# Evaluating the seismic behaviour of rammed earth buildings from Portugal: from simple tools to advanced approaches

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**Abstract:**

Despite the use of rammed earth became marginal in the second half of the past century, Portugal still holds an important built heritage. Recently, a growing use of rammed earth has been observed in modern constructions, but it is putting aside the roots of traditional rammed earth construction. The seismic behaviour of rammed earth buildings is still insufficiently comprehended, constituting a matter of great concern, since most of the traditional dwellings are built on regions with important seismic hazard. Moreover, the complex architecture of modern rammed earth buildings is expected to make their seismic behaviour even more fragile. This paper intends to provide a better comprehension on the seismic behaviour of rammed earth constructions from Portugal. For this purpose, twenty traditional dwellings were evaluated on the basis of a simplified approach, while a modern construction was investigated by means of destructive and non-destructive testing approaches. The main findings of these approaches are discussed in detail, but it can be highlighted that the architectural features of traditional rammed earth buildings benefit their seismic behaviour, while the complex architecture of modern rammed earth buildings demands using advanced engineering tools for their seismic assessment.

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**Keywords:** Rammed earth, seismic behaviour, simplified indexes, kinematic approach, mechanical characterisation, dynamic identification, sonic tests, model updating.

**Highlights:**

- The seismic behaviour of rammed earth buildings was investigated;
- Traditional dwellings were evaluated by means of a simplified approach;
- Destructive and non-destructive testing was used for a modern building;
- The parameters affecting the seismic behaviour are discussed.

## 1. INTRODUCTION

Raw earth is known as a building material used for several thousands of years in many regions of the World. The oldest use of this material is evidenced by archaeological excavations of the first permanent dwellings in Southwest Asia, dating back to 10 000 BC [1]. The continuous use of raw earth resulted in several building techniques, among which the most widespread are adobe masonry and rammed earth [2]. Generally speaking, adobes are sundried mud bricks, typically layered with earth mortar to build walls, arches, vaults and domes [3]. In turn, building in rammed earth consists in compacting moistened earth inside a formwork to erect walls. The formwork constitutes a key element within the definition of this technique, where traditional rammed earth walls are mainly built by means of a crawling formwork made of timber [4]. This type of formwork is constituted by different elements that allow easy mounting, removal and reuse.

A traditional rammed earth wall is formed by several large-dimension blocks composed by compacted layers of earth. The formwork is supported directly on the wall and it is moved horizontally after completion of each block. After conclusion of a lift, the formwork is moved upwards and mounted with mismatched vertical joints, and then the process is repeated until the desired height of the wall is achieved. A formwork externally supported can also be used to build in rammed earth, but it implies assembling a scaffolding structure [5]. The use of this type of formwork reports back to the construction of pre-Muslim rammed earth sites in Spain lacking putlog holes [4]. Modern rammed earth constructions often resort to externally supported formworks, but the shutters of the later cover the entire wall (continuous formwork) and they are mainly composed by metallic elements, which are stronger, stiffer and more durable than those made of timber. In this case, the compaction layers can be extended through the full length of the wall.

Rammed earth construction has a long tradition in Portugal, where it prospered during the Islamic occupation of the Iberian Peninsula between the 8$^{th}$ and 13$^{th}$ centuries, as evidenced by the still existing castles of Paderne and Silves [6]. These fortifications are part of the military rammed earth built heritage and their walls are characterised by large thickness (the thickness of Paderne's castle walls is of about 1.80 m) and high percentage of stabilisation with lime [7], explaining their enhanced durability against weathering. Nevertheless, the Portuguese rammed earth built stock is mainly constituted by civil constructions in the form of dwellings, windmills, farm storehouses and churches [8]. Most of the existing dwellings were built until the 1950's and are located in the southern regions of the country, namely in Alentejo, Algarve and Ribatejo [9].

The vernacular rammed earth dwellings from Alentejo are characterised by several features that vary from place to place, according to the available resources, social and cultural factors [10]. Correia [9] performed a detailed in situ survey that allowed to identify a series of architectonic and constructive features. In terms of geometry, rammed earth buildings present in-plan rectangular shapes and are mainly constituted by a single storey, although some cases of buildings in urban environment can present a second storey. In general, the facades present few openings with small size, where the main facade presents a single door. The surfaces of the walls are in general protected by means of mortar coatings consolidated by limeswash, which is yearly renewed [11]. Rammed earth walls are composed by blocks with 1.40-2.50 m length and 0.40-0.55 m height, compacted on stone masonry plinths or directly on the ground. The thickness of the walls varies between 0.40 m and 0.57 m, but in general is of about 0.50 m. Partition walls can be built in adobe or "*tabique*" (technique similar to wattle-and-daub) and present slimmer thickness, namely 0.1-0.3 m. The soils used in the construction present a large diversity according to the characteristics of the local soils, which can be differentiated in terms of colour (red, yellow or grey), clay content (8-26%) and lithology (calcareous, quarzitic, sandstone and schist) [9][12][13]. In general, rammed earth buildings present lightweight shed or gable roofs made of timber, where the rafters are supported directly on the walls.

Building with rammed earth fell into disuse in Alentejo after the 1950's, as a consequence of the growing use of modern building materials (concrete, steel and fired bricks) and of the rural exodus of the populations [9]. However, the use of this technique was reborn in the 1980's, driven initially by the need of conservation and rehabilitation of the existing constructions [14]. The fact is that three decades of absence of new constructions in rammed earth required relearning the technique, whose process was not an easy task since this traditional knowledge became almost lost in time. This process was led by architects mesmerised by the technique, whose inspiration was based on the teachings of the few living master builders ("*mestres taipeiros*") [14].

Current rammed earth construction in Alentejo still keeps its traditional and vernacular roots, however a paradigm shift is being introduced by a new generation of architects. Their inspiration starts putting aside the original roots of rammed earth dwellings, and looks for a more daring architecture, driven by the particular aesthetics of rammed earth walls and by an enhanced sustainable value. Thus, several changes are being introduced both at the architectonic and technological levels, such as: (i) design of more complex plans, elevations, roof systems and wall shapes; (ii) combination with modern materials (e.g. concrete and steel) (iii) use of cement stabilised rammed earth; (iv) use of mechanised and heavier compaction systems (e.g. pneumatic rammers and externally supported continuous formworks); (v) absence of protective plasters; (vi) surface consolidation with silicate based products. Such changes are in line with industrialised rammed earth architecture from other regions of the world, namely from the United States of America (USA), where this technique has been used in the construction of luxurious houses and public buildings [15].

Building with raw earth brings many associated advantages (e.g. low initial embodied energy, adequate thermal and acoustic performances, good fire resistance and enhanced indoor environment) [2][3][16], however earthen structures show high seismic vulnerability [17][18], as evidenced by recent intense and destructive earthquakes (e.g. Bam 2001, Pisco 2007 and Maule 2010). The high seismic vulnerability of these constructions is a consequence of several factors, among which the poor connection between structural elements, high self-weight and low mechanical properties are systematically the most highlighted. Recent research has been done to characterise the experimental and numerical in-plane behaviour of rammed earth walls by means of diagonal compression tests on wallets [8][19] and cyclic shear-compression tests on walls [20][21][22]. On the other hand, the characterization of the out-of-plane behaviour of rammed earth is lacking in the literature and it is resumed to a single research work [17], where overturning tests on walls and shaking table tests on small-scale models were performed. In general, rammed earth was found to present high variability in terms of mechanical properties and high non-linear mechanical behaviour, which has been object of recent numerical modelling using the finite element method (FEM) [23][24] and the discrete element method (DEM) [25]. FEM was also used to simulate the global seismic response of rammed earth buildings, namely by means of linear dynamic analyses [26], pushover analyses [27] and non-linear dynamic analyses [28]. Nevertheless, these models were not properly validated, because the proper characterisation of the dynamic behaviour of rammed earth structures is lacking in the literature [29].

The seismic behaviour of rammed earth dwellings is still insufficiently comprehended, constituting a matter of concern, namely in the case of southern Portugal. Here, Alentejo region is characterised by a moderate seismic hazard, where the reference ground acceleration can achieve up to 2.0 $m/s^2$ [30]. Thus, assessing the seismic performance of rammed earth structures is a topic requiring urgent investigation in order to promote the protection of the existing vernacular heritage and the safety of modern constructions.

This paper intends to contribute for a better comprehension of the seismic performance of rammed earth structures from Portugal based on the evaluation of simplified indexes and on experimental testing. The first approach was applied to twenty traditional rammed earth dwellings surveyed in past works, while the second one was used for a case study consisting of a recently built modern rammed earth house. It should be noted that the evaluation of the seismic behaviour of traditional buildings based on simplified indexes is justified by the need of adopting a fast and simple method for analysing and screening a large sample. Furthermore, the regular geometry of these buildings is expected to result in a relatively reliable evaluation, in contrast with the much more complex geometry of modern rammed earth structures. In this last case, a reliable evaluation must use more sophisticated tools, such as material and structural characterisation through destructive and non-destructive testing and numerical analyses.

