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SEISMIC VULNERABILITY ASSESSMENT METHOD FOR VERNACULAR ARCHITECTURE

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ABSTRACT

The valorization and preservation of vernacular architecture, as well as traditional construction techniques and materials, is a key-element for cultural identity. As part of this essential objective, the present paper focuses on vernacular architecture earthquake preparedness. Earthquakes come unexpectedly, endangering in-use vernacular architecture and the population who inhabits it. However, conservation efforts are often mainly focused on historical construction and monuments. Furthermore, more detailed and sophisticated approaches typically used for monumental buildings require time, cost and resources that are not commonly assigned to the study of vernacular constructions. That is why the development of a simplified method for the seismic vulnerability assessment of vernacular architecture is of paramount importance.

The paper firstly provides a brief overview of seismic vulnerability assessment methods, specifically the vulnerability index method, on which the proposed method is based. Then, the paper presents the procedure that was followed for the development of the seismic vulnerability assessment method for vernacular architecture proposed, which includes: (a) the identification and selection of constructive aspects and parameters that most influence the seismic behavior of the building; (b) the definition of the parameters seismic vulnerability classes by means of numerical parametric analysis using detailed finite element (FE) modeling and nonlinear static (pushover) analyses; and (c) the definition of the parameters weight, according to a statistical analysis performed on the results of the parametric study. Finally, the paper shows, as an example, the numerical strategy followed for the definition of the classes of one parameter.

Keywords: Vernacular architecture; Seismic vulnerability; Finite element modeling; Parametric study; Masonry

1. INTRODUCTION

Vernacular construction always results from a tight relation between men and environment. Local communities had to eventually apprehend how to make the best use of the available technology at the time and the local materials in order to provide shelter from the climate. Vernacular architecture is thus an accumulation of empirical knowledge, understanding and intuition acquired along generations. As a result, it is extremely heterogeneous because of being intimately associated with a place, the territory and its history. This is the reason why the valorization and preservation of the vernacular heritage, as well as traditional construction techniques and materials, is crucial, not only as a key-element of cultural identity and a witness of the past, but also as a privileged factor for local development, boosting local economies. The revival of small industries of traditional local materials can also reduce waste and energy consumptions in production and transportation.

Vernacular buildings are a significant part of the building stock. However, vernacular architecture located in seismic prone areas can be particularly vulnerable to earthquakes due to a scarcity of resources in generally poor communities, resulting in a lack of construction quality and detailing, the use of poor materials and a poor maintenance. Portugal, in spite of being considered a moderate seismic hazard country, has suffered the strike of several devastating earthquakes, such as the well-known 1755 Lisbon earthquake. Therefore, it is susceptible to significant occurrences in the future, endangering the

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population who inhabits Portuguese vernacular architecture.

Nevertheless, there is a critical gap in knowledge on vernacular architecture earthquake preparedness, since research in vernacular architecture has predominantly focused on building typologies and spatial organization. The study of the seismic behavior and vulnerability of vernacular construction systems has traditionally been ignored, and conservation efforts have been mainly placed on historical construction and monuments. Thus, research in the seismic vulnerability assessment of vernacular architecture is relevant and can eventually contribute to save lives through risk prevention mitigation guidelines.

The seismic assessment of the built vernacular heritage requires a deep knowledge and investigation of the place, traditional techniques and materials. However, the time, cost and resources required to obtain a sufficient in-depth level of information of the analyzed structure are not commonly assigned to the study of vernacular constructions. That is why the development of an expedite method for the seismic vulnerability assessment of vernacular architecture is necessary, since more detailed approaches are typically restricted for individual monumental buildings. Seismic vulnerability assessment methods play an important role on risk mitigation because they are the main components of models capable of predicting damage to the built environment and estimating losses in future earthquakes. They can eventually help in evaluating the need for retrofitting solutions and assessing the efficiency in reducing the seismic vulnerability of proposed structural interventions (Vicente et al. 2011). There is big variety of methods proposed by different authors (Calvi 2006) and choosing a specific one depend on the goal, scale and nature of the study.

The present research work intends to give a step towards the preservation of the vernacular heritage by developing a seismic vulnerability assessment method adapted to the specific characteristics of vernacular architecture. For that matter, the paper firstly provides a brief literature review and understanding of existing seismic vulnerability assessment methods. Particularly, it discusses the vulnerability index methods (Benedetti and Petrini 1984), on which the proposed method is based. Secondly, the paper introduces the procedure that was applied for the development of the seismic vulnerability assessment method for vernacular architecture. It mainly consists of the identification of a set of parameters that are more influent in the seismic response of the building, and the subsequent definition of the selected parameters classes and weights. To do this, a numerical strategy was followed and an example for the definition of the seismic vulnerability classes corresponding to one of the parameters selected is provided..

