EXPERIMENTAL CHARACTERIZATION OF THE STRUCTURAL RESPONSE OF ADOBE ARCHES

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Abstract
Earth was one of the first construction materials used by mankind and has been used as a building material since ancient times until the present days. Its qualities related to thermal comfort, low cost or simple construction techniques have contributed to such a long tradition throughout the world with several different architectural expressions, integrating the culture and history of each region.
With the wide propagation of steel and concrete structures, there has been a general loss of the traditional knowledge in earth construction. This type of construction presents important structural fragilities and requires a special maintenance to preserve its qualities. In order to understand the structural behaviour of this type of structures, the associated construction methods and processes have to be considered.
Aveiro University has been developing studies on adobe constructions, with research on the material mechanical characterization, experimental study of the structural behaviour of adobe masonry walls and, more recently, in the development of a detailed survey methodology for the characterization of buildings in Aveiro district.
Integrated in these studies, arches with different geometries were built using adobe blocks and traditional construction methods. These arches were tested under different types of vertical loading (distributed symmetrical, distributed non-symmetrical and point load) until collapse. The experimental tests performed reproduce the typical loading conditions of these structures during construction and use. The tests conducted, the results obtained and the main conclusions attained are described in this paper.

1. INTRODUCTION

Earth construction has been widely used through times due to its appealing characteristics such as simplicity in construction or interior comfort. In fact, earth as a construction material presents captivating qualities: low cost, locally available, recyclable, good thermal and acoustic properties, being currently associated to simple construction methods with low consumption of energy. The use of this material allows a more sustainable practice in construction, maintenance and use, with preservation of natural resources.

At the present time, it is believed that 30% of the world population lives in earth buildings and that 50% of the population in underdeveloped countries, including the majority of the rural population and 20% of the urban and marginal urban population lives in buildings built with earth [Houben, H., Guillaud, H. (1994)].

Until recently, earth was a common construction material in Portugal, with several applications mainly in different regions, such as Algarve, Alentejo and Beira Litoral, until middle of XXth century. The production and the use of adobe, in particular, was industrially developed at north of Mondego river, mainly in Aveiro District, due to the good characteristics of the raw materials [Santiago, L. (2005)].

Nowadays, approximately 25% of the existing buildings in Aveiro city are made of adobe, with 40% estimates of the whole district. The important expressivity of this construction system has been confirmed in building surveys recently conducted [Silva, S. *et al.* (2010)]. Adobe masonry can be found in several types of construction: rural and urban buildings, most of them still in use, walls, water wells, churches and warehouses. Several of the urban buildings have and important architectonic, cultural and historical value, with a special mention to "Art Nouveau" buildings, a unique expression in adobe in the world [Oliveira, C. *et al.* (2009)].

At the present time, a high percentage of these buildings are inadequately maintained by reasons of non-conservation or incorrect rehabilitation interventions. In effect, due to the loss of the traditional knowledge on the construction of these types of structures, many of the interventions conducted applied materials or rehabilitation solutions that, instead of improving the overall structural performance, reduce it. Also, the study and conservation of this built heritage has been getting little attention. As a consequence, many of the existing earthen buildings present various structural and non-structural anomalies and deficiencies.

Thus, more knowledge on the subject is required, with further research on the materials, type of structures, performance, capacity evaluation and rehabilitation techniques.

Several research studies have been conducted in Aveiro University ([Varum, H. *et al*. (2011)], [Silveira, D. *et al.* (2012)], [Arêde, A. *et al.* (2007)], [Silveira, D. *et al.* (2007)], [Varum, H. *et al*. (2008)], [Varum, H. *et al.* (2005)]) to suppress the existent lack of information, concerning the structural properties of adobe and its constituting materials, such as composition, resistance and stiffness, ductility, energy dissipation capacity and collapse mechanisms. Also, experimental tests on adobe walls ([Arêde, A. *et al.* (2007)], [Figueiredo, A. (2009)], [Pereira, H. (2008)], [Varum, H. *et al.* (2005)], [Varum, H. *et al.* (2008)], [Varum *et al.* (2007)]), have been providing important information regarding future guidelines for the development of reinforcement and rehabilitation solutions for adobe structures.

Integrated in these studies, arches with different geometries were built using adobe blocks and traditional construction methods. To test these arches in order to reproduce the typical loading conditions of these structures during construction and use, an innovative experimental setup was applied, allowing to obtain interesting results.