## 2. SIMPLIFIED SEISMIC EVALUATION

To obtain a better understanding on the seismic performance of the traditional rammed earth heritage from southern Portugal, a sample of case study buildings collected in past surveys is here considered [9]**Erro! A origem da referência não foi encontrada.**. The analysis of these buildings was performed based on the evaluation of simplified indexes, following the approach proposed by Lourenço and Roque [32] and Lourenço et al. [33]. These indexes are computed with basis on geometrical characteristics and on local seismic hazard, and serve to provide a first screening approach to define a priority for further in-depth analysis.

### 2.1 Methodology

The use of simplified methods for seismic assessment is usually valid for masonry structures with “box-behaviour” [34]. Ancient masonry structures, however, are usually disproved of rigid floors and present in-plane shear and out-of-plane bending as dominant collapse modes. In general, traditional rammed earth dwellings can hardly be considered as “box-behaviour” structures, since they are typically constituted by a single storey and by a lightweight roof made of timber. Simplified methods cannot be assumed as valid approaches for quantitative safety assessment of rammed earth buildings, nevertheless they can be used as qualitative indicators of their relative seismic performance.

Four indexes were evaluated for each main direction (longitudinal X and transversal Y) of the investigated rammed earth dwellings, namely three referring to in-plane failure ($\gamma_1$, $\gamma_2$ and $\gamma_3$) and one to out-of-plane failure ($\gamma_\lambda$).

Index $\gamma_1$ corresponds to the in-plan area ratio, as it results from the ratio between the area of the earthquake resistant walls and the total in-plan area of the building:

$$\gamma_{1,i} = \frac{A_{wi}}{A_t} \quad [-] \qquad \text{Eq. 1}$$

where $A_{wi}$ is the area of the earthquake resistant walls in direction "$i$" and $A_t$ is the total in-plan area of the building. Particular attention should be paid to the use of this index as it ignores the slenderness ratio of the walls and the mass of the building. In terms of threshold values for this index, Eurocode 8 [30] recommends values higher than 0.05-0.06 for regular structures with rigid floors. For cases where the design ground acceleration for rock-like soils is larger than 0.20g (high seismicity) a minimum value of 0.1 is recommended for historical masonry buildings [35]. In the case of rammed earth constructions, no threshold values are defined in the literature, whereby it was decided to use those proposed by Lourenço et al. [33] as merely indicative ones. Here, the threshold increases linearly with the peak ground acceleration (PGA).

Index $\gamma_2$ is the area to weight ratio, as it represents the ratio between the area of the earthquake resistant walls and the total weight of the building:

$$\gamma_{2,i} = \frac{A_{wi}}{G} \quad [L^2\,\mathrm{F}^{-1}] \qquad \text{Eq. 2}$$

where $G$ is the quasi-permanent vertical action. Although, it takes into account the height of the building, this index presents the disadvantage of not being non-dimensional, meaning that it must be analysed for a fixed unit, which here is defined as $m^2$/MN. A minimum value of 1.2 $m^2$/MN is recommended for historical masonry buildings [35], but a more recent work [32] recommends a minimum value of 2.5 $m^2$/MN for high seismicity zones. Again, in the absence of any threshold for rammed earth constructions it was decided to use the same threshold proposed by Lourenço et al. [33], which increases linearly with the PGA value.

Index $\gamma_3$ corresponds to the base shear ratio and represents the ratio between the total shear for seismic loading ($F_E$) and the shear strength of the structure ($F_{Rd,i}$). The first parameter can be evaluated from an analysis with horizontal static loads equivalent to the seismic action ($F_E = \beta G$), where $\beta$ is an equivalent seismic coefficient related to the design ground acceleration. The shear strength ($F_{Rd,i}$) can be estimated as the contribution of all earthquake resistant walls $F_{rd,i} = \Sigma A_{wi} f_{vk}$, where, according to Eurocode 6 [36], $f_{vk} = f_{vk0} + 0.4\sigma_d$. Here, $f_{vk0}$ is the cohesion, which can be assumed equal to a low value or zero in the absence of further information, while 0.4 corresponds to the tangent of the friction angle (tan $\phi$). If $f_{vk0}$ is assumed to be equal to zero for rammed earth, $\gamma_3$ becomes independent from the building height and reads:

$$\gamma_{3,i} = \frac{A_{wi}}{A_w} \cdot \frac{\tan\phi}{\beta} \quad [-] \qquad \text{Eq. 3}$$

where $A_w$ is the total area of earthquake resistant walls and $\beta$ is assumed to be equal to the PGA, as recommended by Lourenço et al. [33], due to the high difficulty and uncertainty in defining a more precise value. This index assumes a configuration similar to a traditional safety verification approach used for structural design, meaning that it must be higher than a threshold value of 1.

As for the out-of-plane index, $\gamma_\lambda$ is the slenderness ratio between the height and thickness of the walls and reads:

$$\gamma_{\lambda,i} = \frac{h_{wi}}{t_w} \quad [-] \qquad \text{Eq. 4}$$

where $h_{wi}$ is the height of the earthquake resistant walls subjected to out-of-plane loading in direction "$i$" and $t_w$ is the thickness of the walls. In the case of this index, several references indicate possible maximum threshold values for earthen construction. NZS 4297 [37] is the most permissive by defining a threshold value of 10, while ASTM E2392-10 [38] is the most demanding one by defining a value of 6. Intermediate documents, such as Arya et al. [39], IS 13827 [40], NCB204 [41] and NMAC 14.7.4 [42], define a threshold value of 8.

The out-of-plane seismic performance of the traditional rammed earth dwellings from the case study sample was also evaluated by means of a kinematic approach [43][44] assuming a rigid rotating collapse mechanism. By considering horizontal forces proportional to mass and resorting to the virtual work principle, the capacity curve of a multi degree of freedom (MDOF) system in terms of displacement $d$ and multiplier $\alpha$ can be obtained. The evaluation consists in comparing the seismic demand with the spectral acceleration of a single degree of freedom (SDOF) system equivalent to the MDOF system that activates the mechanism (here termed as $a_0^*$). Since the case study buildings consist of single storey structures, the system is a SDOF one. The centre of rotation was determined assuming no tensile strength and a compressive strength of 1.0 N/mm$^2$. It should be noted that a relatively low value of the compressive strength was assumed when compared with those reported by Miccoli et al. [19] for rammed earth. On the other hand, the assumed value is slightly lower than those (1.2-1.5 N/mm$^2$) reported in research works dealing with the characterisation of unstabilised rammed earth from southern Portugal [8][45]. The seismic demand in the case of the linear kinematic analysis reads [44]:

$$Demand = \frac{a_g \cdot S}{q} \cdot \left(1 + 1.5\frac{Z}{H}\right) \qquad \text{Eq. 5}$$

where $a_g$ is the PGA, $q$ is a ductility factor, $S$ is the type of soil, $Z$ is the position of the centre of gravity and $H$ is the height of the wall. For the analysis, a soil type C ($S$ = 1.20) was selected as the worst likely case scenario provided by the national annex of Eurocode 8 [30]. The ductility factor was defined with basis on the Italian code [44] by assuming that rammed earth behaves similarly to existing masonry structures, whose recommended value is of 2.

## 2.2 Surveyed buildings

As stated previously, the sample of traditional rammed earth dwellings was obtained from past surveys carried out in Alentejo (see Fig. 1), namely 9 buildings were studied by Domínguez [31] and 11 by Correia [9]. These surveys collected a series of information from the buildings, namely location, current use, building materials used, use of stone masonry plinths, number of storeys, surrounding environment, typology of the roof, use of seismic retrofitting solutions and state of conservation. Nevertheless, the most relevant information regards plan and elevation drafts with dimensions, which allowed to compute the indexes detailed in the previous section. The identification of the construction date of the dwellings was not possible in most cases, yet it occurred before the 1950's. This fact means that their construction was not supported by any design project, further evidencing the importance of conducting surveys to identify the features of this type of constructions in order to better understand them.

(a) (b) (c)

Fig. 1 – Examples of analysed rammed earth buildings: (a) ID 1; (b) ID 5; (c) ID 8.

All rammed earth buildings of the sample are constituted by a single storey and their main characteristics are presented in Table 1, namely in terms of typology of the roof, total in-plan area ($A_t$), longitudinal to transversal length ratio ($L/T$), as well as average thickness ($t_w$) and height ($h_w$) of the walls. Furthermore, Fig. 2 illustrates the location of the all dwellings of the sample and overlaps it with the seismic hazard zonation proposed in the Portuguese national annex of Eurocode 8 [30] for far-field earthquakes. Adopting a far-field seismic action was preferred over the near-field, since it presents higher spectral accelerations for larger period ranges, thus representing the worst case scenario. The PGA considered for each of the dwellings is also given in Table 1.

