



SEISMIC VULNERABILITY ASSESSMENT OF THE PORTUGUESE ADOBE BUILDING STOCK

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Abstract

Adobe is a common earth-based construction material that is used widely across the world. These buildings are known to exhibit low seismic resistance capacity due to their brittle behaviour, thus making them vulnerable to ground shaking and more prone to structural damage that potentially causes human fatalities. The Portuguese Adobe building stock is estimated to be 5% of the total building stock according to the Population and Housing Census of the Instituto Nacional de Estatística (INE), 2011. The distribution of these Adobe buildings is scattered across the country, with higher density in the central region owing to the *Art Nouveau* movement which promoted the use of adobe, and in the south, Algarve, where the seismic hazard is highest. A large population of these buildings are still in use for residential and commercial purposes; they are of historical significance and contribute to the cultural heritage of the country. Portugal has witnessed many devastating earthquakes in the past centuries. Benavente, 1909 earthquake has been reported to have caused 46 deaths and widespread damage to 879 buildings, this was a period during which the use of Adobe was prevalent in the region. This research aims to build fragility functions for physical damage, and estimation of indoor fatalities. For this purpose, we have selected three buildings from a building survey database. These buildings, with one, two and two-storey plus attic were then numerically modelled using solid and contact (tie-break) elements. The influence of various contact element input parameters has been assessed in the sensitivity analyses. Calibration and validation of material properties were carried out following the results from full-scale experimental in-plane cyclic tests on adobe walls. Furthermore, a set of 30 ground motion records with bi-directional components have been selected, and non-linear time-histories of the building models were performed until complete collapse. Fragility and fatality vulnerability functions were then derived, to estimate the physical damage and indoor fatalities, respectively. To improve seismic risk mitigation, the latter functions play an essential part. This research gap has been identified and is addressed by conducting this comprehensive vulnerability assessment. This is a novel contribution, that could help in reducing the seismic risk, preventing human losses, and thus improving the seismic resistance of the Portuguese Adobe building stock.

Keywords: Adobe buildings, fragility functions, fatality vulnerability functions, Portugal, Ls-dyna



1. Introduction

In this study, the seismic vulnerability assessment of three Portuguese adobe buildings has been conducted to derive fragility and fatality vulnerability functions, which can be used to estimate losses due to earthquakes. Over the past centuries, Portugal has experienced numerous earthquakes, the 1909 Benavente earthquake, despite its recorded lower intensity Mw 6.0, is known to be the largest crustal earthquake in the Iberian Peninsula [1]. It occurred around a period during in which the Art Nouveau movement was gaining popularity in the central region and adobe constructions were in vogue. According to a post-earthquake survey report of the 1909 Benavente earthquake [2], 879 buildings have been damaged: 20% reported light damage, 40% moderate damage and the remaining 40% were completely damaged. Furthermore, there were severe casualties that resulted in 46 deaths, out of which 30 were from the village of Benavente. The direct and indirect consequences of this event played an important role in influencing the local seismic building culture. The scientific studies on seismic fragility analysis for adobe buildings published over the past years are hereby acknowledged in the current state of practice. A majority of such studies [3], [4], [5] have been focussed on using single-degree-of-freedom (SDOF) oscillators to model the response of the buildings, following the displacement based earthquake loss assessment DBELA methodology [6] mostly pertaining to the South American building stock. Another study [7] proposed similar approaches for commonly found buildings in Pakistan including adobe buildings. Recently [8] developed analytical fragility and vulnerability functions using censored cloud regression method, for one, two and three-storey adobe buildings.

Currently, there is a lack of reliable vulnerability assessment models for adobe buildings in Portugal. In this study, the advances in computational modelling capabilities have been utilized for the development of sophisticated numerical models that can simulate the complete collapse of a full-scale building subjected to bi-directional loading and capable of predicting crack propagation and volume loss. According to [9], the building volume loss and is considered a better damage descriptor for estimating risk to occupants as compared to traditional damage states since it can be directly correlated with earthquake fatalities. Such data is essential to better estimate earthquake-related risk and losses, thus minimizing economic losses and mitigating fatalities. The derivation of fragility and fatality vulnerability functions for the Portuguese adobe buildings with one, two and two-storey plus attic buildings is discussed in the following sections.

2. Selection of the buildings – geometrical and material properties

According to the 2011 Population and Housing Census of Portugal (INE) [10], the total building stock of Portugal comprises 3,353,610 buildings, out of which the adobe building stock amounts to 178,422 buildings, i.e., about 5.32% of the whole Portuguese building stock see Fig.1.

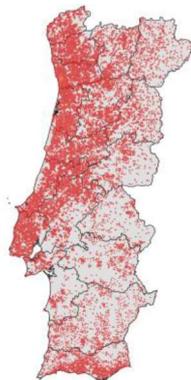


Fig. 1 - Geographical distribution of Adobe buildings in Portugal, as reported in the INE 2011 [10]



In Portugal, earth-based materials have been used to construct loadbearing walls in the form of adobe or rammed earth for the construction of buildings, especially in the central and southern regions of the territory. Locally, earth-based building materials are divided into three different types of building techniques: rammed earth, known as “Taipa”; wattle-and-daub, “Tabique”; and “Adobe” [11]. The central region of Portugal has the highest density of adobe buildings [12], the factor that led to the upsurge in adobe as a construction material of choice, especially in the central region, is credited to the Art Nouveau movement that spread across Europe in various forms. This movement had a significant influence in some Portuguese cities [13], particularly in Aveiro, where it is estimated that 30-40% of the buildings are still adobe [14]. The Southern region of Algarve, where the seismic hazard is the highest in the Portuguese territory [15], has a high density of adobe buildings, as shown in Fig.1.