2. DESCRIPTION OF THE ARCHES

Adobe arches may be found everywhere in the world where adobe construction exists. It provides structural integrity for openings while creating a beautiful and inviting entry [Schroder, L., Ogletree, V. (2010)]. In Aveiro region, it is common to find adobe houses with arches for their windows, doorways or corridor passages.

The geometry of the arch defines the stress transfer to its foundation: the higher the initial angle of the arch, the smaller the horizontal component. Two different geometries were tested, with the same base length (L), but different heights: deep arch (H=L/2) and semi-shallow arch (H=L/3).

In order to simulate an adobe construction representative of the vast patrimony existent in Aveiro district, the choice of adobe blocks and mortar to use in the tests was carefully considered. Three adobe arches with the same span but different geometries were built in laboratory using adobe blocks taken from an existing building in a demolition process. The blocks were homogenously cut in the dimensions 20x10x5cm and a mortar with traditional composition was used. The joints mortar used was composed by hydraulic lime, arenaceous soil and water with the following proportion: 1.5; 1.5; 1.

The two arches were built using the same scheme and support structure, only differing in the arch's height. A formwork made of wood was built reproducing the interior shape of the arch and a concrete base with an angle of inclination was made for placement of the first adobe block in each side. The adobe blocks were placed one after each other bonding them with the traditional mortar. Once the mortar had dried, the wood formwork was removed and, when necessary, side loads were placed to assure stability.

3. EXPERIMENTAL TESTS

Generally, when modelling a structure, it is common to apply the loads considering the final shape and loading of the construction, disregarding the construction process and its influence on the global structural behaviour. Furthermore, the majority of experimental tests in arches, domes and vaults use point loads, due to the difficulty of simulating distributed loading. However, in truth, adobe structures are commonly subjected to vertical distributed load and not to vertical point loads. Here, a unique experimental setup was developed in order to reproduce the real loading process and construction evolution using arches.

3.1 Test Setup

A box, encasing the arch to be tested, was made and filled with sand. The box and its features, explained further on, enabled to direct the loading on the arch, simulating different types of load cases. The sand represents the filling of adobe constructions, allowing representing distributed load. The sand was put in by levels corresponding to the actual loading process.

a) b)

Figure 1 - a) Reaction frame holding the MDF plate; b) Front view of the testing layout with HP Dial Gauges

Figure 1 shows the test setup for the deep arch (H=L/2), with a height of L/2. After being built, the arch was encased in a box made with MDF plates and acrylic glass. Regarding dimensions, the box was 2m high, 3m wide and 0.2m deep. The MDF plate was placed at the back and fastened to a portico in order to prevent its movement. The front plate was made of acrylic glass in order to observe the experimental test development, loading levels and deformations. The two plates (at front and back) were fastened together using steel threaded bars, to prevent relative displacements between them when loading was being applied. High precision dial gauges were placed below the arch to register the displacements suffered by different levels of loading.

3.2 Loading cases

Each arch was subjected to three different loading tests: vertical symmetrical loading, vertical non-symmetrical loading and vertical point loading. Figure 2 displays the three tests performed for the deep arch.

In the vertical symmetric loading test, the loading was made by levels, registering the deformations values at each level. The loading was applied until the sand reached 2m high, the top of the test box. Afterwards, the unloading was conducted by levels and the deformations at each level were registered.

In the non-symmetric loading test, a wooden element was placed vertically in the middle and on top of the arch and the loading was made in one side only. In the same way as for the symmetric loading, the sand was inserted into the box by levels and the correspondent deformations were saved into a record.

In order to simulate a vertical point loading over the arch and its degradation length, two wooden elements separated by 60 cm were placed on the arch. Sand was inserted on the two sides of arch, next to its bottom, to simulate the bracing conferred by the walls adjacent to the arch. The arch was then loaded with sand until the top of the box and an additional load was inserted, in order to increase the deformations and cause the collapse of the arch.

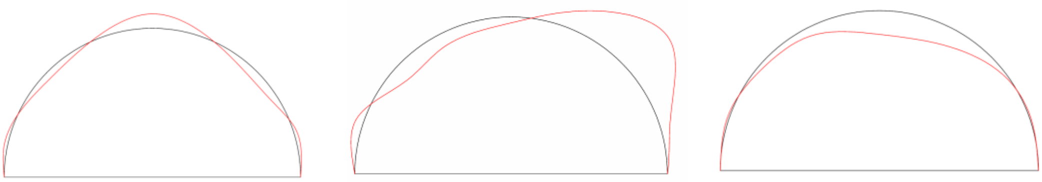
a) b) c)

Figure 2 - a) symmetric vertical loading; b) non-symmetric vertical loading; c) vertical point load

3.3 Test Results

3.3.1 Deep arch: H=L/2

As referred previously, different gauges were placed in this arch and the deformation values were registered periodically after filling the box with an additional sand height. Figure 3 shows the final deformed shape obtained for the deep arch test, under the three loading types considered.



a) Symmetric loading b) Non-symmetric loading c) Point load

Figure 3 – Deformed shape

Figure 4 presents the evolution of the displacements registered on the highest point of the arch for the three loading tests conducted. With the intention of providing a good chart reading, the displacement axis was limited do 4mm. Point load results continue with the same stiffness until reaching 12mm for 41kN/m^2.

