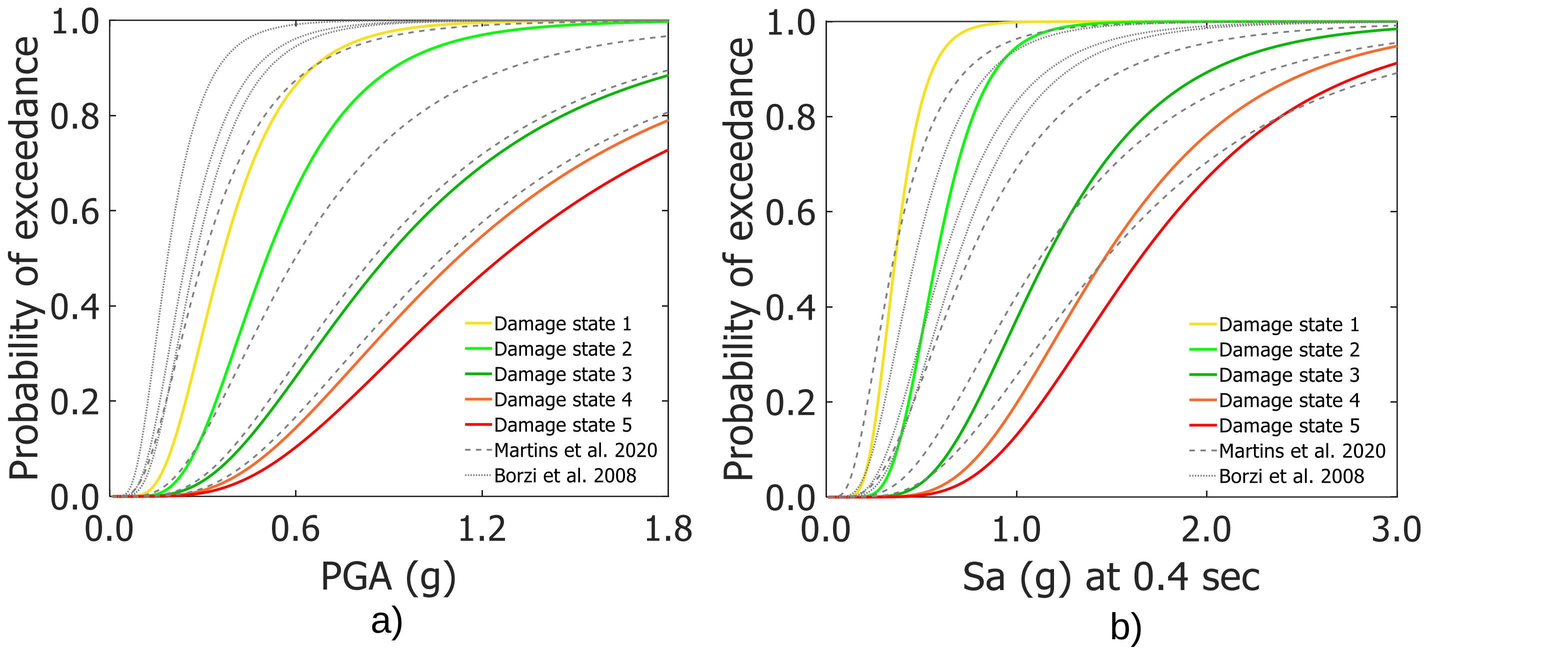


Fig. 13 Fragility functions for a) 1-storey and b) 3-storey limestone masonry buildings

Outcomes were compared with fragility functions developed for URM buildings in Italy [3] and for risk assessment at global scale [4-6].

1-storey URM specimens tested with incremental shaking table tests up to collapse in [4-6] exhibited onset of damage for PGA equal to 0.66g and imminent collapse for 1.02g PGA, which is in agreement with fragility functions herein developed.

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

AAPD ranges 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, once again, because masonry buildings do not have any seismic provision and tends to have a brittle behaviour.

