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Structural Behaviour Assessment and Material Characterization of Traditional Adobe Constructions

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ABSTRACT

In Aveiro district, adobe can be found with abundance in rural and urban buildings, many of which are of cultural, historical and architectonic recognized value. A great number of the existing adobe constructions present pronounced structural damage, which results, in great part, from the lack of maintenance and the limited available knowledge concerning the mechanical behaviour of these structures. It is thus recognised the urgency for the development of research work in the structural analysis and strengthening of this important legacy. This work is of great value to the reduction of the seismic risk associated to these adobe constructions.

The University of Aveiro has been developing studies to help filling the technical information gap concerning the structural behaviour of existing adobe constructions. Cylindrical adobe specimens were subjected to compressive and “splitting” tests, and prismatic mortar specimens were subjected to compressive tests. Small wallets, constructed with materials representative of those found in existing adobe constructions, were subjected to compression tests, perpendicularly and diagonally to the bed joints. The structural non-linear response of adobe walls has also been investigated in a series of full-scale tests, in the laboratory and *in situ*, with imposed horizontal cyclic displacements. This article describes the studies carried out and discusses the principal results. These studies aim to establish a basis of knowledge that can support the interpretation of structural pathologies, calibration of numerical models, structural safety assessment, and design of strengthening solutions for the existing adobe constructions, and even support the design and execution of new edifications.

Keywords: Adobe construction, structural behaviour, seismic vulnerability, rehabilitation, strengthening.

1 INTRODUCTION

In the near past, earth was a very common construction material in Portugal. Adobe and rammed earth were used through years in almost all types of construction, having this utilization declined during the first half of 20th century, with the emergence of cement industry. Rammed earth was more applied in south and adobe, despite its significant heterogeneity confirmed by the many different identified typologies, in littoral centre, especially in Aveiro district (1, 2). Presently, according to information from the municipality, about 25% of the existing buildings in Aveiro city are made of adobe. It is estimated that this percentage rises to 40% when referred to the entire district, reflecting the importance of this construction system in rural areas. Adobe can be found in varied types of construction: rural and urban buildings, many of which are still inhabited, walls for the delimitation of properties, water wells, churches and warehouses (Fig. 1). An important number of the urban adobe buildings are of cultural, historical and architectonic recognized value, namely of the "Art Nouveau" style. The old Aveiro fire station building, the church of Quintãs, and the old flour-mill building recently converted by the University of Aveiro into a space for science results diffusion, among many others, are just good examples of existing adobe buildings in Aveiro district with important socio-cultural value. A more detailed description of the predominant constructive typologies can be found in (3).

Adobe traditional constructions, if not properly designed and strengthened, may present a deficient response when subjected to cyclic actions, as those induced by earthquakes, suffering severe structural damage and frequently reaching collapse. Several recent earthquakes affecting earth building have evidenced the seismic vulnerability associated to this type of construction, when not properly strengthened. The El Salvador earthquakes of January and February, 2001 and the Bam, Iran, earthquake of December 26, 2003 are just two significant examples. In El Salvador earthquakes more than one million people were made homeless, having the majority of the damage occurred in adobe houses.

Portugal has been affected, in the last centuries, by several earthquakes of large and moderate intensity. Aveiro district is located in a region of moderate seismic hazard. However, due to the nature of the foundation soft soils, eventual earthquakes striking the region can be considerably amplified. The techniques adopted in the construction of adobe buildings in Aveiro district were based in the accumulated experience, transmitted from generation to generation, and did not include a preoccupation with seismic safety. Rehabilitation and strengthening of existing adobe constructions have also been disregarded during decades. This constructed park is thus not properly reinforced to resist to seismic actions, suffering of various structural anomalies and deficiencies. The most frequent pathologies found in Aveiro adobe constructions are described in (3).

Structural rehabilitation of the existing adobe constructions in Aveiro district is demanded, and constitutes an urgent matter. It will contribute for quality of life improvement of those who use them and for an increase of associated safety levels, particularly if an effective seismic strengthening is assured. It presents, however, relevant difficulties, essentially due to the lack of information concerning properties and characteristics of the mechanical behaviour of adobe masonry. Technical studies for the determination of these properties and characteristics are thus necessary. The mechanical characterization of adobe existing masonry constitutes a fundamental instrument in the support of rehabilitation and strengthening projects, and even in the support of the design of new adobe constructions (4).