2.1 Case study buildings

The information obtained from the documented evidence such as building surveys was studied in detail three buildings, namely, Buildings 1-3, have been selected for the case study presented herein. The selected buildings are unique buildings due to their exterior wall thickness, storey or inter-storey heights, total area, percentage of openings, and building features such as lintel beams and gable-end walls, which are particularly vulnerable to ground shaking [13], are incorporated when present. Each of these buildings is described in the following subsections.

Building 1, a one storey building with gable end walls, was located in the county Castro Marim in Algarve and was utilized for residential purposes, had been abandoned at the time of the survey. The primary and secondary construction material is adobe, and the external walls are 30 cm thick, (constant along the entire height of the building). The thickness of the walls is modelled adopting a “two-parts” scheme with the corresponding mesh detail to reproduce the thickness. Each visible multicoloured block is termed as a ‘part’, and these different parts constitute the prisms that are numbered from 1-7, the interlocking of blocks is modelled by arranging them in a staggered pattern, and the addition of constraints at the intersections simulate the interlocking of two orthogonal walls, as shown in Fig.2(a). The internal walls are 15 cm thick and divide the various compartments of the building. However, for simplifying the numerical models and reducing the computational cost, these internal walls have not been modelled in this study. The lintel beams are modelled above each of the openings, the nodes of the parts are thereby constrained in the x, y, and z-translational degrees-of-freedom, as shown in Fig.2(a). The gable end walls compose both the left and right façades of the building and do not have any openings, as shown in Fig.2(d). The beams of the roofing system are equally spaced and modelled using a discrete element with compression-only springs added in the two orthogonal directions, see Fig.2(a) and (d). The mechanical properties of the wooden beams of the roofing system were defined according to prescriptions based on Eurocode 5 [16]. The dimensions of the building are summarized in Table 1, and the geometrical details and features that have been modelled in the LS-DYNA [17] environment are shown in Fig.2(a), (d), (g). Further details pertaining to numerical modelling are discussed in Section 3.

Building 2, a two-storey residential building is located in Ílhavo and is currently in use. The primary construction material is adobe, the external walls are 60 cm thick, (constant along the entire height of the building). The interior walls are 15 cm thick and are built using a secondary construction material, tabique. The beams of the roofing system are equally spaced and modelled using a discrete element with compression-only springs added in one direction in this case, since there are no gable end walls as shown in Fig.2(b). The dimensions of the building are summarized in Table 1, and the geometrical details and features that have been modelled in the LS-DYNA environment shown in Fig.2(b), (e), (h).

Building 3, a two-storey plus attic with gable-end walls is a residential building located in Ílhavo, and is also currently in use. The external walls are 40 cm thick (constant along the entire height of the building). The gable end walls which are vulnerable to ground shaking [18] compose the main and rear façades. The flooring system consists of wooden beams that are equally spaced at 40 cm and the roof that consists of wooden trusses. The beams of the roofing system are modelled using a discrete element with compression-

only springs added in the two orthogonal directions as shown in Fig.2(c, i). The dimensions of the building are summarized in Table 1, and the geometrical details and features that have been modelled in the LS-DYNA environment shown in Fig. 2(c), (f), (i).