Table 1 – Main characteristics of the traditional rammed earth dwellings in the case study sample.

| ID | Ref. | Use | Location | Roof | PGA (g) | $A_t$ (m$^2$) | $L/T$ (-) | $t_w$ (m) | $h_w$ (m) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | [31] | House | Colos | Gable | 0.20 | 117 | 4.7 | 0.54 | 3.4 |
| 2 | [31] | House | Serpa | Gable | 0.10 | 149 | 1.6 | 0.54 | 2.9 |
| 3 | [31] | House | Vales Mortos | Gable | 0.10 | 236 | 2.9 | 0.58 | 3.3 |
| 4 | [31] | House | Vales Mortos | Gable | 0.10 | 146 | 1.3 | 0.50 | 2.5 |
| 5 | [31] | House | Mértola | Gable | 0.15 | 169 | 2.8 | 0.58 | 3.4 |
| 6 | [31] | House | Aljustrel | Gable | 0.15 | 65 | 1.1 | 0.52 | 2.9 |
| 7 | [31] | House | Montes Velhos | Gable | 0.10 | 96 | 1.6 | 0.50 | 3.0 |
| 8 | [31] | House | Cuba | Gable | 0.10 | 82 | 1.2 | 0.50 | 3.6 |
| 9 | [31] | Farm | Pedrogão | Gable | 0.10 | 250 | 4.4 | 0.50 | 3.3 |
| 10 | [9] | Cellar | Montoito | Gable | 0.06 | 130 | 3.2 | 0.54 | 3.1 |
| 11 | [9] | Warehouse | Montoito | Gable | 0.06 | 30 | 2.1 | 0.47 | 2.7 |
| 12 | [9] | Warehouse | Montoito | Shed | 0.06 | 40 | 2.0 | 0.50 | 2.9 |
| 13 | [9] | House | Montoito | Gable | 0.06 | 40 | 1.9 | 0.50 | 2.5 |
| 14 | [9] | House | Safara | Shed | 0.10 | 35 | 3.1 | 0.50 | 2.9 |
| 15 | [9] | House | Vila Nova de S. Bento | Gable | 0.10 | 85 | 1.7 | 0.46 | 2.4 |
| 16 | [9] | House | Santana de Cambas | Gable | 0.10 | 75 | 1.5 | 0.55 | 3.2 |
| 17 | [9] | Corral | Saraiva | Gable | 0.15 | 52 | 1.1 | 0.45 | 2.1 |
| 18 | [9] | House | Ermidas-Sado | Gable | 0.15 | 82 | 1.8 | 0.45 | 2.6 |
| 19 | [9] | House | Ermidas-Sado | Gable | 0.15 | 60 | 1.3 | 0.50 | 2.8 |
| 20 | [9] | House | S. Maria do Castelo | Gable | 0.15 | 67 | 4.3 | 0.50 | 2.9 |

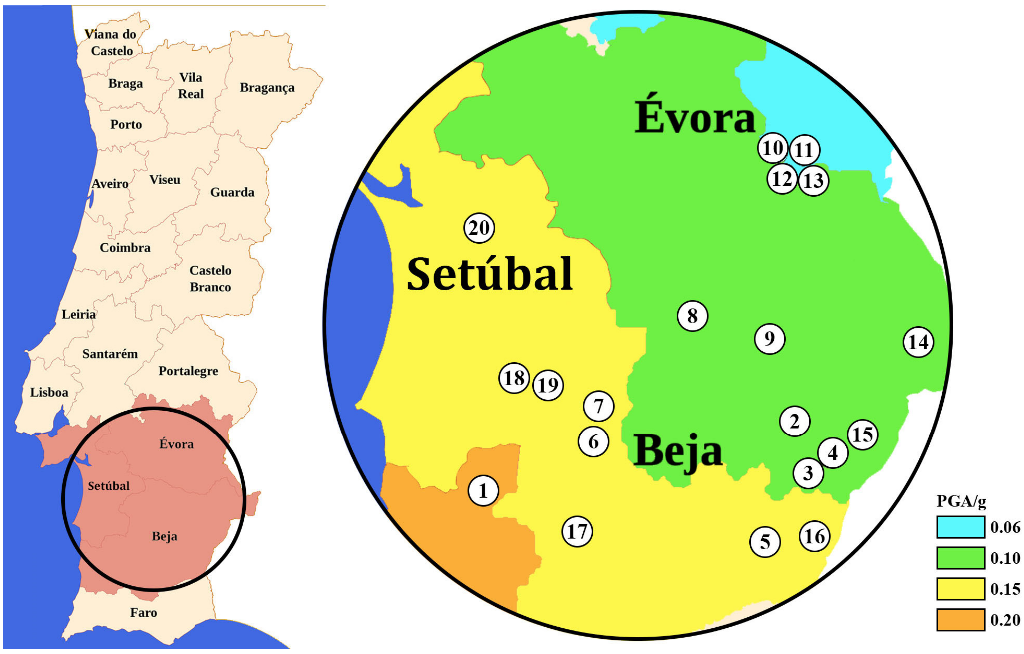



Fig. 2 – Location of the rammed earth dwellings of the sample and comparison against the seismic hazard for far-field earthquakes.

## 2.3 Results and analysis

To compute the simplified indexes, the density of the rammed earth was assumed as 1900 kg/m$^3$, corresponding to an intermediate value of this property [19], whose variation may be beneficial or detrimental depending on the index. The value of tan $\phi$ involves high uncertainty in its estimation, whereby it was decided to adopt the minimum value presented by Jaquin et al. [46], namely 0.70 ($\phi = 35°$).

The in-plane indexes obtained for all buildings, according to their main directions, are presented in Fig. 3 and are compared with the threshold values referred in Section 2.1. In general, the values of the indexes in the longitudinal direction (X) are higher than those in the transversal direction (Y), as a result of the rectangular plan development of this type of constructions. In fact, most of the resisting walls area in these buildings is positioned according to the longitudinal direction, indicating a potential better in-plane seismic response in this direction. The values obtained for $\gamma_1$ are located above the threshold, except for four buildings in the transversal direction (Y). In the case of $\gamma_2$ and $\gamma_3$, the threshold is not violated in any direction. Furthermore, $\gamma_3$ is shown to be an index depending greatly on the local PGA, as the index value shows a clear decrease with the PGA increase. This situation seems to indicate that the in-plane seismic performance of traditional rammed earth constructions is compromised only in areas with high to very high seismic hazard (PGA above 0.2g). Furthermore, the decrease of index $\gamma_3$ with PGA increase and apparent random variation of indexes $\gamma_1$ and $\gamma_2$ with the PGA seem to indicate that no apparent correlation can be found between the local seismicity and the geometry of the dwellings.

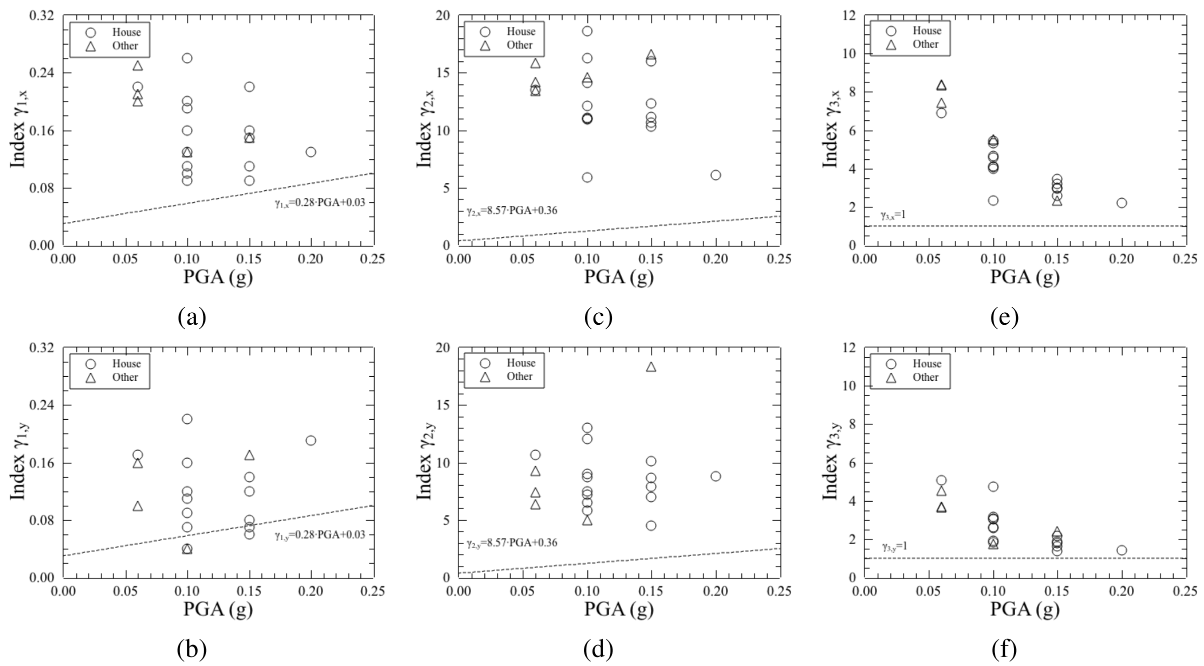



Fig. 3 – In-plane analysis of the buildings by index: (a) $\gamma_{1,X}$; (b) $\gamma_{1,Y}$; (c) $\gamma_{2,X}$; (d) $\gamma_{2,y}$; (e) $\gamma_{3,X}$; (f) $\gamma_{3,Y}$.