Existing methods have mainly based on empiric post-earthquake damage observation. The method presented herein intends to obtain a sound understanding of the seismic behavior of vernacular constructions by means of advanced numerical analysis. Detailed finite element (FE) modeling and nonlinear static (pushover) analysis were the tools selected to perform an extensive parametric study intended to evaluate and quantify the influence of the different selected parameters. The parametric analysis uses a reference model that simulates a representative vernacular rammed earth construction commonly found in the South of Portugal. Therefore, this paper also contributes to for a better insight of the seismic behavior of Portuguese vernacular rammed earth and stone masonry typologies under seismic loading, for which few results are available in the literature.

2. SEISMIC VULNERABILITY ASSESSMENT METHODS

Considering that vulnerability can be broadly defined as the potential for loss, the seismic vulnerability of a structure can be defined as its intrinsic proneness to suffer damage as a result of a seismic event of a given intensity. Therefore, the main objective of seismic vulnerability assessments is to measure the probability of a specific building to reach a given level of damage when subjected to a seismic action with specified characteristics. Seismic vulnerability assessment methods for the built environment are one of the main components of earthquake loss models, together with hazard analysis, i.e. evaluation of the probability of exceedance of a certain level of seismic intensity, and exposure data, i.e. inventory of elements at risk. Earthquake loss models are capable of predicting consequences of an earthquake quantitatively, in terms of economic impact (e.g. probability of collapsed and unusable buildings), repair cost and human casualties. They are an essential tool for seismic risk mitigation because they are important for emergency response and disaster planning.

There exists a wide range of methods in the literature suitable for different types of analysis with different goals. First of all, the selection of a specific method will depend on the scale of the analysis and the level of detail required from the targeted buildings (Vicente 2008). Large-scale analyses comprising areas with buildings showing diverse construction characteristics typically require certain types of method that can simply rely on qualitative information. These methods are commonly known as empirical, since they are supported by previous data gathered from post-earthquake damage observation. More complex analytical approaches require more detailed information and a better understanding of construction details and materials to prepare the models. Thus, they can be very computationally expensive when a great number of constructions are involved. The vulnerability index method (Benedetti and Petrini 1984) is supported by statistical studies of post-earthquake damage information but also rely on expert opinion. It will serve as basis for the development of the present seismic vulnerability assessment method.

2.1 The vulnerability index method

The vulnerability index method was originally proposed by Benedetti and Petrini (1984). It is based on the identification of those constructive aspects that are more influential in the seismic structural behavior of the building, which results in the definition of several qualitative and quantitative parameters. The selection of these parameters relies on a vast set of post-seismic damage survey data and expert judgment. The original formulation accounted for a total of eleven parameters, including among others the type of vertical structural system, the type of horizontal diaphragms, the plan configuration or the conservation state. The parameters are related to four classes of increasing vulnerability – from A (lowest) to D (highest) – that are associated with a qualification coefficient (C_{vi}). A weight factor (p_i) is also included to emphasize the relative importance of each parameter. Each parameter can then be qualified individually, and the overall vulnerability of the building is calculated as the weighted sum of the parameters, expressed by means of a vulnerability index (I_v).

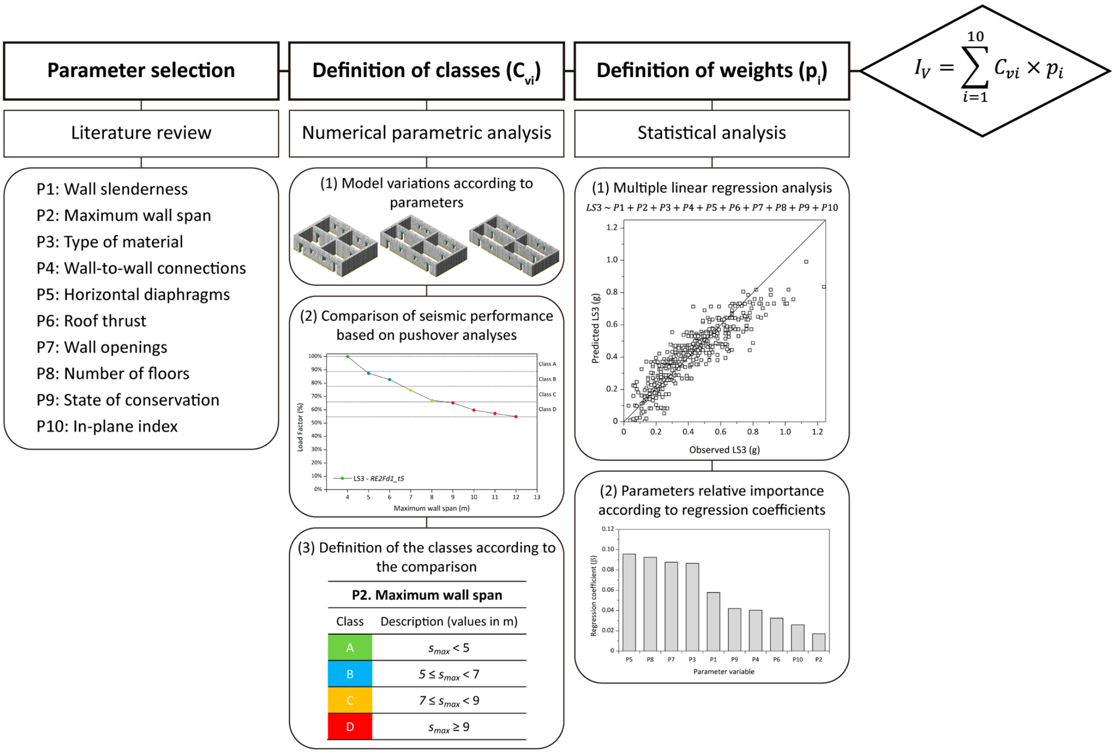
$$I_V = \sum_{i=1}^{11} C_{vi} \times p_i \tag{1}$$