Figure 1. Examples of existing adobe constructions in Aveiro district.

2. EXPERIMENTAL WORK DEVELOPED

2.1 Introduction

A research group of the Civil Engineering Department, from the University of Aveiro, has been developing studies and experimental tests to aid filling the technical information gap concerning the structural behaviour of existing adobe constructions. The mechanical characteristics of adobe units and mortar samples taken from existing houses and land dividing walls and of reduced scale wallets constructed in the laboratory were investigated. The structural non-linear response of adobe walls has also been investigated in a series of full-scale tests, in the laboratory and *in situ*.

2.2 Simple Compression and Splitting Tests on Adobe Specimens

Adobe sample units representative of the different existing adobe construction typologies were collected from eight houses and eight land dividing walls, from different locations. Cylindrical cores, with diameters ranging between 60 and 95mm, were extracted from the collected units. These cylindrical cores had a height of approximately two times the diameter. 83 cylindrical specimens were submitted to compression, and 18 to splitting tests.

The adobe specimens present significant compressive strength values, varying from 0.32 to 2.46MPa. For each construction analysed, the tensile strength corresponds to approximately 20% of the compressive strength. Results for the analysed adobe samples reveal a clear tendency for samples with larger fractions of small dimension particles to present superior compressive and tensile strength values.

The detailed description of the mechanical characterization testing campaign and of the obtained results can be found in (5, 6).

2.3 Simple Compression Tests on Mortar Specimens

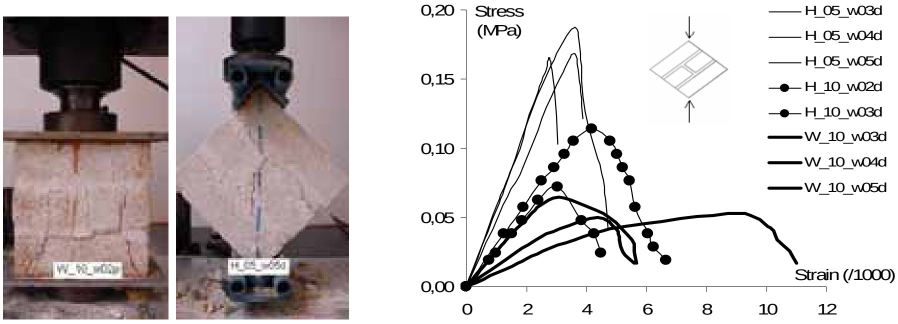
10 mortar samples (2 from plaster and 8 from joints) taken from 3 different houses were submitted to compression tests. The load applied by the compression testing machine was transmitted through two square steel plates, with 40mm side. It was obtained for the unconfined average strength: 1.68MPa (house 1); 1.07MPa (house 5); and 0.45MPa (house 12).

2.4 Perpendicular and Diagonal to the Bed Joints Compression Tests on Small Wallets

To estimate the compressive and shear strength of adobe traditional masonry walls, 13 small wallets with 17×17×10cm were constructed and submitted to compression tests, perpendicular to the bed joints and diagonally (Fig. 2). The wallets were constructed at a reduced scale (1:3). For the construction of the wallets, prismatic blocks were extracted from adobe units taken from existing constructions, and a mortar with a composition similar to the traditionally used was adopted.

The compressive and shear strength obtained from compression tests on wallets are between 0.77 and 1.57MPa; and between 0.05 and 0.19MPa, respectively. For the wallets constituted by adobe units with a lower compressive strength, lower shear and compressive strengths were obtained. Transversal modulus of elasticity and shear strength, for each series of tested wallets, are about 1/10 of the corresponding modulus of elasticity and compressive strength evaluated in compression tests perpendicular to the bed joints.