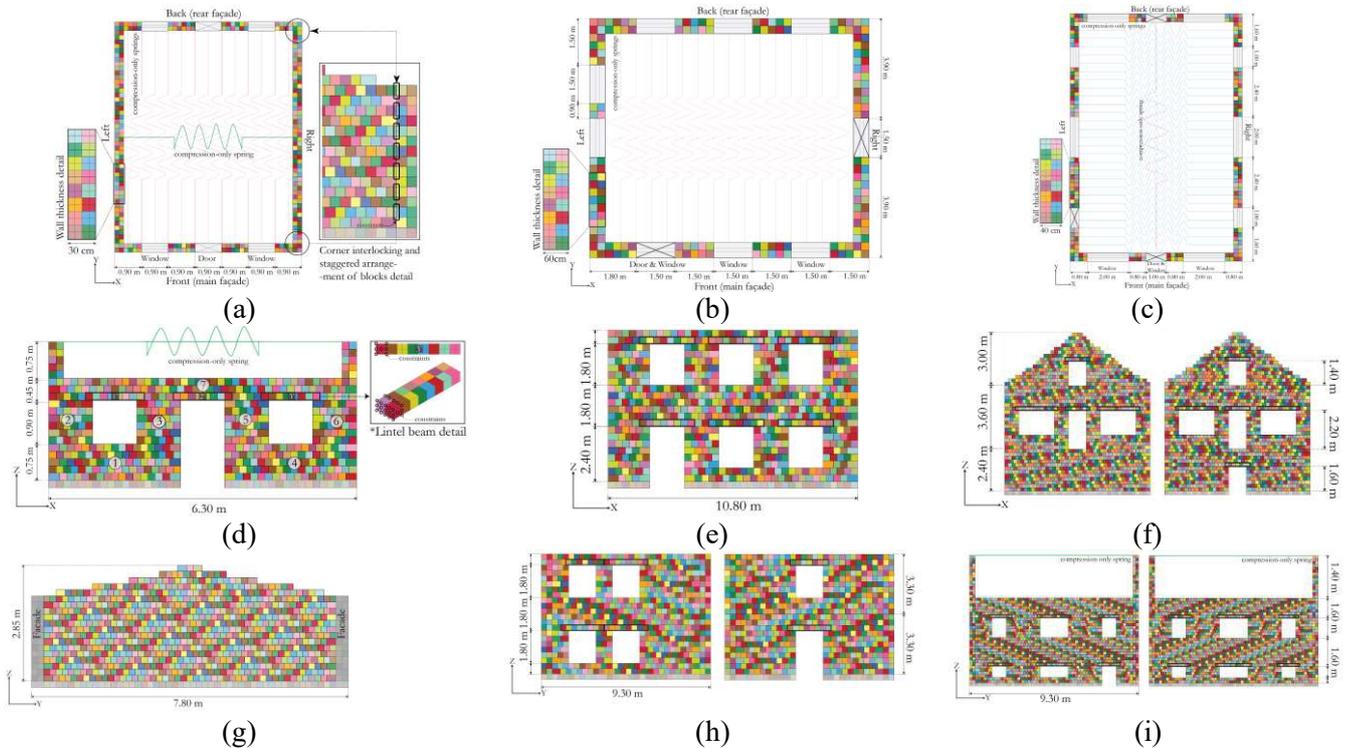


Fig. 2 – (a, b, c) Plan view showing dimension and features that are modelled in the LS-DYNA environment. (d, e, f) Elevation view of the main and rear facades. (g, h, i) Elevation view of the left and right walls.

Table 1 Building characteristics and dimensions

Building characteristics		Building 1	Building 2	Building 3
Total no. of stories		1	2	2+Attic
Length (m)	X-direction	6.30	10.80	8.20
	Y-direction	7.80	9.30	12.00
Area (m ²)		49.14	100.44	98.40
Height (m)	1 st Storey	2.85	3.30	2.40
	2 nd Storey	-	3.30	3.60
	Attic	-	-	3.00
Total height (m)		2.85	6.60	9.00
External wall thickness (cm)		30	60	40
Total percentage of openings (%)		10	20	14

2.2 Material properties

Several studies and experimental campaigns that have been conducted at the Civil Engineering Department of the University of Aveiro since 2005 have provided crucial insights and information to sustain more robust numerical models. Adobe has also been studied vastly in Portugal; however, mainly on the characterization of its mechanical properties [19], [20]. The experimental campaigns on in-plane cyclic tests on full-scale double-T adobe walls carried out by [21] provided the value of Young's modulus (E) adopted herein. A case study [22] conducted incorporated these results to create finite element models and developed fragility functions of two selected case study two-storey buildings. A numerical model of the adobe double-T wall experiment reported in [21] was recreated in the LS-DYNA environment, and a trial range of values of



Young's modulus was applied and tested. Each of the eigenmodes and their corresponding eigenfrequencies was checked, and it was found that at Young's modulus 738 MPa, the corresponding frequency was 23 Hz, henceforth providing a match to the experimental results. Adobe masonry exhibits brittle behaviour owing to its low compressive, tensile, and shear strength [18], [23], [24], [25]. The tensile strength is assumed to be 0.05 MPa, [26], [27] provided the initial range of parameters such as tensile strength, normal and shear energy release rate that can be employed for numerical models of adobe buildings. According to [35], it is acceptable to assume equal shear and tensile parameters for masonry. Based on the parametric analysis conducted, the final values of normal energy and shear energy release rate adopted in this study for building 1, building 2, and building 3 are 10 N/m, 30 N/m and 20 N/m, respectively. From the parametric analysis, there was no clear recommendation for the coefficient of friction. Thus, a static coefficient of 0.4 and a dynamic coefficient of 0.3 was assumed. A summary of all the mechanical properties and input parameters adopted for the numerical models of the adobe buildings presented herein are given in Table 2.

Table 2 Mechanical properties and input parameters of the numerical models

Element	Mechanical properties	Value	Unit
Solid elements	Young's modulus	0.74	GPa
	Poisson's ratio	0.30	-
	Density	1500	kg/m ³
	Normal and shear failure stress	0.05	MPa
	Normal and shear energy release rate	10, 30, 20	N/m
	Normal stiffness and tangential stiffness	0.74	GPa
Springs	Timber elasticity modulus	7.00	GPa
	Timber elasticity modulus (5%)	4.70	GPa
	Design compressive strength	16.00	MPa
	Design bending strength	14.00	MPa

3. Framework for vulnerability assessment

A framework for vulnerability assessment of adobe buildings is shown in Fig.3 and each of the steps are discussed in the following subsections.

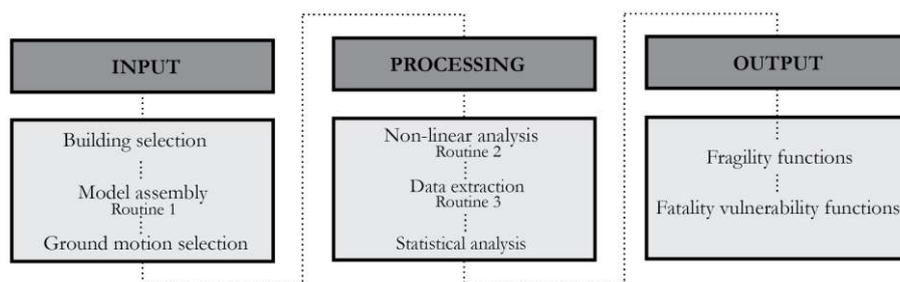


Fig. 3 - Framework for vulnerability assessment of adobe buildings

3.1 Numerical modelling

LS-DYNA, a general-purpose finite element software capable of simulating complex real-world problems, is used in this study. An SMP double precision solver has been utilized to improve the convergence of the non-linear analyses, and a combined finite-discrete element [29] strategy was adopted to simulate various stages of damage such as cracking of walls and volume loss. In the state-of-the-art, there has been a significant effort in the overall landscape of studies related to adobe masonry buildings, from characterization of mechanical properties, experimental campaigns, numerical modelling of full-scale structures to seismic