The vulnerability index can be understood as a measure of the lack of building safety under seismic loads. Guagenti and Petrini (1989) used a set of post-earthquake recordings to calibrate vulnerability functions that relate I_v with a damage factor (d) for a given seismic event, expressed in terms of PGA (peak ground acceleration). The damage factor is an economic index that ranges from 0 to 1 and represents the structural state of the building after an earthquake taking into account the expected repair cost. They assumed a linear variation of the damage factor between two PGA threshold values representing the initial acceleration that leads to the onset of damage and the acceleration that causes the collapse of the building. Vulnerability curves can thus be developed, and the damage suffered by a building or a group of buildings presenting a specific vulnerability index can be estimated in a fast and simple way for a given seismic event. It constitutes a reliable large-scale assessment and has been extensively applied in Italy, with the development of the GNDT II level method (GNDT 1994).

Most recent seismic vulnerability assessment methods have adopted the vulnerability index formulation. Vicente (2008) proposed the combination of the vulnerability index method with the macroseismic method (Lagomarsino and Giovinazzi 2006). An analytical expression was developed in the macroseismic method that correlates the expected mean damage grade (μ_D) and the seismic input, as a function of the building vulnerability. However, it was proposed to use the vulnerability index formulation to estimate the seismic vulnerability of the building using predefined parameters. This allows an individual evaluation of the buildings instead of using a general vulnerability class for a specific building typology, as in the macroseismic method. This method, more or less modified and adapted to its context, has been implemented for the seismic vulnerability assessment of Portuguese masonry structures in several historic city centers (Vicente et al. 2011; Neves et al. 2012; Ferreira et al. 2016) and for other particular structures, such as Nepalese pagoda temples (Shakya 2014), obtaining useful and reliable results as a first level approach.

3. PROPOSED SEISMIC VULNERABILITY ASSESSMENT METHOD FOR VERNACULAR ARCHITECTURE

The method proposed will also make use of the vulnerability index method to evaluate the seismic vulnerability of vernacular buildings. For this, three aspects have to be defined: (1) the number of parameters representing features of vernacular buildings that influence their seismic behavior; (2) seismic vulnerability classes for each parameter; and (3) weights for each parameter enabling the account of the seismic vulnerability index. The procedure followed for the development of the vulnerability index method for vernacular architecture is presented in Figure 1.



P2. Maximum wall span

Class	Description (values in m)
A	$s_{max} < 5$
B	$5 \leq s_{max} < 7$
C	$7 \leq s_{max} < 9$
D	$s_{max} \geq 9$

Figure 1. Procedure used in the development of the seismic vulnerability assessment method

The identification of the parameters is mainly based on literature review and validated with the numerical parametric study that follows. The definition of the parameters classes are addressed by means of advanced numerical analysis and an extensive parametric study based on pushover analyses. The strategy consists of modeling variations on a reference model according to the different parameters considered. The variations on the seismic performance of the structure are evaluated and compared in order to quantify each parameter influence. The variations in the parameters are thus associated to classes of increasing vulnerability. For the definition of the parameters weight, a statistical analysis is performed. All models built for the parametric analysis compose an extensive database that is used to perform a regression analysis. The regression analysis provides regression coefficients that can be used to compare the relative strength of the parameters to estimate the seismic behavior of the model. These coefficients are associated with the weights of the seismic vulnerability assessment parameters and can lead to their numerical definition.

It is acknowledged that a deep understanding of the seismic behavior of vernacular constructions based on detailed FE modeling and nonlinear analysis is missing. In this scope, it is considered that quantitative analysis was missing to strengthen the reliability of these methods that are typically based on existing empirical knowledge, particularly concerning vernacular constructions. Few studies have combined analytical approaches to add robustness to mostly empirical methods (Shakya 2014). The present paper focuses on the first two steps of the procedure. Thus, it firstly shows the selection of the parameters and then presents the numerical strategy that was followed for the definition of the seismic vulnerability classes. An example of the definition of the classes for one of the parameters selected is given for reference.