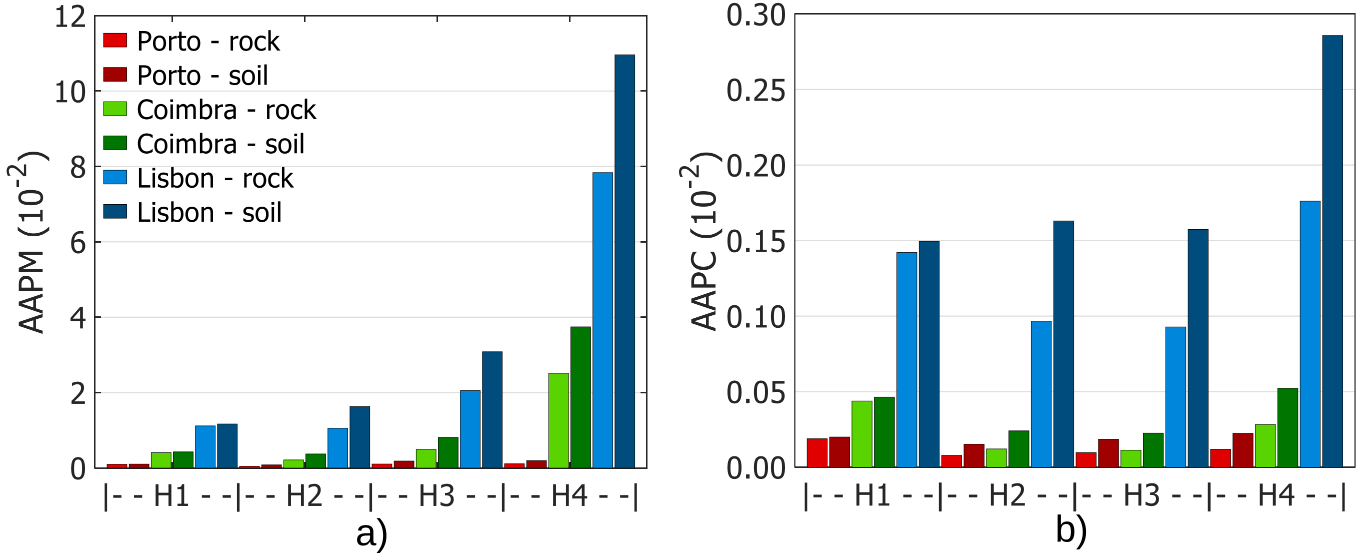
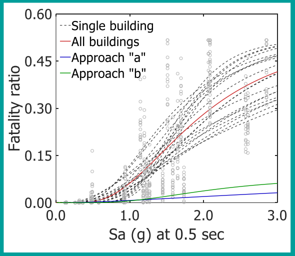


Fig. 14 Average annual a) moderate damage probability, and b) collapse probability for buildings from 1 to 4 storeys (H1 – H4) in Porto, Coimbra and Lisbon.

Results have been documented in a journal paper currently under review.

Lovon H, Silva V, Vicente R, Ferreira T (2021). Seismic Vulnerability Assessment of Portuguese Masonry Buildings. Engineering structures (in review).



Current research

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 rates are constant for all IMs.

Using advanced numerical models allows the estimation of volume loss, which has been found to have a direct correlation with probability of human loss