Fig. 4 presents the results of the out-plane analysis in terms of the index $\gamma_\lambda$ and the kinematic approach verification. With respect to $\gamma_\lambda$, all buildings comply with the most permissive threshold and almost all buildings comply with the intermediate threshold, with the exception of one case in the Y direction. However, the most demanding threshold is violated by 8 and by 5 buildings in X and Y directions, respectively. It should be noted that direction X is the most critical, since in most cases the height of the out-of-plane resisting walls is amplified due to the presence of gabble walls. Also in the case of this index no apparent trend is observed with respect to the PGA, which seems to indicate that the different seismicity of the region had no influence on the definition of the geometry of the dwellings studied.

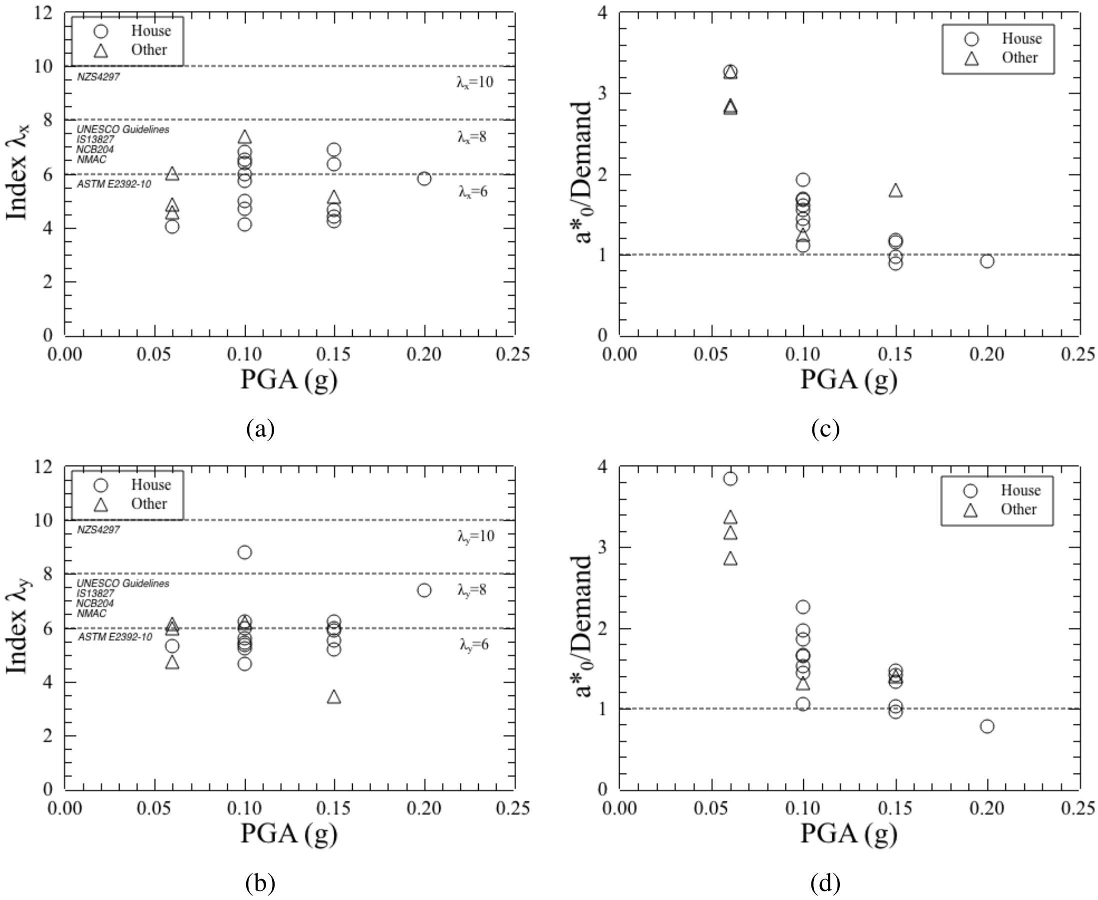



Fig. 4 – Out-of-plane analysis of the buildings: (a) $\gamma_{\lambda,X}$; (b) $\gamma_{\lambda,Y}$; (c) kinematic approach in direction X; (d) kinematic approach in direction Y.

With respect to the kinematic approach, the results outline a decreasing trend of the out-of-plane safety with increasing PGA, as expected. Nevertheless, it should be noted that the seismic capacity satisfies the seismic demand (threshold equal to 1) in almost all the cases, except for three buildings in the zones with PGA between 0.15g and 0.20g. Furthermore, the seismic capacity of some buildings can be up to 1.5-4 times higher than the seismic demand for PGA lower than 0.15g.

In general, it can be stated that the capacity of most of the analysed buildings in satisfying the defined thresholds results from the use of traditional construction practices, namely the use of rectangular and regular plans, as well as the use of very thick and low height rammed earth walls. In fact, it was observed that the height of the walls was the characteristic presenting the highest variation among the buildings, whose importance can be assumed to be high for the seismic performance of traditional rammed earth constructions. For instance, rammed earth dwellings built to be used as low rise warehouses tend to be safer than houses, since fulfilling living conditions required adopting taller walls.

## 3. ADVANCED SEISMIC EVALUATION

Modern rammed earth buildings can present complex structural systems, as consequence of adopting irregular geometries (in-plan and elevation) and openings with unusual size and distribution, as well as of the ineffectiveness of the connections between different structural elements (in particular those made with different materials) and of the high non-linear behaviour of the rammed earth material. In general, the modelling of such structures can be achieved by adopting advanced FEM models incorporating non-linear material behaviour and time history analysis, which constitute time-demanding approaches, despite their high reliability. Nevertheless, using such models requires knowing the material behaviour of the rammed earth and the dynamic properties of the structure in detail.

### 3.1 Methodology

The material behaviour of rammed earth and the dynamic properties of the structure are adequately determined by means of testing, following both destructive and non-destructive approaches. Within this context, this section presents an experimental program aiming at characterising the mechanical and dynamic properties of the rammed earth from a modern construction used as case study. The destructive approach included the execution of compression tests on representative rammed earth specimens manufactured during the construction of the walls. The non-destructive approach included the execution of sonic tests and dynamic identification tests on a selected rammed earth wall of the case study. Furthermore, the subsequent analysis of the results through model updating addressed the identification of material specificities affecting the dynamic response of rammed earth structures, constituting a great contribute for the topic, given the general lack of investigation done so far. The subsequent structural modelling and safety assessment of the whole structure is not addressed in this work, as the focus of this research was on the use of advanced approaches able to provide suitable inputs to the aforementioned FEM-based models.

## 3.2 Description of the case study

The case study consists of a private modern rammed earth house being built in Esposende, northern Portugal. It should be noted that traditional houses from this region are mainly built with stone masonry, while reinforced concrete (RC) framed structures with brick masonry infill dominate as building solution of modern houses [10]. Despite rammed earth construction has almost no tradition in northern Portugal, there are few reported cases, namely in the nearby municipality of Viana do Castelo [47].

The house has an implantation area of about 230 $m^2$ (Fig. 5) and a maximum height of about 6.60 m (see Fig. 6), allowing inclosing a second storey. The vertical structure consists mainly of rammed earth walls with 0.60 m thickness, built on RC beams embedded in a foundation RC slab (Fig. 8a). The structure also includes additional granite stone masonry walls and vertical steel elements, which are mainly used to support the second storey, independently from the rammed earth walls. The rammed earth walls are mainly distributed in the transversal direction, while in the longitudinal direction it is highlighted the lack of shear walls at the southern façade. The roof consists of sandwich insulation panels supported on a timber structure. Furthermore, the doors located in rammed walls are reinforced by means of RC frames built before compaction, while the windows openings consist of pre-fabricated granite frames. These frames were placed at the desired position inside the formwork, which was externally supported by metallic elements, while the shutters consisted of timber boards covering the entire development of the wall (Fig. 8b). The rammed earth walls were built by a company with a long experience in building with this technique. Despite the continuous formwork used, the compaction was made by blocks (as in traditional rammed earth) with a horizontal indention (see Fig. 8c) and using pneumatic rammers.