3.1 Definition of seismic vulnerability assessment parameters

The parameters used in the original formulation (Benedetti and Petrini 1984) make reference to geometrical, structural, constructive and material aspects of masonry buildings. They are common to most of the applications of the vulnerability index method that can be observed in the literature (Sepe et al. 2008; Boukri and Bensaibi 2008; Vicente et al. 2011; Shakya 2014). Even though different studies have adapted it to specific structure typologies, identifying the most relevant parameters for those typologies, while discarding those that are less significant for those structural types.

Based on the work developed by these authors, a new set of parameters is proposed addressing Portuguese vernacular architecture, whose structural system typically consists on load bearing masonry or earthen walls coupled with horizontal timber diaphragms. Parameters are selected according to the singular behavior of this structural typology, acknowledging that other vernacular constructions around the world share a similar concept at the structural level. Therefore, it is considered that method will not be restricted to the Portuguese context. The selected ten parameters are listed below together with a brief description of each of them.

P1. Wall slenderness: This parameter can be defined as the ratio between the height of the wall and its thickness (*h/t*). Given the traditional materials commonly used for the walls (stone and earth), vernacular buildings typically present a low slenderness ratio below 9, and is rare to find ratios over 12.

P2. Maximum wall span: This parameter takes into account the maximum length of a wall prone to out-of-plane movements, which is the wall spanning the maximum distance between two in-plane earthquake resistant walls.

P3. Type of material: This parameter takes into account the type of material used for the vertical structural elements of the buildings. In the cases included in this study, only earthen and masonry (brick and stone) materials are considered, while the type of structure of the buildings always consists of load bearing walls. Materials can vary from adobe masonry or irregular not worked stone masonry to workmanlike constructed dressed stone masonry.

P4. Wall-to-wall connection: This parameter takes into account the quality of the connection between structural walls. The quality may vary from visible separation between orthogonal walls to efficiently built connections with good interlocking between the masonry units at the corners in the case of masonry buildings.

P5. Horizontal diaphragms: This parameter takes into account the type of horizontal diaphragm (floors and roofs), focusing on the quality of its connection to the load bearing walls and its in-plan stiffness. Typically, the diaphragms may vary from diaphragms of negligible stiffness with beams poorly connected to the walls to rigid timber diaphragms well-connected to the walls.

P6. Roof thrust: This parameter takes into account the possible thrust that the roof may exert to the load bearing walls. Roofs may vary from thrusting types with considerable weight and low inclination to non-thrusting types.

P7. Wall openings: This parameter takes into account the number and area of wall openings, which can be measured as a percentage of the total area of each wall.

P8. Number of floors: This parameter takes into account the number of floors of the studied building. Vernacular buildings rarely present more than three stories.

P9. State of conservation: This parameter takes into account the state of conservation of the building and the existing damage that can be observed, mainly focused on the state of degradation of the structural elements of the building (i.e. the walls). A poor maintenance and abandonment is common for many vernacular buildings, which may present an advanced state of deterioration of the materials.

P10. In-plane index: This parameter is defined as the ratio between the in-plan area of earthquake resistant walls in each main direction and the total in-plan area of earthquake resistant walls, providing direct information about the in-plane stiffness of the structure along each main direction. Values that deviate significantly from 0.5 will indicate that one direction is clearly predominant.

3.2 Numerical strategy adopted for the parametric study

The extensive parametric study that aims at the assessment and quantification of the influence of the different parameters in the seismic behavior of buildings was performed using detailed FE modeling and pushover analyses. FE modeling following a common macro-model approach has already been extensively and successfully applied with the aim of analyzing the seismic behavior of complex masonry and rammed earth structures (Lourenço et al. 2007; Saloustros et al. 2014; Lourenço et al. 2016). Pushover analyses with distribution of forces proportional to the mass is also a generally accepted and recommended tool used for the seismic assessment of existing masonry buildings (Lourenço et al. 2011). It mainly consists of simulating the seismic loading as static horizontal forces that are applied incrementally on the structure until its collapse. It allows assessing the ability of the building to resist the characteristic horizontal loading caused by the seismic actions taking into account the material nonlinear behavior, while being simpler than other methods of analysis like nonlinear dynamic analysis. The response of the structure is described by the capacity or pushover curve, which represents the base shear coefficient or load factor (i.e. the ratio between the horizontal forces at the base and the self-weight of the structure) versus the displacement at the control point, which is usually the point where the highest displacements take place.

3.2.1 Definition of limit states

Structural limit states can be defined based on the obtained capacity curves in order to quantitatively compare the performance of the building according to the variations defined for each parameter. Several methods have been proposed in the literature for a quantitative definition of limit states associated to a certain damage level exhibited in the structure, based on the results of nonlinear analyses (Rota et al. 2010; Mouyiannou et al. 2014). In this work, four limit states (LS) are defined based on the capacity curve obtained for each building. Figure 2 shows a general example with the identification of the four limit states on the pushover curve obtained for a typical vernacular building. The criteria defined for each limit state will be considered independent from the failure mechanism (in-plane and out-of-plane collapse).