fragility and vulnerability studies [26], [30], [31]. The pre-processing, processing and post-processing of the numerical models can be broadly categorised into a three-step process. Firstly, the detailed building drawings are to be reproduced into the software environment – in the case of the present work, LS-PrePost [32]. Secondly, the assembled models have to be processed and the data stored. Finally, the relevant data has to be extracted and further post-processed to obtain the results. Overall, this is a time-consuming and extremely cumbersome process to be executed manually. To improve the speed and accuracy of these primary yet important steps, automatic processes have been implemented in MATLAB software [33], using specifically developed MATLAB routines. This approach allowed to accelerate the process of creating a building model for producing fragility and fatality vulnerability functions, also improving organization and efficiency.

To suit this study's objectives, it is pertinent to model the collapse mechanism of the buildings, including in that analysis the crack propagation and the volume loss that the buildings have incurred. According to a classification given by [34], this modelling strategy can be considered a block-based approach; following the combined finite and discrete modelling approach [29], the building is discretized uniformly into blocks, shown in Fig.4(a). In this study, the buildings were modelled utilizing three different mesh size discretization given in Table 3 to reproduce the exact wall thickness given previously in Table 1.

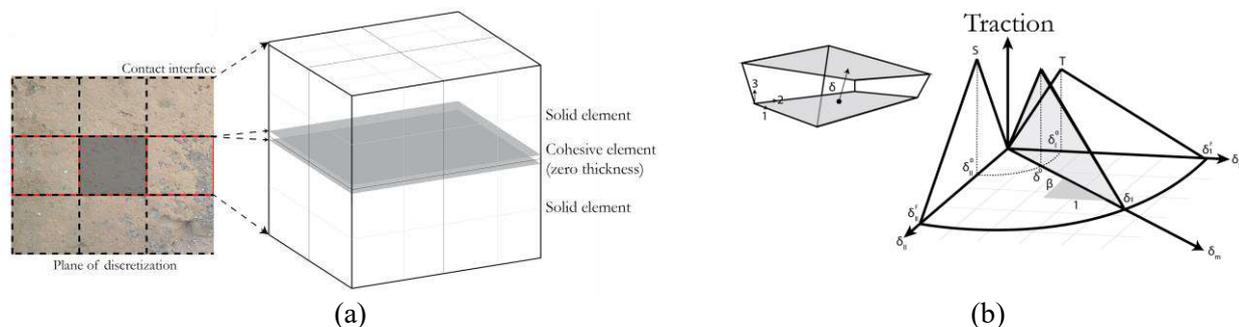


Fig. 4 - Schematic of (a) the plane of discretization of an adobe wall and the arrangement of two solid elements joined with cohesive elements. (b) Mixed-mode traction-separation law adapted from [36].

Table 3 Numerical modelling characteristics

	Building 1	Building 2	Building 3
Mesh size (cm)	7.5	15	10
No. of nodes	141,408	123,156	300,654
Volume of blocks of walls (m ³)	17.80	124.90	89.90
Roof	Spring-based	Spring-based	Spring-based

Standard three-dimensional solid elements are used, with *MAT_001, an isotropic elastic material model [35]. The computational cost of such a combination is affordable to perform multiple non-linear time histories. Under integrated solid elements have the potential to develop Hourglassing (HG). To control this numerical artefact, an HG control (IHQ4) that follows a stiffness form of type 2 Flanagan-Belytschko has been utilized, and after a series of calibration tests, the Hourglass coefficient (QH) was set to 0.05, similar calibrations can be found in [28].

A penalty stiffness approach is used to model the treatment of separation, impact and sliding along interfaces, as it is an important capability of LS-DYNA [38], [44], and this approach is numerical stable for explicit solutions. A *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK (Option 9) is used as these automatic contacts are non-oriented. The selected contact algorithm is based on *MAT_138 [35] that has a Discrete Crack Model, which is governed by a linear traction separation law show in Fig.4(b) with quadratic mixed-mode delamination criterion and a Power law (P) and Benzeggah-Kenane (B-K)



damage formulation. A summary of the mechanical properties and input parameters adopted for the numerical models of the adobe buildings presented herein are given in Table 2.

3.2 Hazard demand

A set of 30 bi-directional ground motions records were selected based on the local tectonic regime. The IM considered is PGA, and the records selected based on the geometric mean of the bi-directional components have been segregated into five bins between 0.05g and 1.05g. Some of these records were scaled to cover the range of PGA needed to induce collapse, primarily due to the scarcity of such records. Fig.5 illustrates the acceleration spectra for the selected ground motion records along with the median spectrum and the 16th and 84th percentile spectra.

