Engineering Structures 157 (2018) 144–156

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

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

Rui A. Silva[a,*], Nuno Mendes[a], Daniel V. Oliveira[a], Antonio Romanazzi[a], Oriol Domínguez-Martínez[b], Tiago Miranda[c]

[a] ISISE, University of Minho, Department of Civil Engineering, Azurém, P-4800-058 Guimarães, Portugal
[b] Terrachidia Association, Madrid, Spain
[c] ISISE & IB-S, University of Minho, Department of Civil Engineering, Azurém, P-4800-058 Guimarães, Portugal

ARTICLE INFO

Keywords:
Rammed earth
Seismic behaviour
Simplified indexes
Kinematic approach
Mechanical characterisation
Dynamic identification
Sonic tests
Model updating

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.

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 BCE [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 8th and 13th 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

* Corresponding author.
E-mail addresses: ruisilva@civil.uminho.pt (R.A. Silva), nunomendes@civil.uminho.pt (N. Mendes), danvco@civil.uminho.pt (D.V. Oliveira), aromanazzi89@gmail.com (A. Romanazzi), oriol.arq@gmail.com (O. Domínguez-Martínez), tmiranda@civil.uminho.pt (T. Miranda).

https://doi.org/10.1016/j.engstruct.2017.12.021
Received 26 June 2017; Received in revised form 7 December 2017; Accepted 12 December 2017
0141-0296/

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 1950s 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 1950s, 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 1980s, 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 [20–22]. On the other hand, the characterisation 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 [9,1]. 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.