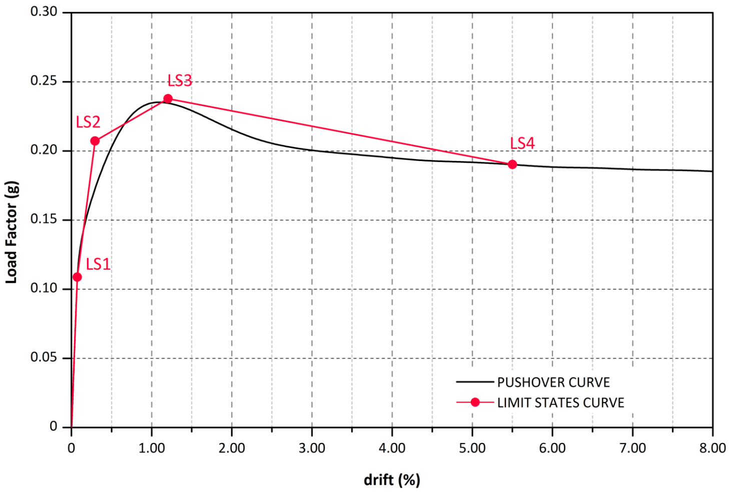


Figure 2. Identification and definition of the four considered limit states on an exemplary pushover curve

LS1: Represents the beginning of the cracking and the end of the elastic behavior. It can be defined as immediate occupancy limit state because, before this limit, the behavior of the building is essentially elastic, and the structure can be considered as fully operational. The beginning of cracking is assumed to start when there is a degradation of the initial stiffness of the wall up to 2%.

LS2: This limit state represent the transition between a point where the structure is still functional and retains most of its original stiffness and strength, showing minor structural damage and cracks, and a state where significant damage is visible so that the building could not be used after without significant repair. This limit state is calculated based on energy criteria so that the area below the three-linear curve formed by LS1, LS2 and LS3 coincides with the area below the pushover curve from LS1 to LS3. The criterion also involves that the point that defines LS2 is on the slope associated to the secant stiffness corresponding to 70% of the maximum resistance.

LS3: Determined by the base shear coefficient and displacement corresponding to the attainment of the building maximum resistance. The building shows significant structural damage and has lost a significant amount of its original stiffness. However, it still retains some lateral strength and margin against collapse even if it cannot be used after the earthquake.

LS4: The ultimate limit state is related to the collapse of the building and corresponds to the point where the building resistance deteriorates below an acceptable limit, which is set at the 80% of the maximum resistance. It is known as near collapse limit state because repairing the building after reaching this limit state is neither possible nor economically reasonable.

3.2.2 Reference numerical model

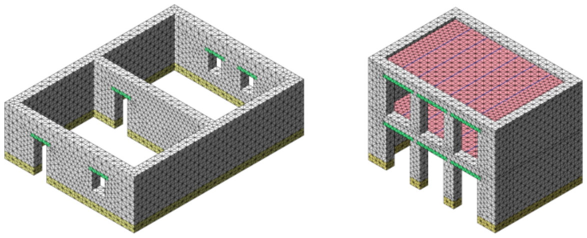
The reference FE models used are initially based on representative vernacular rammed earth constructions commonly found in the South Portuguese region of Alentejo. Rammed earth, known as *taipa* in Portugal, has traditionally been the most widespread technique in this region and is still in use in some places. Traditional dwellings in Alentejo have generally small dimensions, simple rectangular shape and one to two floors (Correia 2002). They are simple regarding their plan configuration, little compartmentalized and present massive shapes with few or no openings, other than a single door, as a measure of protection for the hot summers. Rammed earth walls are usually around 0.5 m thick and present a base course or *soco* built in stone masonry, aimed at protecting the rammed earth from the humidity and rain penetration, by preventing the action of rising damp. Timber lintels are usually placed over windows and doors. Roofs are commonly gable roofs with low slope, consisting of a simple framework of timber beams. Figure 3 presents some examples of this typology.

(a) (b)

Figure 3. (a) Traditional rural one-floor rammed earth vernacular construction in Alentejo, Portugal (Correia 2007); and (b) traditional urban two-floor rammed earth construction in Alentejo, Portugal (Correia 2002)

The models are simplified in order to easily accommodate the variations required to assess the influence of the different parameters. The models were constructed using DIANA software (TNO 2009). Figure 4 shows, as an example, the two reference models that were prepared for the definition of the seismic vulnerability classes for P3 (type of material). The models show varying number of floors, type of diaphragm and number of openings, in order to evaluate the influence of this parameter for different combinations of the other parameters. The one-floor model walls are 3 m high and 0.5 m thick. The in-plan area is 8x10.5 m^2. In the two-floor models, the ground floor walls are 3 m high, while the upper floor walls are 2.6 m high. All walls are 0.5 m thick and the in-plan area is 8x5.5 m^2. With respect to the modeling of the diaphragm in the two-floor models, it is considered to be composed by timber beams and cross-board sheathing. The cross section considered for the timber beams is 0.3x0.225 m2 with a spacing of 1 m. The diaphragm thickness is considered as 0.036 m.