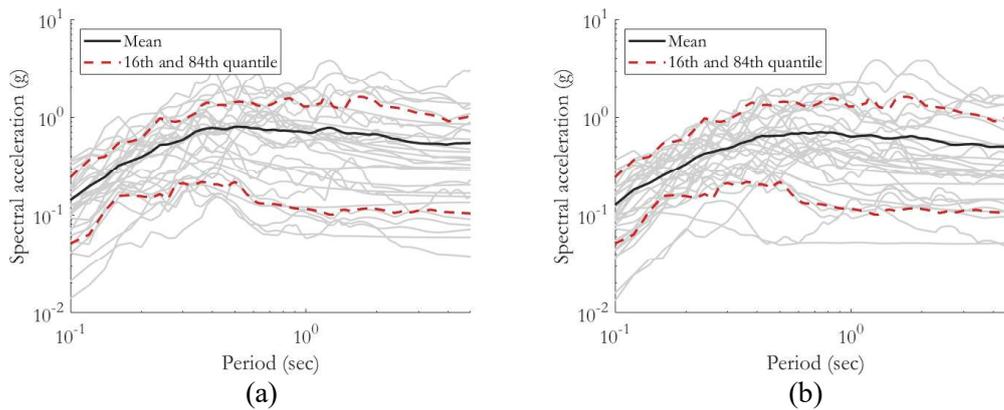


Fig. 5 - Response spectra of the bi-directional components (a-b) of the selected ground motion records

3.3 Non-linear time history analysis, EDPs and DSs

Non-linear time history analyses are performed on all three building models using the set of selected ground motion records comprising of their bi-directional components. The pre-loading was performed using a high damping, in order to get a soft response (pseudo-static) to avoid important dynamic effects, whereas for the non-linear time histories a damping of 3% is assumed [26].

In these analyses it is expected that depending on the intensity of the ground motion records, the contact interfaces develop cracks due to the energy input, the solid elements of the walls get displaced from their original position and trigger a combined collapse mechanism. The failure modes of these buildings under seismic loading depend on the mechanical properties and on the overall geometric configuration of the building [38] in terms of the slenderness ratio of the walls, boundary conditions and additional vertical loading according to [26]. Examples of the end stage of the non-linear time history analyses according to the different assumed damage states are shown in Fig.6(a-e).

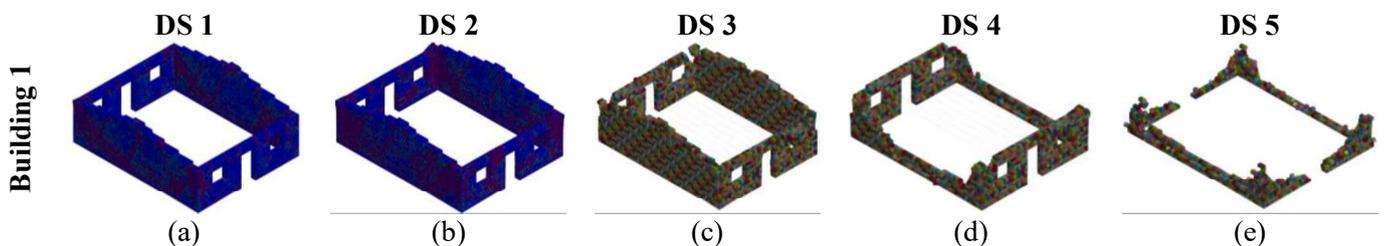


Fig. 6 - Damage and volume loss to building 1 (a-e) DS thresholds at the end stage of the non-linear time history analyses.

To develop the probability of exceedance of a set threshold of a given damage state given the IM, the European Macroseismic Scale (EMS 98) [39] has been adopted for the two novel EDPs that are sub-categorized into with five damage states (DSs) from DS1 to DS5 further elaborated in Table 4.



Table 4 EDPs and DSs and the corresponding damage thresholds

EDPs	DSs	Description	Threshold
Crack propagation ratio	DS 1	Negligible to slight	15%
	DS 2	Moderate	25%
Volume loss ratio	DS 3	Substantial to heavy	10%
	DS 4	Very heavy	25%
	DS 5	Destruction	40%

3.4 Cloud analysis

Fragility assessment is important step in seismic risk assessment [40]. The Cloud analysis procedure proposed by [40] is followed, it has been used in recent structural fragility studies due to its capability to consider both record-to-record variability and other sources of uncertainty related to structural modelling. The steps of the fragility assessment are broken down as follows for clarity and to illustrate the simplicity of the method.

- i. The expected value of the dependent variable that is EDP given an IM is calculated as described in Eq. (1). A homogeneity of variance is assumed for the IM-EDP random variables.

$$\left\{ \begin{array}{l} E[\log(EDP)|IM] = b \times \log(IM) + \log(a) \\ \sigma_{rec-rec} = \sqrt{\frac{\sum_{i=1}^n (\log(EDP_i) - E[\log(EDP)|IM_i])^2}{n-2}} \end{array} \right. \quad (1)$$

Where $E[\log(EDP|IM)]$ stands for the expected logarithm of EDP given an IM, b and $\log(a)$ are the regression parameters, $\sigma_{rec-rec}$ is the calculated record-to-record variability, n is the no. of records and EDP_i corresponds to the i -EDP value obtained from the non-linear analysis for the corresponding IM_i .

- ii. The structural fragility functions obtained from the probabilistic model can be expressed using Eq. (2).

$$P[EDP \geq ds_i | IM] = 1 - \Phi \left(\frac{EDP_{ds_i} - E[\log(EDP|IM)]}{\sigma_{rec-rec}} \right) \quad (2)$$

Where Φ is the cumulative normal standard distribution, EDP_{ds_i} is the EDP damage threshold level (eg. 15%) corresponding to the damage state (eg. DS1) respectively.