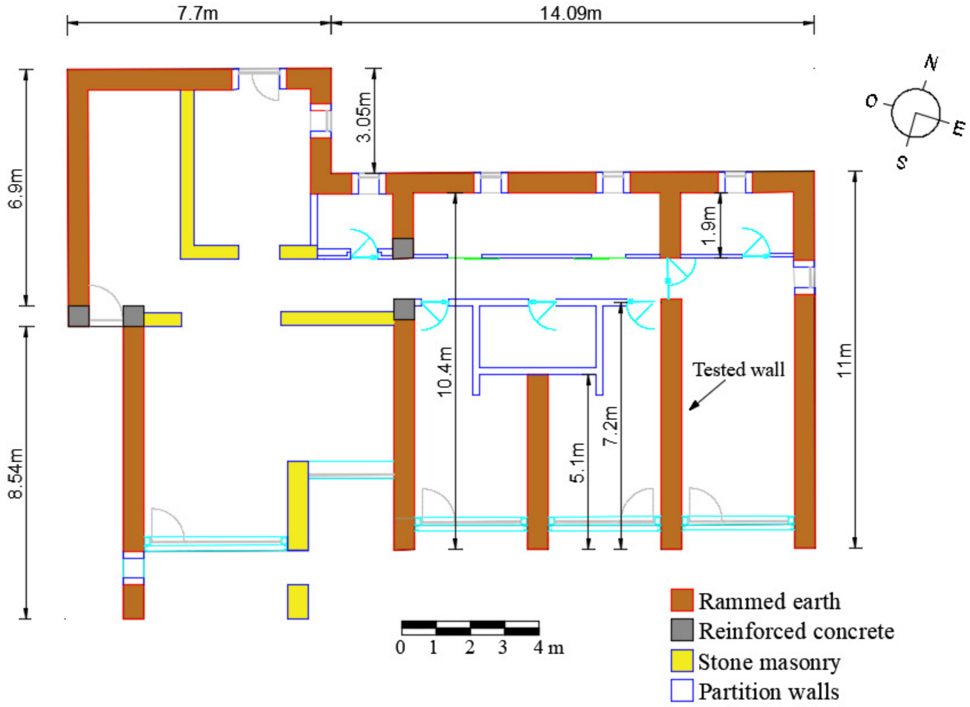



Fig. 5 – First storey plan of the house adopted as case study.

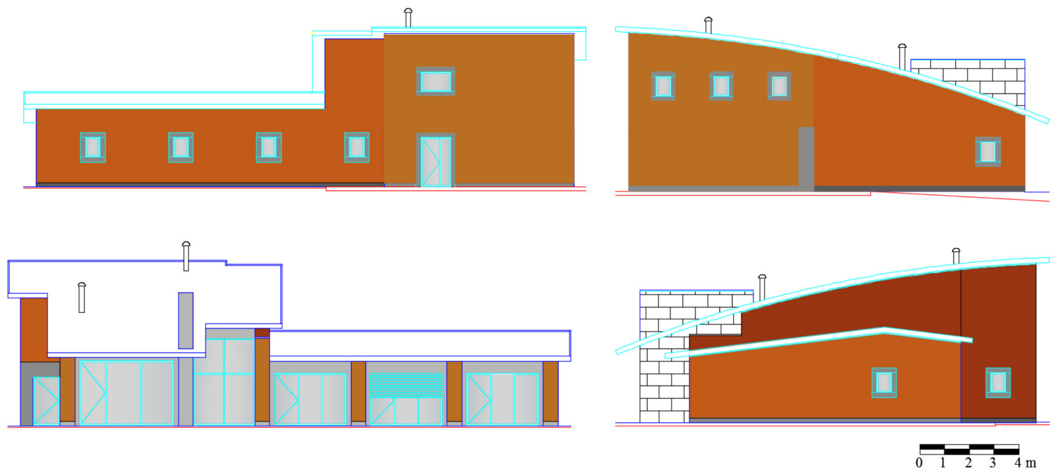



Fig. 6 – Elevation views of the house adopted as case study.

The soil used in the construction of the rammed earth walls consists of a mixture of two other soils, namely a locally available soil (SFE) and a soil transported from a village located about 20 km away (SVC). SFE is a granitic residual soil with greyish colour, while SVC is a soil resulting from degradation of schist rock with brown-reddish colour. Both soils were characterised in terms of particle size distribution [48], consistency limits [49] and standard Proctor compaction [50]. The particle size distribution of the soils is presented in Fig. 7, while

Table 2 presents the liquid limit (LL), plastic limit (PL), plasticity index (PI), maximum dry density ($\gamma_{dmax}$) and optimum water content ($W_{opt}$).

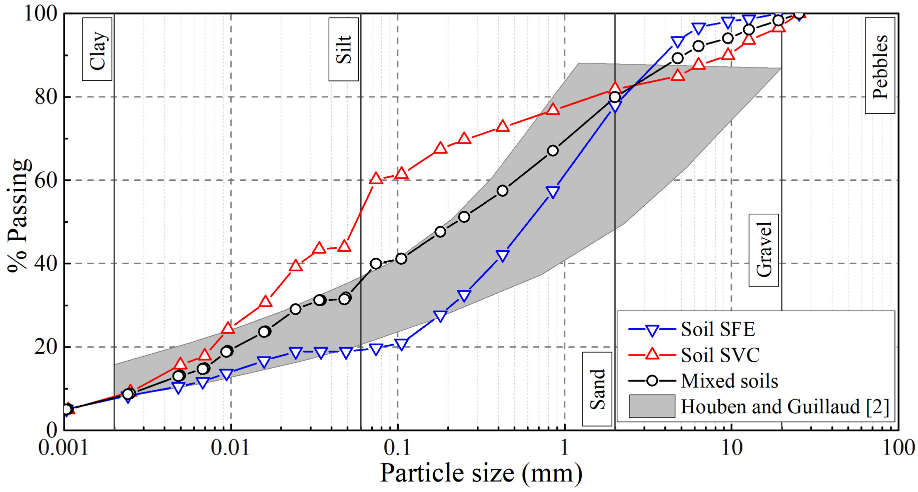



Fig. 7 – Particle size distribution of the soils and comparison with the envelope proposed by Houben and Guillaud. [2].

Table 2 – Properties of the soils.

| Soil | LL (%) | PL (%) | PI (%) | $\gamma_{dmax}$ (kg/m$^3$) | $W_{opt}$ (%) |
|---|---|---|---|---|---|
| SFE | | Non-plastic | | 2020 | 10.2 |
| SVC | | Non-plastic | | 1650 | 10.1 |

Both soils present a clay content lower than 10%, which can be considered insufficient for unstabilised rammed earth construction, according to the envelope of suitable soils for rammed earth constructions proposed by Houben and Guillaud [2]. This observation means that using any of these soils for building rammed earth construction is expected to require introducing an additional amount of binder in order to promote adequate mechanical and durability characteristics. This enhancement can be achieved with chemical stabilisation, where cement is expected to be the most efficient binder for both soils, since they are deemed as non-plastic. Furthermore, the relatively high $\gamma_{dmax}$ of soil SFE indicates that the resulting rammed earth is expected to present better mechanical performance than that of soil SVC. Despite the expected better performance of the local soil, the resulting aesthetics of the rammed earth was not as appealing as that of soil SVC, which results in rammed earth aesthetics similar to that of traditional rammed earth from Alentejo. Taking into account both mechanical performance and aesthetics preference criteria, the soil adopted for the construction of the walls resulted from the mixture of both soils in the proportion 1:1. The resulting mixed soil was stabilised by adding about 7% of Portland cement CEM II/B-L 32,5 N. The mixing of all constituents was processed mechanically, where water was added using a hose and in proportions defined as adequate for compaction, according to the experience of the workers (see Fig. 8d).

(a) (b) (c) (d)

Fig. 8 – Construction of the rammed earth walls: (a) foundation RC beams; (b) externally supported formwork; (c) horizontal indentation of the rammed earth blocks; (d) preparation of the soil mixture.

### 3.3 Destructive testing

The destructive testing approach consisted in compression tests performed on specimens' representative of the rammed earth material of the walls. For this purpose, two sets of five specimens were sampled during the construction of the walls, namely from two mixtures selected randomly. The specimens were compacted by the workers while building the rammed earth walls, using cylindrical steel moulds (typically used for concrete sampling) with 150 mm diameter and 300 mm height and a pneumatic compactor. The specimens were not compacted in the full height of the mould due to limitations of the procedure (need of free space to introduce loose soil mixture plus the compactor piston), meaning that the average height of the specimens was of about 230 mm (see Fig. 9a). After sampling, the moulds were covered with plastic and were moved to the Laboratory of Structures from University of Minho (LEST), where they stayed under ambient conditions. Demoulding of the specimens was processed at 7 days of age, which were then put to cure inside a climatic chamber with temperature and relative humidity set as 20ºC and 57.5%, respectively.