The walls of the reference numerical models are built using ten-node tetrahedron solid 3D elements (CTE30). The models have at least two elements within the thickness of the walls and the displacements of the elements at the base are fully restrained. The timber beams are simulated using three-node beam elements (CL18B) and are considered fully embedded within the wall, going through the whole thickness. The cross boards are modeled using six-node triangular shell elements (CT30S). The connections between the board sheathing and the walls share all degrees of freedom. In both cases, the roof load is modeled as distributed load along the walls.



model *RE1F*
21,998 elements
39,558 nodes

model *RE2Fd1*
27,293 elements
48,079 nodes

Figure 4. Reference numerical models prepared to assess the influence of the type of material in the seismic behavior of vernacular buildings

Four different materials were considered for the reference models. Rammed earth is used for the structural walls. Stone masonry is used for the base course on rammed earth buildings, which is assumed to be built with irregular schist or granite masonry. Timber is used for the lintels over all openings and beams. Different properties are used for the timber cross boards. It should be noted that only the elastic properties are considered for the timber structural elements, since the failure mode and nonlinearities are expected to take place in the walls. The material model adopted to represent the nonlinear behavior of the rammed earth and stone masonry is a standard isotropic Total Strain Rotating Crack Model (TSRCM). Table 1 presents the material properties adopted for the reference models based on data collected from different authors.

Table 1. Mechanical properties adopted for the four materials used in the reference models.

Material	**E (MPa)**	**v**	**f_c (MPa)**	**G_{fc} (N/mm)**	**f_t (MPa)**	**G_{ft} (N/mm)**	**W (kN/m^3)**
Stone masonry	1500	0.2	1.5	2.4	0.15	0.012	20
Rammed earth	300	0.3	1	1.6	0.1	0.012	20
Timber	10000	0.2	-	-	-	-	8
Cross-boards	200	0.3	-	-	-	-	7.5

4. DEFINITION OF SEISMIC VULNERABILITY CLASSES: P3 – TYPE OF MATERIAL

This parameter reflects the nature of the material used to construct the walls. Walls primarily differ in the constituent material, usually consisting of stone, brick, adobe and rammed earth for Portuguese vernacular buildings. Undoubtedly, the use of different materials for the loadbearing elements affects the seismic performance of the building under an earthquake, since the mechanical properties of the materials vary highly among them. With respect to masonry fabric typologies, there can be als significant variations in the morphology, including: (a) type, shape and size of the masonry units (ashlar stone masonry, irregular rubble stone masonry, brick masonry, etc.); (b) masonry layout (irregular/regular horizontal courses, presence of several leaves, lack of connection between the leaves, etc.); or (c) type of mortar used, if any. These aspects determine the quality of the masonry and the capacity of the building to withstand horizontal forces resulting from the seismic load.

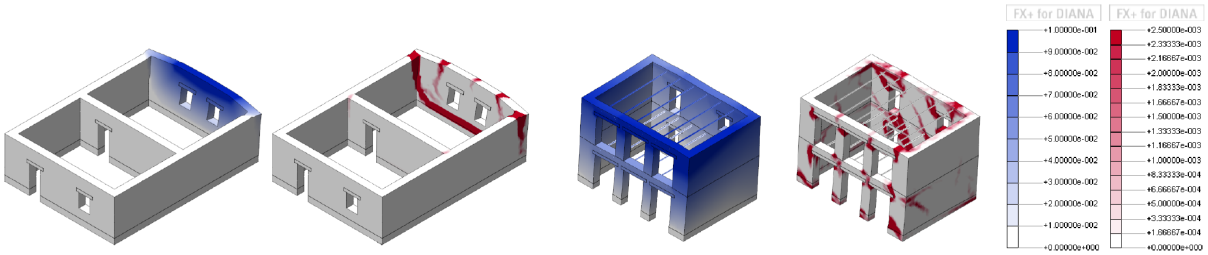
In order to assess the influence of this parameter, the material properties of the walls are modified based on representative values of different materials obtained from the literature. A series of models were defined by varying the Young's modulus (E), the compressive strength (f_c) and the tensile strength (f_t), which are the values defining the TSRCM material model adopted in the analysis. The values for the compressive fracture energy (G_{fc}) are varied in proportion with the compressive strength used in each analysis, and the mode I fracture energy (G_{fI}) is kept constant. Table 2 presents the ranges of variation considered for the different mechanical properties, which can be associated to different types of material that are commonly applied in vernacular buildings for the construction of the walls.

Table 2. Ranges of variation considered for each mechanical property, associated to different materials.