3.5 Fatality vulnerability functions

The method to estimate volume loss fatalities in this study follows in the methodology proposed by [9] in which a volume loss-fatality ratio relationship is used to estimate indoor fatalities. The buildings volume loss, is a damage descriptor, that measures the obstruction of interior space due to the volume of debris (V_d), and the space capacity (V_c) is measured up-to a height of 2 m from the floor level according to Okada [41] as shown in Fig.7, thus the volume loss can be calculated by using Eq. (3).

$$Volume\ loss = \frac{V_d}{V_c} \quad (3)$$

A cloud of fatality ratio (FR) – IM data is produced by multiplying the volume loss obtained from each of the structural analysis and the corresponding FR proposed by [9]. This cloud of points is then fitted to a truncated lognormal cumulative density function defined in Eq. (4).



$$\text{Fatality ratio} = 0.52 \cdot \Phi \left(\frac{\ln(IM) - \theta}{\beta} \right) \quad (4)$$

Where 0.52 is the maximum fatality ratio corresponding to 100% volume loss as per [9], Φ is the cumulative normal standard distribution, θ - logarithmic mean, β - logarithmic standard deviation.

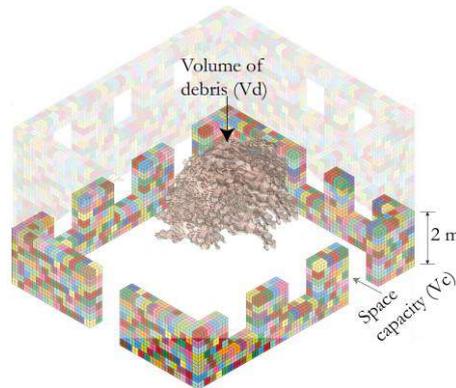


Fig. 7 - Illustration of volume loss using Building 2 (adapted from Okada [41])

4. Results

The results of this study pertaining to the three representative adobe buildings classes are presented in terms of the derived fragility and fatality vulnerability functions shown in Fig.8(a-f) and the corresponding fragility parameters (i.e., μ - logarithmic mean and σ - logarithmic standard deviation) given in Table 5 and the fatality vulnerability parameters given in Table 6.

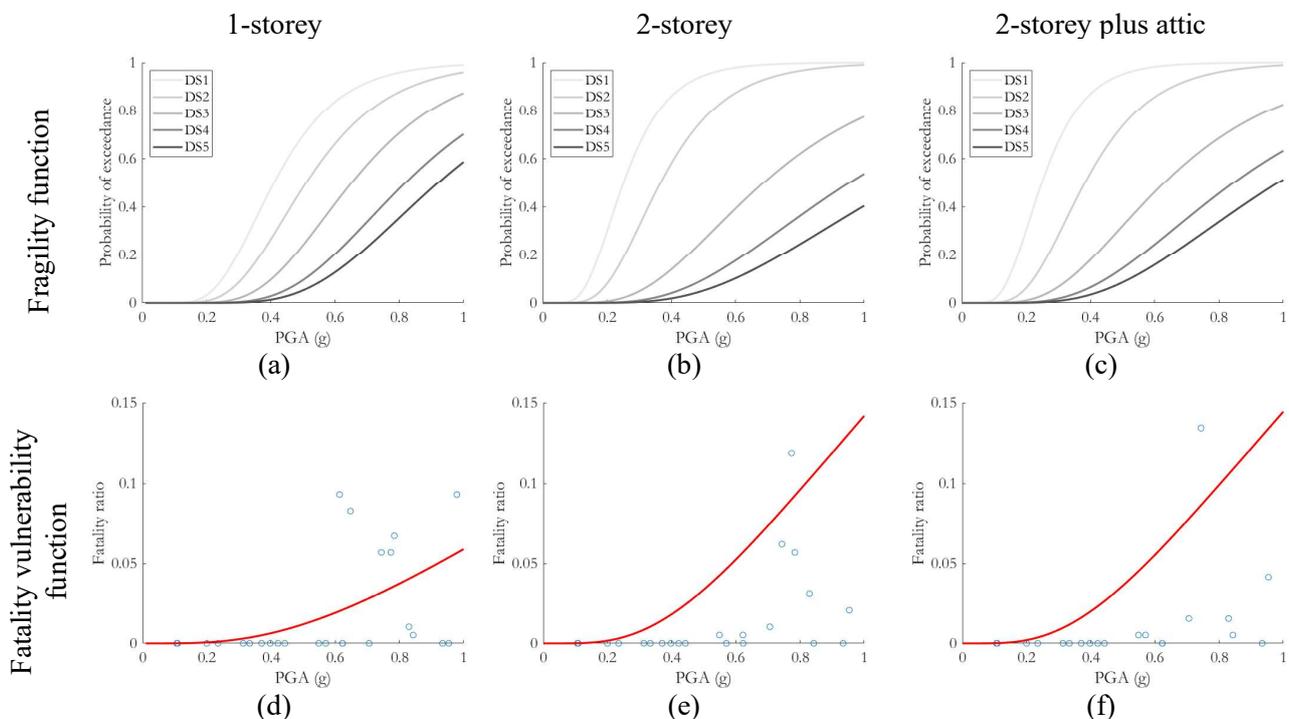


Fig. 8 – Fragility (a,b,c) and fatality vulnerability function (d,e,f) for building classes 1-storey, 2-storey, and 2-storey plus attic



It can be inferred from the values of dispersion (i.e., σ) given in Table 5, that there are two different values for the dispersion, one value corresponding to DS1-DS2 and another for DS3-DS5. The difference arises here, because the two novel EDPs selected are used to predict different phenomenon namely, crack propagation and volume loss that occurs to the building.