The detailed description of the testing procedures and of the obtained results can be found in (7).



a) b) c)

Figure 2. Compression test on wallet, a) perpendicular and b) diagonal to the bed joints. c) Stress vs strain relation obtained in diagonal to the bed joints compression tests on small wallets.

2.5 Tests on Full-Scale Adobe Masonry Walls

2.5.1 Laboratory tests

The wall tested in the laboratory was constructed with adobe units taken from an existing construction. These units have an average compressive strength of 0.85MPa and an average modulus of elasticity of 143MPa. For the joints it was adopted a mortar having a composition similar to the one traditionally used, with a compressive strength of 1.42MPa and a modulus of elasticity of 113MPa. The wall was constructed with the following dimensions: 1.08m height, 1.02m width and 0.185m thickness. The boundary conditions at the base of the wall avoid lateral displacements and rotations.

The wall was subjected, initially, to a non-destructive dynamic test, to estimate the natural frequencies in each direction. These measured frequencies help on the dynamic characterization of the adobe masonry wall, and also on the calibration of numerical models. In a second phase, it was conducted a destructive test imposing constant vertical load combined with in-plane horizontal cyclic forces.

2.5.1.1 Dynamic test

The natural frequencies in the two horizontal directions (transversal and longitudinal) were measured with a seismograph. The average modulus of elasticity of the wall can be estimated using the following equation:

$$\boldsymbol{\omega} = 1{,}875^2 \, (\mathbf{EI} \,/\, (\mathbf{ml}^4))^{1/2}$$

where: $\boldsymbol{\omega}$ is the natural frequency [rad/s]; **E** is the average modulus of elasticity; **I** is the moment of inertia of the cross-section; **m** is the mass per unit length of the wall; and **l** is the total height. This expression is valid if it is assumed: i) cantilever dynamic behaviour for the wall; ii) constant cross-section; iii) uniformly distributed mass in height. An average modulus of elasticity of 316MPa was estimated using this expression and considering the measured transversal frequency (10.94Hz).

2.5.1.2 In-plane cyclic test

A constant vertical load of 2.86kN was applied on the top of the wall, to simulate the behaviour of a wall with double height, as commonly observed in existing constructions, and in-plane horizontal forces were imposed, in cycles of increasing amplitude, till the collapse was reached (Fig. 4). In Fig. 3 is presented a general scheme of the testing layout, including the wall specimen and the loading and displacement measuring systems.

A maximum horizontal force of 3.2kN was applied. The failure mode was traduced by the opening of a horizontal crack at the base of the wall. This observed failure mode corresponds to the typical response of this type of masonry walls for low vertical stress levels. The reduced value of the vertical stress in the wall induces a rigid body behaviour, when subjected to horizontal cyclic loads, which is traduced by a rotation of the wall, almost intact, over its inferior and superior edges ("rocking").

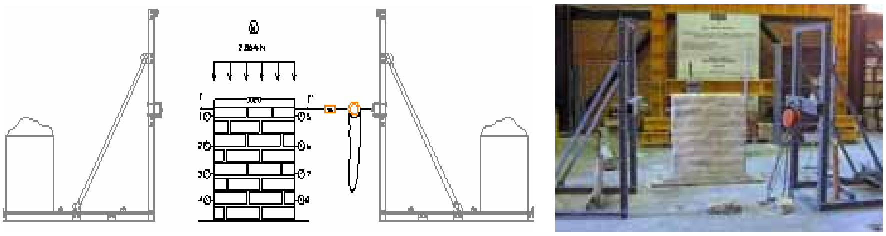


Figure 3. In-plane cyclic testing layout: wall specimen; reaction frames; horizontal displacement transducers; dynamometer; and horizontal loading system.