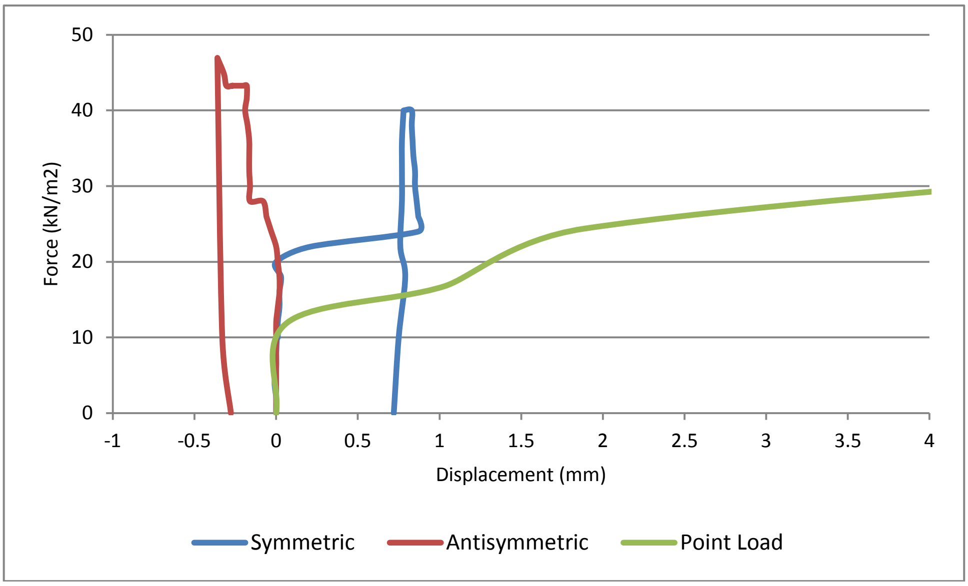


Figure 4 – Loading cases comparison for top gauge

During the symmetric loading, as the box was being filled with sand, and before topping the arch's height, the arch receives mainly horizontal forces directed to its inside, due to the horizontal impulse of the sand. This causes lateral movement of the arch towards its inside and upwards movement of the highest point of the arch, while the horizontal impulse of the sand is more important than the vertical load. For forces higher than 26kN/m^2, the vertical load input brings the arch's top point slightly downwards. After removal of all loading there is a residual deformation, which happens for all the points in the arch.

In the non-symmetric loading, only the left side of the arch was loaded. As seen in Figure 3, this causes a general movement of the arch to the right, where there is no restriction of movement. The evolution of the displacements of the highest point of the arch is rather irregular, with almost null stiffness at certain stages, which indicates brittle behaviour with the formation of cracks. The maximum displacement at this point is lower (approximately half) than on the symmetric loading case. Again, with the unloading, a residual deformation is observed.

Before analyzing the results for the point load test, it should be said that the tests were conducted for the same arch and followed the order here displayed: first the symmetric loading, after the non-symmetric loading and, at last, the point load test. Thus, in spite of applying the point load directly above the highest point of the arch, and therefore, in the symmetry axis of the arch, the deformed shape is not symmetric (see Figure 3). This is due to the accumulation of damages from the previous tests. Also, while for the previous test, the loading value refers to loading placed from the test box's bottom to the top, in the point load test, the sand is placed right over the highest point of the arch. In Figure 4 it is possible to observe that the arch is able to withstand with no significant deformation until a force of 10kN/m^2. However, after this point the stiffness lowers drastically, with total collapse for a force of 41kN/m^2 and a displacement of 12mm.