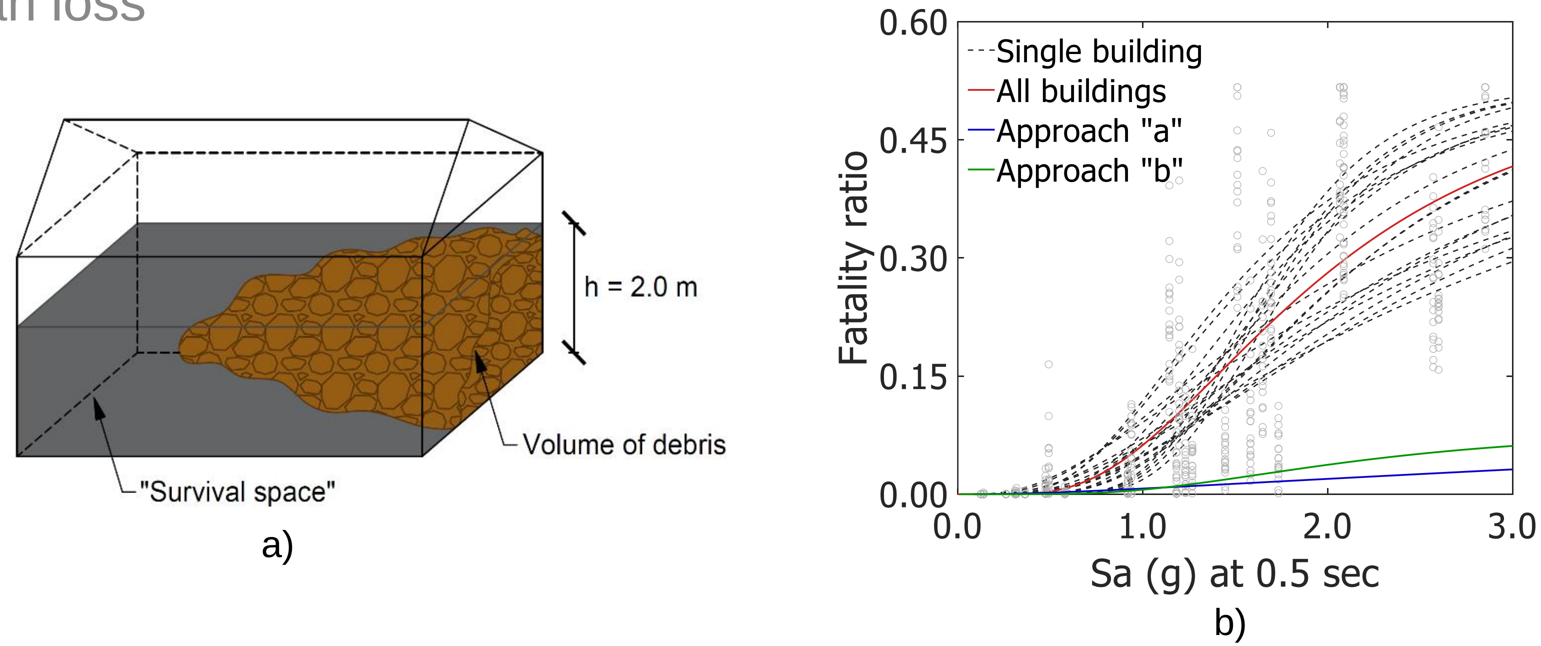


Fig. 15 a) Illustration of survival space and volume debris, b) Fatality vulnerability function for 3-storey limestone masonry building

Currently we are finishing the derivation of fatality and injured vulnerability functions for most common URM classes.

Fatality vulnerability functions will be used for estimation human losses and injuries for specific historical and hypothetical earthquake scenarios.

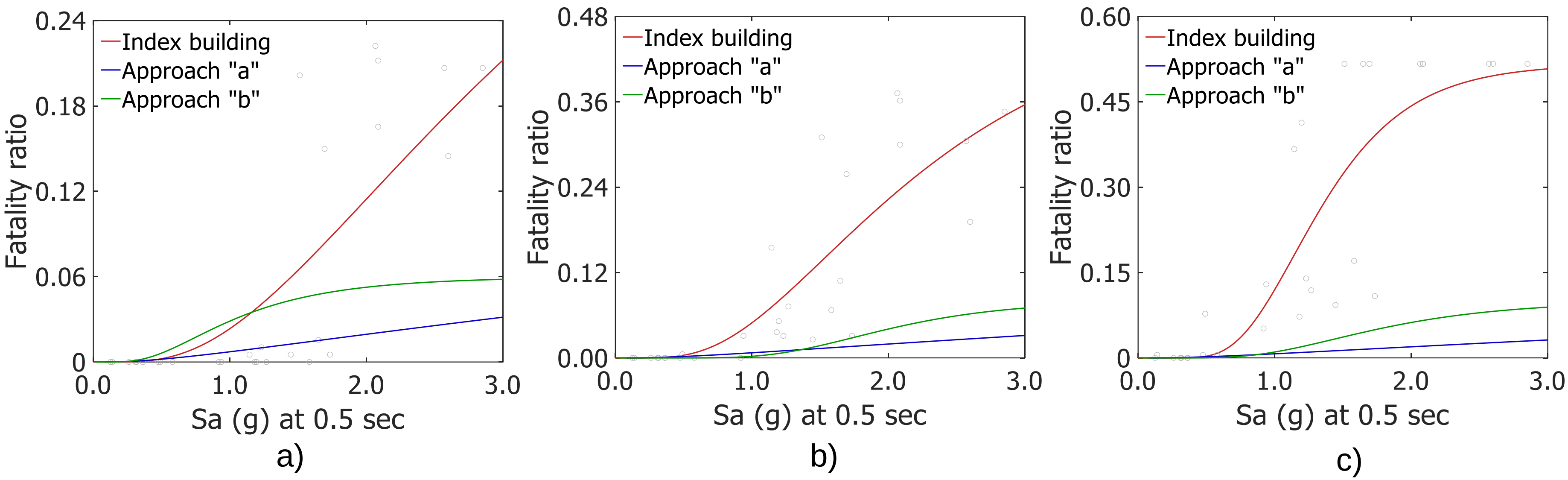
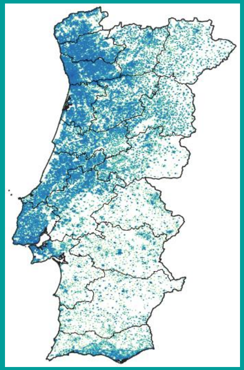


Fig. 16 Fatality vulnerability functions for a) 1-storey, b) 2-storey and c) 4-storey limestone masonry buildings



Future research

Future research

- To estimate fatalities and injured for specific scenarios for Portugal.
- Assess earthquake risk at the national scale for Portugal using the new vulnerability models.
- Explore retrofitting techniques and adjust numerical model to derive retrofitted vulnerability functions
- Perform benefit-cost analysis in Portugal to identify the regions where risk mitigation should be prioritized

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 (submitted)
- 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 (2021). Seismic Vulnerability Assessment of Portuguese Masonry Buildings. Engineering structures 23, 111857.

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. Pending to publish
- 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. Pending to publish

Many thanks!

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