(a) (b)

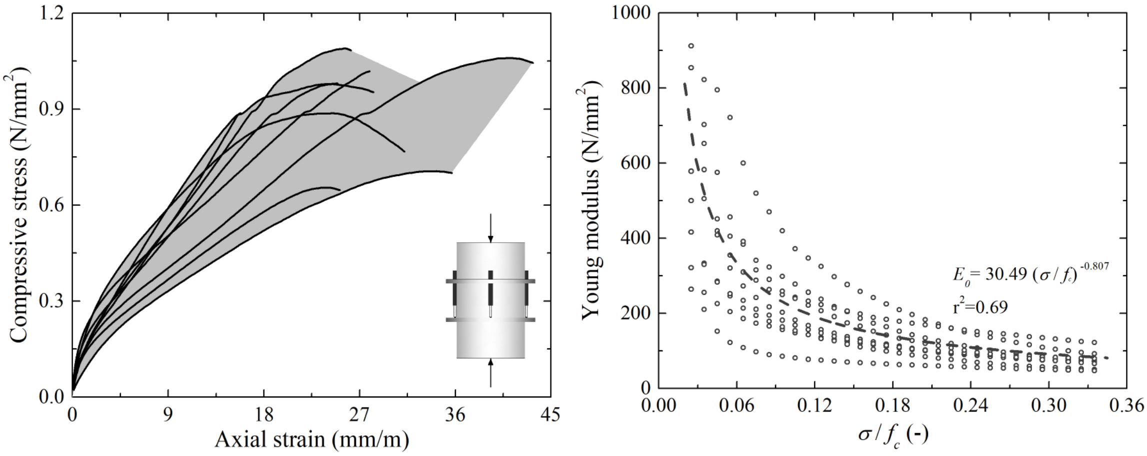
Fig. 9 – Compression tests: (a) sampling of the rammed earth specimens; (b) test setup.

The specimens were tested with average age of about 32 days and density of about 1723 kg/m$^3$ (CoV = 1.7%). In the day before testing, the specimens were removed from the climatic chamber in order to regularise the loading surfaces with fast hardening mortar. The compression tests were carried out under monotonic displacement control with speed of 5 μm/s. The applied load was measured by means of a load cell, while the vertical deformations at the middle third of each specimen were measured by means of three linear variable displacement transducers (LVDT) radially-disposed (see Fig. 9b).

Fig. 10a presents the axial compressive stress-strain curves of the specimens of both sets, which evidence an expressive scattering in terms of deformation behaviour. The average compressive strength of both sets of specimens was of about 1.0 N/mm$^2$ (CoV = 16%), which is a value fitting within the range of values found in the literature, namely 0.6-3.9 N/mm$^2$ [19].

The Young's modulus of each specimen was defined by linear fitting of the stress-strain curves at 5-30% of the compressive strength, as proposed by Silva et al. [8], resulting in an average value of about 67 N/mm$^2$. Nevertheless, the compressive stress-axial strain curves exhibit a pronounced non-linear behaviour during loading, meaning that the Young's modulus depends on the stress level imposed to specimens, thus defining a single value for this parameter seems to be a reckless procedure. This non-linear behaviour is clearly evidenced in Fig. 10b, which presents the Young's modulus (secant modulus) of each specimen as function of the compressive stress normalised by the compressive strength ($\sigma / f_c$). For low values of loading, the Young's modulus assumes high values, which rapidly decrease (more than one order of magnitude) as the loading level increases. Despite the high scattering of the results between specimens, this relationship seems to follow a power law.

The fact is that insufficient discussion is available in the literature regarding the determination of the Young's modulus of rammed earth materials by destructive means, namely with respect to the definition of the geometry of the specimens, loading protocol and method to measure deformations. In general, rammed earth specimens found in the literature [8][10][17][19][51] present very variable shapes (cubes, prisms, wallets, cylinders), the loading protocols are found to be monotonic or with stepwise loading-unloading cycles, and the deformations are monitored either by means of transducers measuring displacements between testing platens or of traducers fixed directly on the specimen.




(a) (b)

Fig. 10 – Results of the axial compression tests: (a) stress-strain curves; (b) variation of the Young's modulus with the compression level.

## 3.4 Non-destructive testing

### *3.4.1 General description of the tests*

An experimental in-situ campaign on a rammed earth wall of the case study described in Section 3.2 was carried out 27 days after compaction (see also Fig. 5). This experimental campaign involved two types of non-destructive tests, namely sonic tests and a dynamic identification test. Both types of tests aimed at estimating the dynamic Young's modulus of the rammed earth and the dynamic properties of the wall (frequencies, mode shapes and damping ratios).

The rammed earth wall includes a RC beam at its base (Fig. 11), connected to each other by means of vertical steel rebars (see Fig. 8a). All the other wall edges do not present any boundary condition and are free to deform. The rammed earth wall has a length of 7.20 m and variable height (maximum and minimum equal to 3.60 m and 2.75 m, respectively). The thickness of the wall is constant and equal to 0.60 m (slenderness of about 5.3). The RC beam has 0.20 m high and the width is equal to the thickness of the wall.

In the non-destructive testing, piezoelectric accelerometers (sensitivity equal to 10 V/g, frequency range from 0.15 to 1000 Hz, dynamic range ± 0.5g, 210 gram weight), coaxial cables and one 24 bits data acquisition board with software developed by University of Minho were used. The accelerometers were fixed to timber cubes with screws. The timber cubes were glued to the wall with a small amount of fast-acting adhesive. Furthermore, an instrumented hammer (22240 N pk) was used for the sonic tests.

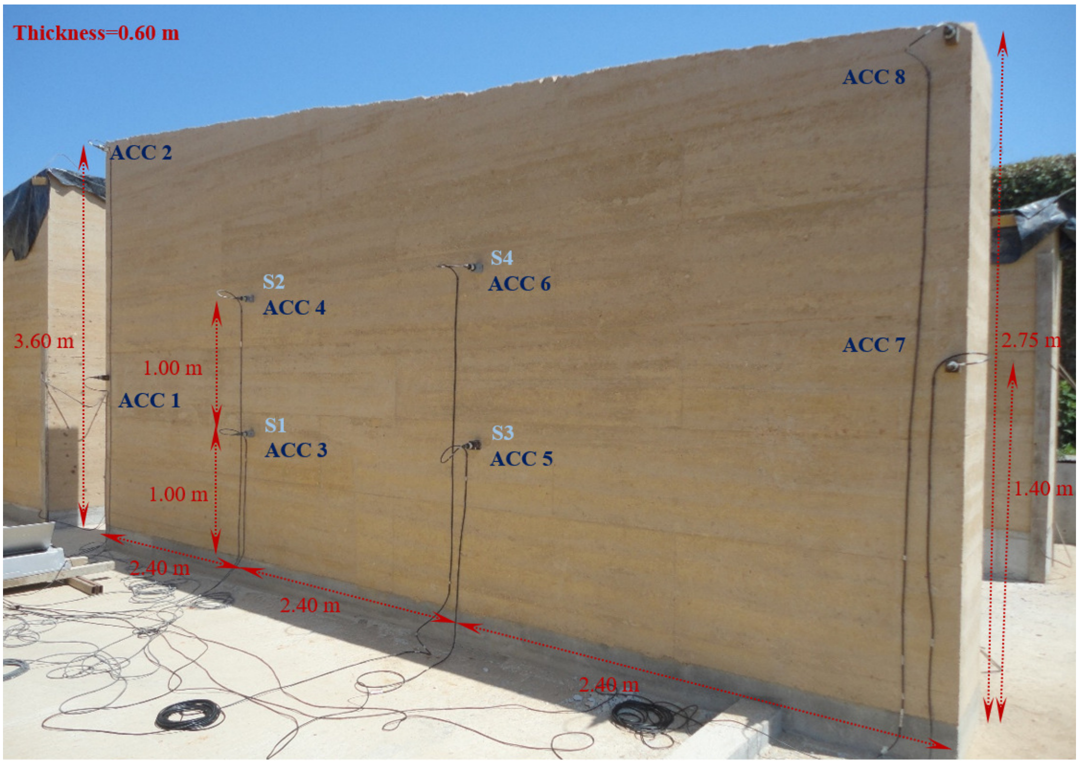



Fig. 11 – Rammed earth wall adopted for the non-destructive testing. ($ACC_i$ and $S_i$ correspond to the location of accelerometers used for dynamic identification tests and sonic tests, respectively)

### *3.4.2 Sonic tests*

Direct sonic tests were carried out in four points (S1-S4) at the middle of the rammed earth wall (Fig. 11). The velocity of the P waves ($V_P$) in direct tests can be obtained by estimating the time ($\Delta t$) between the hammer impact and the arrival of the waves (signal of the accelerometer), and by knowing the thickness of the element ($s$) (Eq. 6):

$$V_P = \frac{s}{\Delta t} \qquad \text{Eq. 6}$$

The dynamic Young´s modulus ($E_d$) can be determined as function of the velocity of the P waves ($V_P$) and reads [52]:

$$E_d = \rho V_p^2 \frac{(1+v)(1-2v)}{(1-v)} \qquad \text{Eq. 7}$$

where $\rho$ is the density and $v$ is the dynamic Poisson´s ratio. In this case study, the density is equal to 1723 kg/m$^3$ and the $s$ is equal to 0.6 m. A Poisson´s ratio equal to 0.2 was adopted. Six tests were carried out at each of the four points of the wall. Table 3 presents the average results obtained in the direct sonic tests. The average of the velocity and dynamic Young´s modulus in the perpendicular direction of the wall (in-plane direction of the layers) is equal to 544 m/s and 462 N/mm$^2$, respectively. Giamello et al. [53] carried out direct sonic tests on a rammed earth wall of an ancient Italian building and obtained an average velocity equal to 542 m/s, which is a value similar to that obtained here. Furthermore, the dynamic Young's modulus is found to be of about one order of magnitude higher than the Young's modulus reported from the compression tests. This large difference results from the fact that these parameters were evaluated accounting different stress levels, as discussed later.