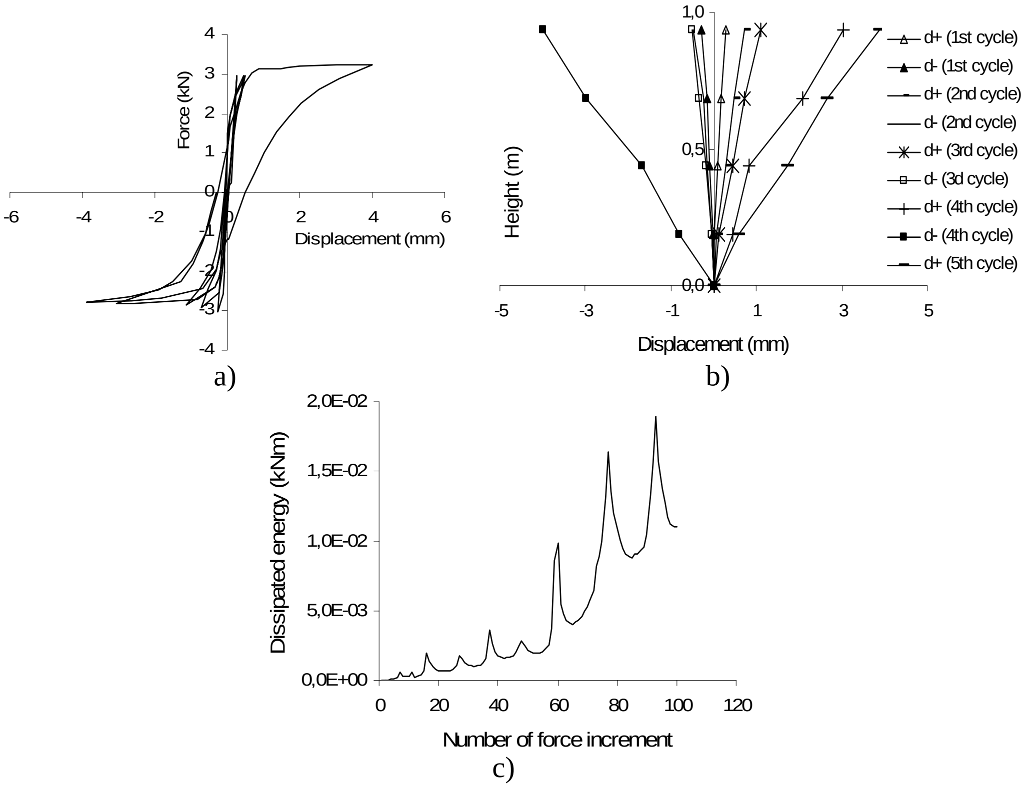


Figure 4. In-plane cyclic laboratory test results: a) applied horizontal force vs top-displacement; b) displacement profiles for peak horizontal forces; c) dissipated energy evolution.

2.5.2 In situ tests

The mechanical behaviour of an adobe masonry wall of a single storey building, *in-situ* conditions, with representation of the real material and support conditions, was studied. In *in-situ* tests, a more rigorous evaluation of the structural behaviour conditions of existing constructions, namely of the connections between perpendicular walls, the influence of roofing structural systems in the global response, as well as the influence of openings and other singularities, can be achieved.

The wall tested *in-situ* conditions had the following dimensions: 2.03m height, 3.73m width and 0.22m thickness. It presented a significant deterioration level, as can be observed in Fig. 6. This wall was subjected to dynamic characterization tests, and to two horizontal cyclic mechanical tests, namely: an in-plane semi-destructive test and an out-of-plane destructive test.

2.5.2.1 Dynamic test

Dynamic tests were conducted on the wall, to estimate its natural frequencies and modulus of elasticity. It was followed the same testing procedure described for the wall tested in laboratory. A frequency of 2.20Hz in the transversal direction was measured. With the measured natural frequency, an average modulus of elasticity of 101MPa was estimated.

2.5.2.2 Cyclic tests

2.5.2.2.1 In-plane cyclic test

For the cyclic tests it was not applied an additional vertical load. Initially, in-plane horizontal cyclic forces were imposed, in cycles of increasing amplitude (Fig. 5). The scheme of the testing layout is similar to the one adopted for the test in laboratory conditions (Fig. 3).

A maximum horizontal force of 10.7kN was applied. This force was not raised to a higher level in order to allow performing the out-of-plane test.