Table 5 Fragility parameters for adobe buildings

Building class	DS 1		DS 2		DS 3		DS 4		DS 5	
	μ	σ								
1-storey	-0.89	0.39	-0.67	0.39	-0.43	0.37	-0.20	0.37	-0.08	0.37
2-storey	-1.38	0.43	-1.00	0.43	-0.38	0.50	-0.05	0.50	0.12	0.50
2-storey plus attic	-1.39	0.42	-0.96	0.42	-0.46	0.49	-0.17	0.49	-0.02	0.49

μ - logarithmic mean, σ - logarithmic standard deviation

Table 6 Fatality vulnerability parameters for adobe buildings

Building class	θ	β
1-storey	1.06	0.88
2-storey	0.45	0.75
2-storey plus attic	0.45	0.77

θ - logarithmic mean, β - logarithmic standard deviation

5. Conclusions

This study presented the development of fragility and vulnerability functions for typical adobe buildings in Portugal, one of the most vulnerable types of construction in the country. The selection of the buildings to numerically model was carried out based on survey data comprising building drawings, photographs, and information regarding the construction practice and material properties. The sensitivity of mechanical properties and modelling options has been assessed, and calibration and validation of material properties were carried out following the results from a full-scale experimental in-plane cyclic tests on adobe walls. A set of 30 ground motion records with bi-directional components have been selected, and non-linear time-history analyses were performed until collapse was reached. Two novel EDPs have been adopted and damage thresholds were proposed such that they can be correlated with damage classifications in agreement with the European Macroseismic Scale (EMS-98) [39]. Fragility functions were then derived following the cloud analysis methodology [40].

The fragility functions proposed herein can be used directly in the assessment of damage due to earthquake scenarios, or in probabilistic risk analysis to identify regions in the country where the probability of collapse of these structures is particularly high. Similarly, the vulnerability functions in terms of fatality rates can be employed to assess human losses, which is particularly important for the development of risk management measures.

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8. References

- [1] G. Sousa and E. S. Gallaecia, "Historical Seismicity in Portugal," no. January, 2015.
- [2] Choffat P, "Le tremblement de terre du 23 Avril 1909 dans le Ribatejo. Revista de Obras Pu 'blicas e Minas, Tomo XLIII, Imprensa Nacional, Lisboa (in French)," 1912.
- [3] N. Tarque, H. Crowley, R. Pinho, and H. Varum, "Displacement-based fragility curves for seismic assessment of adobe buildings in Cusco, Peru," *Earthq. Spectra*, vol. 28, no. 2, pp. 759–794, 2012.
- [4] M. Villar-Vega *et al.*, "Development of a fragility model for the residential building stock in South America," *Earthq. Spectra*, vol. 33, no. 2, pp. 581–604, 2017.
- [5] G. Sumerente, H. Lovon, N. Tarque, and C. Chácaras, "Assessment of combined in-plane and out-of-plane fragility functions for adobe masonry buildings in the peruvian andes," *Front. Built Environ.*, vol. 6, no. May, pp. 1–10, 2020.
- [6] H. Crowley, R. Pinho, and J. J. Bommer, "A probabilistic displacement-based vulnerability assessment procedure for earthquake loss estimation," *Bull. Earthq. Eng.*, vol. 2, no. 2, pp. 173–219, 2004.
- [7] N. Ahmad, Q. Ali, H. Crowley, and R. Pinho, "Earthquake loss estimation of residential buildings in Pakistan," *Nat. Hazards*, vol. 73, no. 3, pp. 1889–1955, 2014.
- [8] L. Martins and V. Silva, "Development of a fragility and vulnerability model for global seismic risk analyses," *Bull. Earthq. Eng.*, no. 0123456789, 2020.
- [9] S. Abeling and J. M. Ingham, "Volume loss fatality model for as-built and retrofitted clay brick unreinforced masonry buildings damaged in the 2010/11 Canterbury earthquakes," *Structures*, vol. 24, no. April, pp. 940–954, 2020.
- [10] "I. N. de Estatística, 'Census data 2011,' Lisbon, 2011. [Online]. Available: <http://censos.ine.pt/>."
- [11] C. Costa, D. Arduin, F. Rocha, and A. Velosa, "Adobe Blocks in the Center of Portugal: Main Characteristics," *Int. J. Archit. Herit.*, vol. 0, no. 0, pp. 1–12, 2019.
- [12] M. Fernandes, "Adobe architecture in Portugal: Differences and analogies between vernacular and 'designed' architecture," *Vernac. Herit. Earthen Archit.*, pp. 111–116, 2013.
- [13] H. Varum, A. Costa, A. Velosa, T. Martins, H. Pereira, and J. Almeida, "Caracterização mecânica e patológica das construções em Adobe no distrito de Aveiro como suporte em intervenções de reabilitação," *Proj. Cult. 2000/Mediterrae - Houses cities built with earth Conserv. significance urban Qual. Monsaraz, Port.*, pp. 41–45, 2006.
- [14] D. Silveira, H. Varum, A. Costa, and C. Neto, "Survey of the Facade Walls of Existing Adobe Buildings," *Int. J. Archit. Herit.*, vol. 10, no. 7, pp. 867–886, 2016.
- [15] CEN, "NP EN 1998-1: Eurocódigo 8 - Projecto de Estruturas para resistência aos sismos. Parte 1: Regras gerais, acções sísmicas e regras para edifícios," *Inst. Port. da Qual.*, 2010.
- [16] EN 1995-1-2:2004. *Eurocode 5: Design of timber structures—Part 1–2: General—Structural fire design*. CEN. Brussels, Belgium, 2004.
- [17] J. O. Hallquist and LIVERMORE SOFTWARE TECHNOLOGY CORPORATION (LSTC), *LS-DYNA Keyword User's Manual Volume I*, vol. II, no. October. 2018.
- [18] W. S. Ginell and E. L. Tolles, "Seismic stabilization of historic adobe structures," *J. Am. Inst. Conserv.*, vol. 39, no. 1, pp. 147–163, 2000.
- [19] D. Silveira, H. Varum, A. Costa, T. Martins, H. Pereira, and J. Almeida, "Mechanical properties of adobe bricks in ancient constructions," *Constr. Build. Mater.*, vol. 28, no. 1, pp. 36–44, 2012.
- [20] D. Silveira, H. Varum, and A. Costa, "Influence of the testing procedures in the mechanical characterization of adobe bricks," *Constr. Build. Mater.*, vol. 40, pp. 719–728, 2013.