Table 3 – Average of the results obtained in the direct sonic tests (CoV inside parenthesis).

| | S1 | S2 | S3 | S4 | Average |
|---|---|---|---|---|---|
| $V_P$ [m/s] | 554.6 (7%) | 537.5 (6%) | 574.9 (10%) | 509.4 (5%) | 544.1 (5%) |
| $E_d$ [ N/mm$^2$] | 479.2 (15%) | 449.4 (12%) | 516.9 (20%) | 403.3 (10%) | 462.2 (10%) |

### *3.4.3 Dynamic identification test*

The dynamic identification tests aim at estimating the dynamic properties, namely the frequencies, mode shapes and damping ratios of structures. The experimental modal identification techniques can be divided in three main groups [54]: (a) Input/output vibration tests, where the excitation applied to the structure and the vibration response are measured; (b) Output only vibration tests, where only the vibration response is measured during the service conditions of the structure; (c) Free vibration tests, where the structure is forced to an initial deformation and is then quickly released. Furthermore, several methods can be used to identify the dynamic properties through vibration tests, such as the Peak Picking, Circle Fit, Rational Fraction Polynomial or Complex Exponential. These methods are classified according the type of domain (frequency or time), the type of formulation (indirect or direct), the type of estimates (global or local), the number of the degrees of freedom (SDF - Single Degree of Freedom or MDF - Multiple Degree of Freedom), and the number of the input/output signals (SISO - Single Input and Single Output; SIMO - Single Input and Multiple Output or MIMO- Multiple Input and Multiple Output). For further details about the methods see Edwins [55], Peeters and De Roeck [56] and Gentile and Saisi [57].

The output-only technique was adopted in the dynamic identification test carried out on the rammed earth wall, in which the ambient vibration was the source of excitation (such as wind and traffic). This test aimed to estimate the out-of-plane vibration modes of the wall. Eight accelerometers fixed at several levels were used for the instrumentation of the wall, see Fig. 11. The signals were acquired with a sampling frequency equal to 200 Hz and a total duration of 30 min. The results were processed in the ARTeMIS software [58] and the SSI-

UPC (Stochastic Subspace Identification-Principal Component) method [59] was adopted for estimating the dynamic properties of the wall.

The dynamic identification test allowed to estimate six out-of-plane experimental modes, with frequencies ranging from 5.09 Hz to 34.94 Hz (Fig. 12). Mode 1 (5.09 Hz) corresponds to the first global bending mode with first curvature in elevation. The second mode (9.15 Hz) is an in-plan distortional mode. Mode 3 (16.38 Hz) corresponds to an in-plan bending mode. The fourth mode presents second curvature in elevation (25.32 Hz). Mode 5 (29.17 Hz) corresponds to an in-plan mode with second curvature and mode 6 (34.94 Hz) is a combined bending mode with second curvature both in-plan and in elevation. The average of the damping ratios is equal to 1.8%, in which the damping ratio of the first mode equals 2.3% (Fig. 12). It is noted that the damping ratio is a very sensitive parameter and difficult to estimate experimentally [60]. Furthermore, low values are expected for the damping ratios when ambient vibrations are used to excite structures [61].

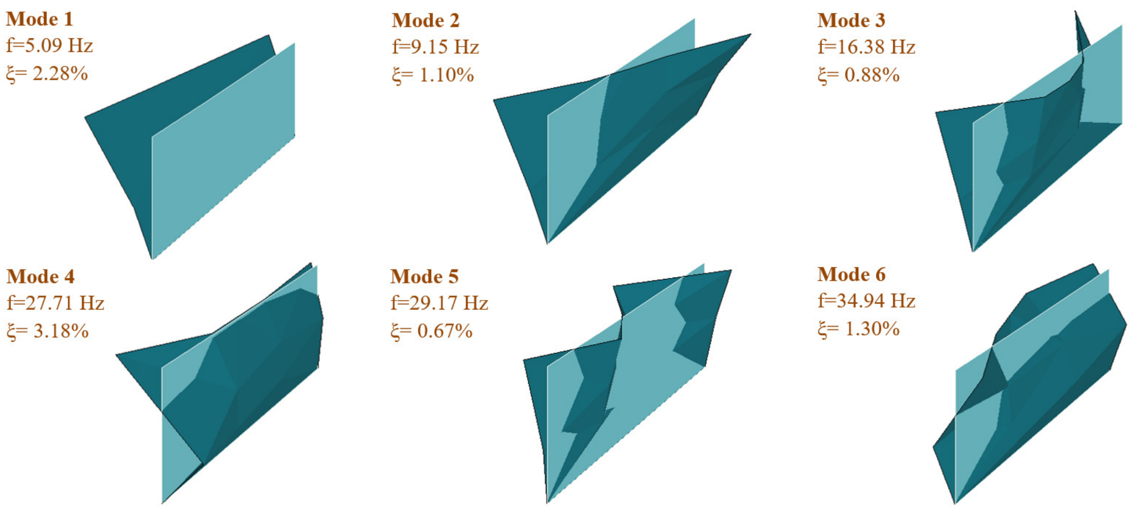



Fig. 12 – Dynamic properties estimated from the dynamic identification test.

## 3.5 Model updating

A numerical model of the rammed earth wall was prepared based on FEM [62], using eight-node shell elements, based on the Mindlin-Reissner theory, and assuming that the base of the wall was fixed. The numerical modelling aimed to estimate the elastic properties of the rammed earth based on the calibration of the dynamic properties. The density (1723 kg/m$^3$) was considered constant during the model updating. The calibration was carried out based on the Douglas-Reid proposal [63].

In the first attempt of the calibration process, six frequencies were considered and isotropic behaviour was assumed for the rammed earth material. The numerical frequencies presented high errors with respect to the experimental ones (average and highest error equal to 12% and 22%, respectively). Furthermore, the sequence of the numerical modes was not in agreement with that of the experimental ones. Thus, a comprehensive sensitivity analysis was carried out, aiming at evaluating the parameters with influence on the dynamic properties of the wall. The boundary conditions at the base (spring elements), the Poisson's ratio, the consideration of several horizontal layers with different Young´s modulus (isotropic behaviour) taking into account different compacting energy, and the orthotropic (vertical direction and horizontal plan) behaviour of the material were evaluated. The results of the sensitive analysis allowed to conclude that the orthotropic behaviour had the highest influence on the dynamic properties. The Young's modulus in the vertical direction (i.e. perpendicular to layers) of the wall ($E_{\perp}$) presents high influence on modes 1, 2, 4 and 6 (Fig. 12). In turn, the Young's modulus in the horizontal direction (i.e. parallel to layers) of the wall ($E_{//}$) has high influence on modes 3 and 5. Finally, the shear modulus that relates the perpendicular and parallel directions ($G_{\perp //}$) presents high influence on modes 2, 3 and 5.