Material	**E (MPa)**	**f_c (MPa)**	**f_t (MPa)**
Rammed earth	[150-500]	[0.6-1.5]	[0.05-0.2]
Adobe masonry	150	1	[0.05-0.2]
Soft stone masonry	1000	1	[0.05-0.2]
Irregular stone masonry	[500-1000]	0.6	[0.05-0.2]
Uncut stone masonry	[1000-1500]	1.5	[0.1-0.3]
Cut stone masonry	[1500-2000]	[1.5-2]	[0.1-0.4]
Solid brick masonry	[2000-2500]	[2-3]	[0.1-0.6]
Dressed stone masonry	[2500-3000]	[3-4]	[0.15-0.6]

4.1 Building of capacity curves and identification of limit states

Pushover analyses were performed on the different models constructed using different material properties in the ranges presented in Table 2. The one-floor models were tested in the direction perpendicular to the walls presenting the maximum wall span (Y direction). The failure mode observed in all models consists of the out-of-plane overturning mechanism of the exterior walls (Figure 5a). The two-floor models with a diaphragm were tested in the direction parallel to the walls with openings (X direction). The failure mode was also the same for all models but it is seen that in-plane mechanism of the walls parallel to the seismic load also develop (Figure 5b).



(a) RE1F (rammed earth)

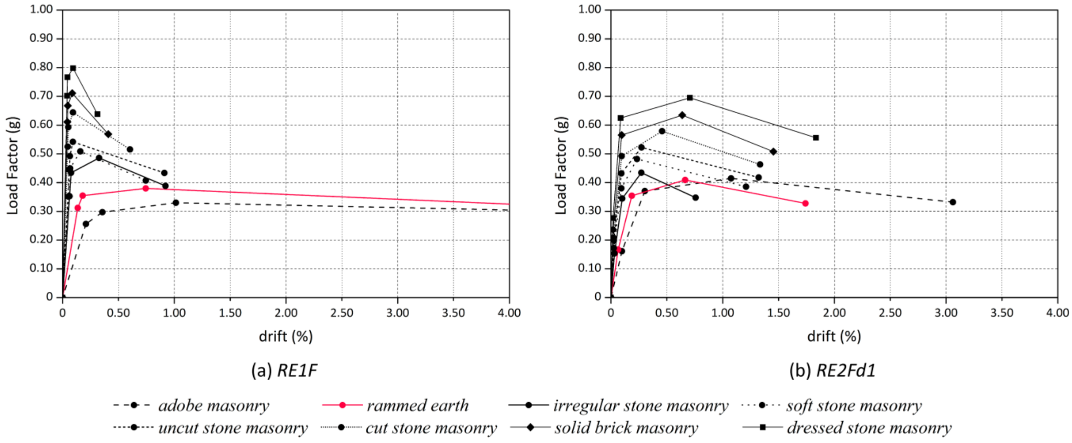
(b) RE2Fd1 (rammed earth)

Figure 5. Representative failure modes obtained for: (a) *RE1F*; and (b) *RE2Fd1* set of models, in terms of: (blue) total displacements (scale in m); and (red) crack width (scale in m). Results at the ultimate limit state (LS4)

In order to compare the seismic performance of the buildings, the four structural limit states previously defined were determined. Figure 6 shows the four-linear capacity curves constructed from the pushover analyses performed, divided by materials that can be associated to the different combinations of mechanical properties. The curves are constructed using average values obtained from the results of all the models associated to each material. They clearly show the variation of the capacity of the building according to the different material properties considered, confirming the influence of this parameter. Both buildings are sensitive to the variation of the material properties in terms of maximum capacity, which decrease gradually when decreasing the material properties of the resisting walls. However, the one-floor building where the diaphragm is not modeled is particularly sensitive in terms of initial stiffness and ductility. Materials like adobe or rammed earth, which present low values for the Young's modulus, show a more ductile behavior, illustrated in the post-peak behavior of the building, reaching high values of drift for LS4.

4.2 Definition of seismic vulnerability classes

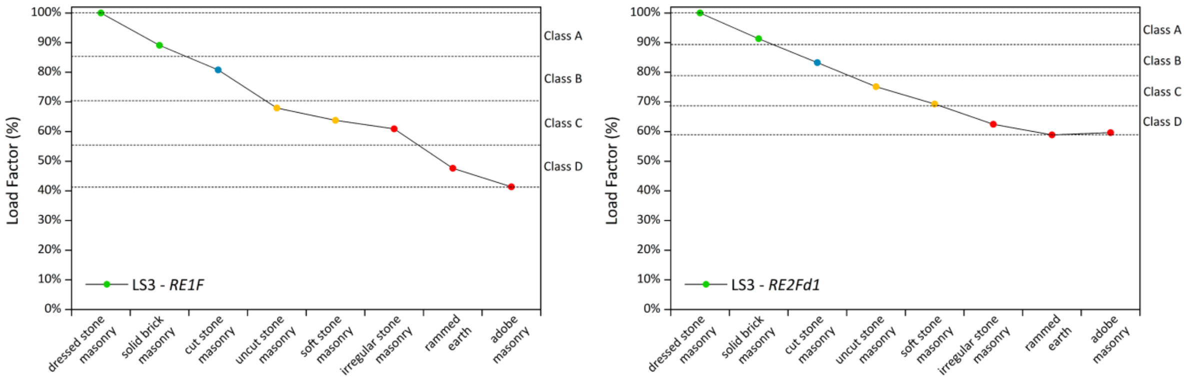
Based on the results from the parametric analysis, the four seismic vulnerability classes can be defined according to the variation of the load factor corresponding to the attainment of LS3, i.e. the maximum resistance of the building. Figure 7 shows the criteria followed for the definition of the four seismic vulnerability classes for vernacular buildings according to the type of material of the walls. The same criterion is applied to both set of models independently, leading to a very similar definition of classes in both cases, considering always the most unfavorable case. The variations are normalized using as reference the models with dressed stone masonry material properties, which show the maximum capacity. The graphs show an almost linear decreasing trend in the capacity of the building when reducing the material properties. The one-floor model with no diaphragm effect shows slightly greater variations but the trend is similar for both models.