- [21] D. Silveira, H. Varum, A. Costa, H. Pereira, L. Sarchi, and R. Monteiro, “Seismic behavior of two Portuguese adobe buildings: Part I - in-plane cyclic testing of a full-scale adobe wall,” *Int. J. Archit. Herit.*, vol. 12, no. 6, pp. 922–935, 2018.
- [22] L. Sarchi, H. Varum, R. Monteiro, and D. Silveira, “Seismic behavior of two Portuguese adobe buildings: part II —numerical modeling and fragility assessment,” *Int. J. Archit. Herit.*, vol. 12, no. 6, pp. 936–950, 2018.
- [23] J. Vargas, J. Bariola, M. Blondet, and P. K. Mehta, “Seismic strength of adobe masonry,” *Mater. Struct.*, vol. 19, no. 4, pp. 253–258, 1986.
- [24] M. Blondet, F. Ginocchio, C. Marsh, G. Ottazzi, G. Villa-Garcia, and J. Yep, “Shaking Table Test of Improved Adobe Masonry Houses,” *9th World Conference on Earthquake Engineering*. 1988.
- [25] R. Illampas, I. Ioannou, and D. C. Charmpis, “Adobe bricks under compression: Experimental investigation and derivation of stress-strain equation,” *Constr. Build. Mater.*, vol. 53, pp. 83–90, 2014.
- [26] G. Karanikouloudis and P. B. Lourenço, “Structural assessment and seismic vulnerability of earthen historic structures. Application of sophisticated numerical and simple analytical models,” *Eng. Struct.*, vol. 160, no. December 2016, pp. 488–509, 2018.
- [27] Paulo B. Lourenço and João M. Pereira, “Seismic Retrofitting Project Recommendations for Advanced Modeling of Historic Earthen Sites,” 2018.
- [28] O. AlShawa, L. Sorrentino, and D. Liberatore, “Simulation Of Shake Table Tests on Out-of-Plane Masonry Buildings. Part (II): Combined Finite-Discrete Elements,” *Int. J. Archit. Herit.*, vol. 11, no. 1, pp. 79–93, 2017.
- [29] M. Hazay and A. Munjiza, “Introduction to the Combined Finite-Discrete Element Method,” pp. 123–145, 2016.
- [30] N. Tarque, G. Camata, E. Spacone, and H. Varum, “Numerical modelling of in-plane behaviour of adobe walls,” *Proc. 8th Congr. Seismol. Earthq. Eng.*, no. Figure 1, pp. 1–12, 2010.
- [31] W. Jäger, T. Bakeer, and P. Schöps, “Simulation of Masonry in ANSYS and LS-DYNA The Features and Challenges,” *ANSYS Conf. 27th CADFEM Users’ Meet.*, no. NOVEMBER 2009, pp. 1–15, 2009.
- [32] C. Dis, “LS-DYNA / LS-PrePost Ex. 0. Introduction,” vol. 31, no. suppl 1, pp. 1–74, 2011.
- [33] “T. M. Inc., ‘MATLAB.’ Natick, Massachusetts, 2018.”
- [34] A. M. D’Altri *et al.*, *Modeling Strategies for the Computational Analysis of Unreinforced Masonry Structures: Review and Classification*, vol. 27, no. 4. Springer Netherlands, 2020.
- [35] J. O. Hallquist and LIVERMORE SOFTWARE TECHNOLOGY CORPORATION (LSTC)., *LS-DYNA Keyword User ’ S Manual Volume II: Material Models*, vol. II, no. October. 2018.
- [36] J. O. Hallquist, “LS Dyna Theory Manual,” 2006.
- [37] S. Bala, “Tie-Break Contacts in LS-DYNA”. Livemore Software. USA,” 2007.
- [38] H. Varum, A. Costa, J. Fonseca, and A. Furtado, “Behaviour Characterization and Rehabilitation of Adobe Construction,” *Procedia Eng.*, vol. 114, pp. 714–721, 2015.
- [39] Comisión Sismológica Europea, *Escala Macro Sísmica Europea EMS - 98*, vol. 15. 1998.
- [40] F. Jalayer, R. De Risi, and G. Manfredi, “Bayesian Cloud Analysis: Efficient structural fragility assessment using linear regression,” *Bull. Earthq. Eng.*, vol. 13, no. 4, pp. 1183–1203, 2015.
- [41] S. Okada, “Okada, S. (1996). Description for indoor space damage degree of building in earthquake. Paper presented at the Eleventh World Conference on Earthquake Engineering, Acapulco, Mexico, 23-28 June.,” 1996.