In the final model updating of the model considering orthotropic behaviour, the three most important uncorrelated variables, $E_{\perp}$, $E_{//}$ and $G_{\perp //}$, were considered in the calibration process, whereas the Poisson's ratio in the vertical direction ($\nu_{\perp}$) and that in horizontal direction ($\nu_{//}$) were fixed as equal to $\nu$ (0.2). The shear modulus in the plan of the layers ($G_{// //}$) was assumed equal to $E_{//}/(2(1+\nu))$. It should be noted that despite the material behaviour being assumed orthotropic, any value of $E_{//}$ evaluated in the direction perpendicular to the wall has no influence on the dynamic properties estimated from the dynamic identification test. The calibrated model presents an average error for the six frequencies less than 3% (Fig. 13 and Table 4), in which the error of the first mode is equal to 0.3%. Furthermore, the average Modal Assurance Criteria (MAC) [59] is equal to 0.96 and the MAC for the first mode equals 0.99 (Fig. 13), showing that the correlation between the numerical and experimental mode shapes is very good. The calibrated properties (Table 4) obtained by the model updating are equal to 515 N/mm$^2$, 998 N/mm$^2$ and 316 N/mm$^2$ for $E_{\perp}$, $E_{//}$ and $G_{\perp //}$, respectively. Thus, $G_{// //}$ is computed as 416 N/mm$^2$. Now, if the equation $E/(2(1+\nu))$ is used for each direction, the shear modulus is equal to 215 N/mm$^2$ and 416 N/mm$^2$ for the directions perpendicular ($E_{\perp}$ = 515 N/mm$^2$) and parallel ($E_{//}$ = 998 N/mm$^2$) to the layers, respectively. The average value of these shear moduli is equal to 315 N/mm$^2$, which is approximately equal to the shear modulus $G_{\perp //}$ (316 N/mm$^2$) obtained from the calibration assuming the variables as uncorrelated.

The numerical modelling showed that an orthotropic behaviour should be considered for this case study. Bui and Morel [51] carried out an experimental study on the anisotropy of rammed earth, in which the Young's moduli in the perpendicular and parallel directions to the specimen's layers were determined for several amplitudes of preloading. The results showed that for low levels of preloading (0.06 N/mm$^2$ to 0.12 N/mm$^2$) the Young's modulus in the parallel direction to the layers ($E_{//}$) is higher than the Young's modulus in the parallel direction ($E_{\perp}$) for about 25%. However, for preloading equal to 0.40 N/mm$^2$ the difference is insignificant. In this case study, the compressive stress on the wall ranges from zero (top) to 0.06 N/mm$^2$ (base), thus a ratio between $E_{//}$ and $E_{\perp}$ higher than 1.25 should probably be expected. In fact, the $E_{//}$ to $E_{\perp}$ ratio reaches 1.94. It is noted that the highest compressive stress in the wall is equal to 6% of the compressive strength of the rammed earth (Section 3.3).

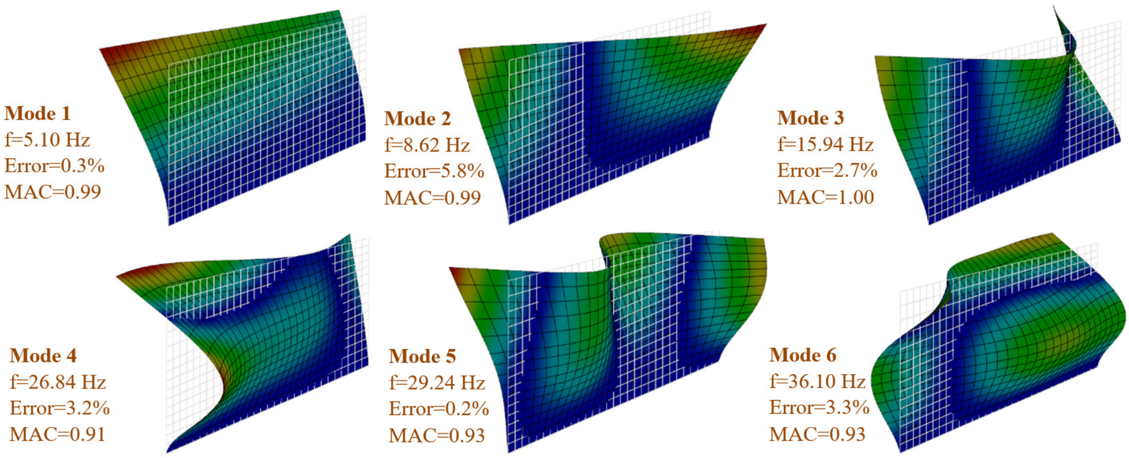



Fig. 13 – Dynamic properties of the numerical model (only the modes estimated in the dynamic identification test are presented).

Table 4 – Experimental and numerical results obtained from the model updating.

| Modes | Frequency | | |
|---|---|---|---|
| | Experimental [Hz] | Numerical [Hz] | Error [%] |
| Mode 1 | 5.09 | 5.10 | 0.3% |
| Mode 2 | 9.15 | 8.62 | -5.8% |
| Mode 3 | 16.38 | 15.94 | -2.7% |
| Mode 4 | 27.71 | 26.84 | -3.2% |
| Mode 5 | 29.17 | 29.24 | 0.2% |
| Mode 6 | 34.94 | 36.10 | 3.3% |

| Material properties | Updated value |
|---|---|
| $E_{\perp}$ [N/mm$^2$] | 515 |
| $E_{//}$ [N/mm$^2$] | 998 |
| $G_{\perp //}$ [N/mm$^2$] | 316 |
| $G_{// //}$ [N/mm$^2$] | 416 |
| Density [kg/m$^3$] | 1723 |
| Poisson's ratio | 0.2 |

## 4. CONCLUSIONS

This paper presents an investigation that allows to better comprehend the seismic behaviour of rammed earth constructions from Portugal, by addressing both cases of traditional and modern constructions. Alentejo region was selected as case study for evaluating the seismic behaviour of a sample constituted by 20 traditional rammed earth dwellings, using simplified methods based on the analysis of in-plane and out-of-plane indexes, as well as by means of a kinematic approach. As for modern rammed earth construction, a rammed earth construction recently built in Northern Portugal was used as case study, where factors affecting the seismic behaviour were evaluated by means of destructive and non-destructive testing.

Despite the limitations of the simplified seismic evaluation carried out, it allowed to conclude that in general the analysed dwellings are expected to perform reasonably well to a far-field earthquake. As for the in-plane behaviour, four buildings (20%) violated $\gamma_1$ threshold, while none violated $\gamma_2$ or $\gamma_3$. Nevertheless, it should be noted that this conclusion results mainly from threshold values that were not defined specifically for rammed earth constructions, thus the conclusions above must be taken with caution.

In the case of the out-of-plane behaviour, no building violated the most permissive threshold defined for $\gamma_\lambda$, while only one building (5%) violated the intermediate threshold and 8 buildings (40%) violated the most demanding threshold. The kinematic approach showed that only 3 buildings (15%) do not satisfy the demand performance. Moreover, the longitudinal direction was shown to be the most critical due to the presence of gable walls, which increase the height of the walls subjected to out-of-plane loading.

The advanced seismic evaluation consisted of destructive and non-destructive tests carried out within the framework of the selected case study. The destructive testing involved a series of compression tests on representative specimens, which mainly allowed to conclude that the compression behaviour of rammed earth is highly non-linear. Furthermore, the Young's modulus of the rammed earth was shown to be highly dependent on the stress level used for its evaluation.

The non-destructive tests involved carrying out sonic tests and a dynamic identification test on a rammed earth wall from the case study. The sonic tests allowed to conclude that the dynamic Young´s modulus in the perpendicular direction to the wall (parallel to the layers) is equal to 462 N/mm$^2$. The dynamic identification tests allowed to estimate the dynamic properties of the wall, namely six out-of-plane modes. Furthermore, a numerical model was prepared and calibrated based on the dynamic properties estimated through the dynamic identification test. The model updating presented an average error for the frequencies and MAC values of about 3% and 0.96, respectively. The calibration of the numerical model allowed also to conclude that rammed earth should be considered as an orthotropic material for this case study, which presents low vertical loading and several local modes. For walls subjected to higher stress levels (loaded slabs or heavy roofs at the top), the influence of orthotropic behaviour of rammed earth would be probably less significant. The numerical Young's modulus perpendicular to the layers is equal to 515 N/mm$^2$, which is significantly higher than the Young´s modulus computed between 5-30% of stress-strain curves (67 N/mm$^2$). Nevertheless, when accounting for the stress level of the walls at the middle section, the Young's modulus can be estimated from the destructive tests (see equation in Fig. 10b) as 516-677 N/mm$^2$, which is a value relatively similar to that obtained from the model updating. These aspects lead to the conclusion that the characterisation of the elastic properties of rammed earth is still a challenge and more research should be conducted on this topic, namely in the study of the anisotropy and the relationship between the static and dynamic Young´s moduli.

Finally, it can be stated that the seismic behaviour of traditional rammed earth buildings from Alentejo benefits from many features resulting from the local architectural culture, among which are the construction of buildings with no more than a single storey (low rise buildings), with relatively regular plan and elevation and with very thick walls. Nevertheless, modern rammed earth construction has been leading to increasingly more complex structures, where some of the aforementioned features are neglected. Thus, the design of these structures in regions with important seismic hazard requires using reliable design tools, capable of taking into account the key factors affecting the seismic response. Here, the adequate determination of the mechanical properties of rammed earth by means of experimental testing assumes a central role, but it was shown to be a topic needing further research.

## ACKNOWLEDGEMENTS

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