(a) *RE1F*

(b) *RE2Fd1*

Figure 6. Results in terms of four-linear capacity curves constructed based on the computed limit states for the set of models: (a) *RE1F*; and (b) *RE2Fd1*



(a) (b)

Figure 7. Variation of the load factor leading to the attainment of the maximum resistance (LS3) according to the type of material for the two set of models evaluated: (a) *RE1F*; and (b) *RE2Fd1*

The maximum resistance of the building with adobe masonry walls is around 40% of the maximum resistance of the model used to normalize the load factors and the one-floor model has a maximum resistance around 60% for the two-floor model. These ranges of variation are divided equally into four parts and the four classes are defined according to this, leading to the classification shown in Table 3. Since the classification is made according to the variation of the material properties, a range of material properties is given as a reference for the four classes defined. This can be useful when an experimental campaign can also be performed along with the survey or if quantitative data is available. It is worth highlighting that, during this sensitivity analysis, it was noted that the variation of the Young's modulus leads to the highest differences in terms of maximum capacity of the building. Thus, if this value of the material property is known, it can provide relevant information about the seismic performance of a building. Notice that this property is related directly with the quality of the materials. In addition, a qualitative description of the material that belongs to each class is also provided in case that the survey can only be made by means of visual inspection.

Table 3. Vulnerability classes proposed according to the type of material.

P3: Type of material				
		Reference material properties		
Class	**Description**	***E*** **(MPa)**	**f_c (MPa)**	**f_t (MPa)**
A	Stone masonry consisting of well-cut homogeneous units in terms of material and dimensions with parallelepiped shape. Carefully worked horizontal courses with not-aligned mortar head joints. The mortar has good quality and properly fills vertical and horizontal joints. Proper transversal connection among wall leaves using through-stones or stone or brick bands crossing the entire wall thickness. Brick masonry with well-arranged joints and good quality mortar.	2000-3000	2-4	0.1-0.6
B	Non-homogeneous stone masonry in terms of materials and dimensions but well-arranged longitudinally and transversally with generally respected horizontal courses, not-aligned mortar head joints and good quality mortar. Proper transversal connection among wall leaves using through-stones or stone or brick bands crossing the entire wall thickness. Brick masonry with well-arranged joints and average quality mortar.	1500-2000	1.5-2	0.1-0.4
C	Coarsely carved stone masonry irregularly shaped with poor arrangement of the stones and weak or average quality mortar. Few or no transversal connection elements. The core of multiple-leaf walls has a reasonably consistency.	1000-1500	1-1.5	0.05-0.3
D	Irregular not worked stone masonry of low quality, with not respected horizontal courses or aligned mortar head joints. Poor quality mortar. There are no transversal connection elements. Multi-leaf masonry with partially unstable empty core showing voids. Adobe masonry and rammed earth walls are also included within this class.	150-1000	0.6-1.5	0.05-0.2

5. CONCLUSIONS

The present paper introduces the procedure adopted to develop a simplified seismic vulnerability assessment method for vernacular architecture. The necessity of expedite approaches for the seismic assessment of vernacular buildings is crucial given the lack of resources that can be commonly assigned to the study and conservation of this fragile heritage. This method is based on vulnerability index methods, which correlate the vulnerability of a structure to different parameters that relate to constructive and geometric characteristics. Therefore, these simplified approaches provide the possibility of performing a primary seismic safety assessment and obtaining an indicator of the seismic performance of a building or group of buildings based on expedite surveys that can be carried out even solely by means of simple visual inspection.

The paper particularly focuses on the numerical strategy applied for the definition of the seismic vulnerability classes required for the development of the proposed method. One parameter is used as an illustration showing the different steps of the numerical approach followed. Four vulnerability classes were, as a result, defined for this parameter based on the numerical results, validating the strategy that is followed for the rest of the parameters. The use of an analytical procedure for the definition of the seismic vulnerability assessment classes can help in strengthening the reliability of these simplified methods that typically rely solely on empirical knowledge obtained from post-earthquake damage observation. Moreover, the vulnerability classes proposed are in line with existing classifications available in the literature. Additionally, the numerical parametric analysis presented in the paper is not only helpful for the definition of the classes but also contributes for a better understanding of the seismic behavior of representative Portuguese vernacular constructions.

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