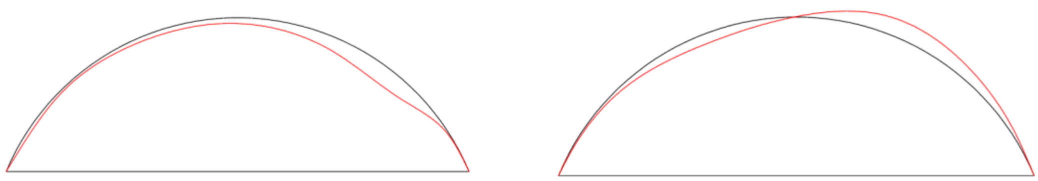
3.3.2 Semi-shallow arch: H=L/3

Regarding the tests conducted for the semi-shallow arch, the final deformed shape is shown in Figure 5 for symmetric and non-symmetric loading cases. For this arch, no point load was applied as it reached collapse for the non-symmetric loading case.

The final deformed shape for the symmetric loading is not entirely symmetric. Although all the efforts were made to produce a symmetric loading, the sand was introduced using manpower and slight asymmetries in the levelling of the sand are inevitable. In addition, fragilities on the construction of the arch may have been introduced as it was carried out in a traditional way. The values obtained from the lateral right gauge indicate sudden decrease of stiffness, possibly due to a sudden crack formation.

By analyzing Figure 6, which shows the displacement of the top gauge versus applied force, it is possible to observe that the semi-shallow arch behaved differently than the deep arch. For the symmetric loading, again the horizontal impulses of lateral sand pushed the arch inside and the top point upwards, but for a force higher than $12kN/m^2$, there is an inversion of movement with a significant downfall of the highest point of the arch.

As for the non-symmetric loading, as the load was applied of the left side of the arch, there is a general movement to its left. While the sand is being placed laterally to the arch, there is a clear movement of the top point to its left. When the sand tops the arch, the action of filling the test case with sand provides some stability to the arch causing a regression of the displacement felt. For higher forces than $24kN/m^2$, the top point begins again its rise, until collapse.



a) Symmetric loading b) Non-symmetric loading

Figure 5 – Deformed Shape

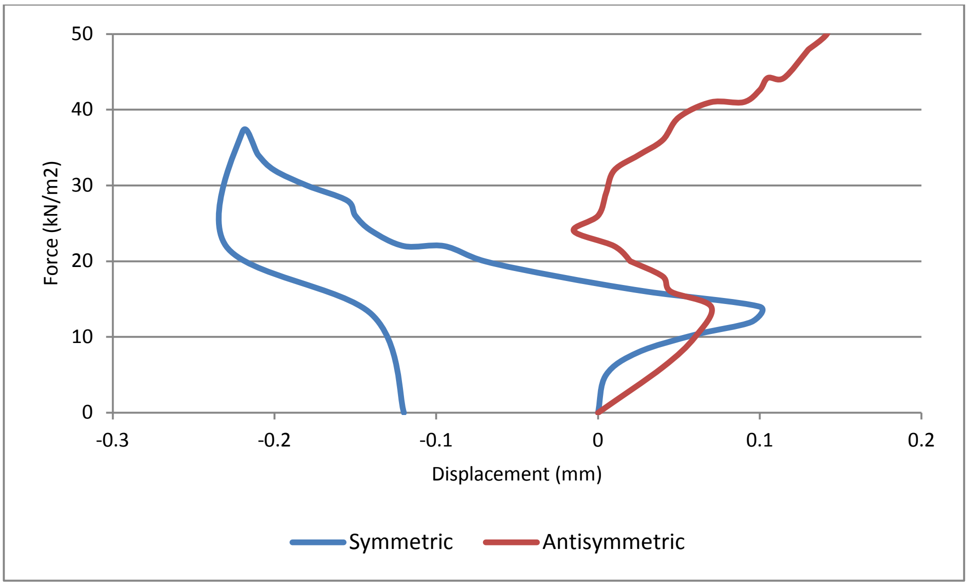


Figure 6 – Loading cases comparison for top gauge

7. CONCLUSIONS

Arches with different geometries were built and tested. The experimental test method was able to reproduce real loading conditions. Two geometries were tested, deep arch (H=L/2) and semi-shallow arch (H=L/3) and different vertical loadings were applied, symmetric loading, non-symmetric loading and point load.

In the symmetric loading test, the deep arch (H=L/2) showed higher displacements, due to a faster decrease of the friction connections between blocks, as well as a less compression component in the arch.

Regarding the non-symmetric loading, the semi-shallow arch presented significantly higher deformations, with a quick general loss of stiffness, leading to its collapse.

The shape of the arch, together with the loading type, influences the structural behaviour of adobe arches. Shallow arches display a higher stiffness for symmetric loadings, presenting a deficient behaviour for non-symmetric loading cases. This is due to the direction of the resultant force, as it actuates along the direction of the blocks connections, without compensation on the foundation.

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