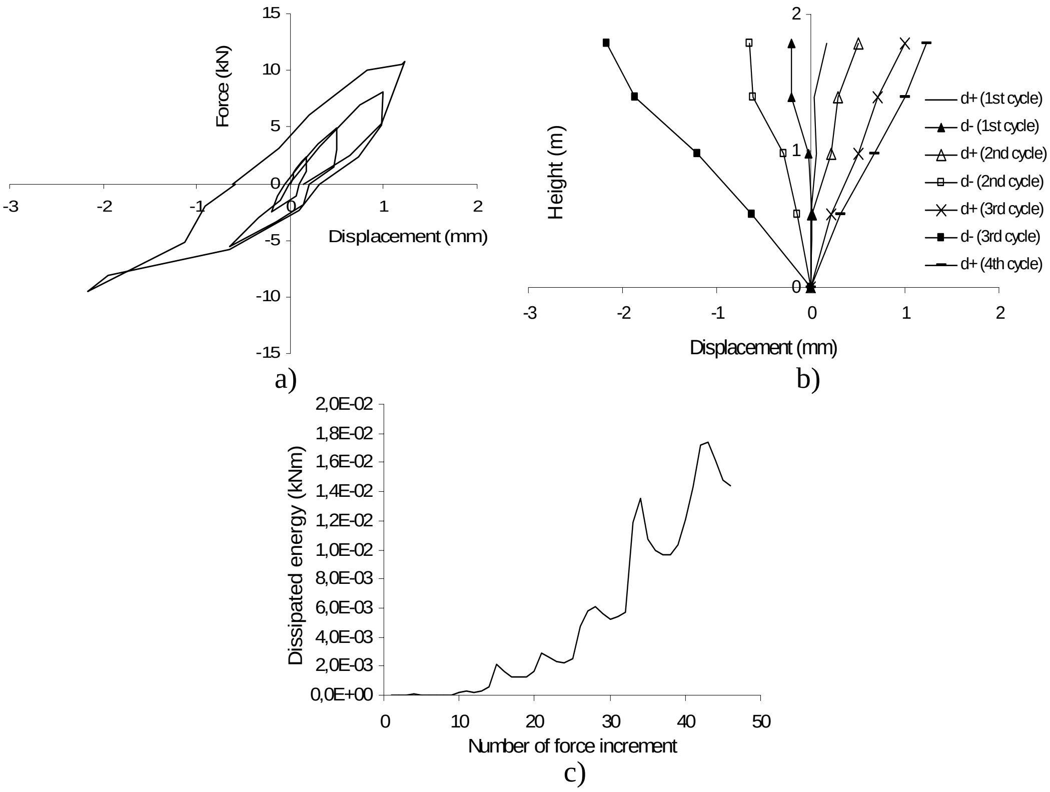


Figure 5. In-plane cyclic in-situ test results: a) applied horizontal force vs top-displacement; b) displacement profiles for peak horizontal forces; c) dissipated energy evolution.

2.5.2.2.2 Out-of-plane cyclic test

In a second phase, adopting a different testing setup (Fig. 6), out-of-plane horizontal forces were applied to the wall, in cycles of increasing amplitude, but without inversion of the force signal, till the collapse was reached (Fig. 7).

A maximum horizontal force of 0.69kN was applied in the out-of-plane direction. The out-of-plane collapse happened for an imposed horizontal displacement of 16mm (approximately 0.95% drift). For the in-plane test similar drift values were imposed for forces 15 times superior without collapse. This, and the fact that the out-of-plane wall strength is less than 7% of the corresponding in-plane strength, demonstrate that this type of adobe wall elements are significantly more vulnerable to out-of-plane actions. The failure mode observed is characterized by a rotation at the base, with damage spreaded through the wall height.

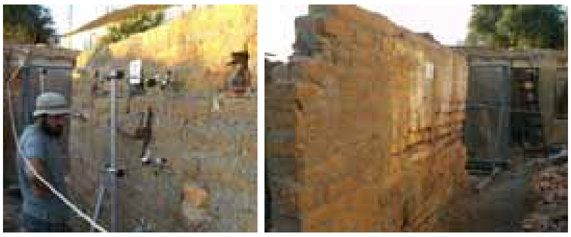
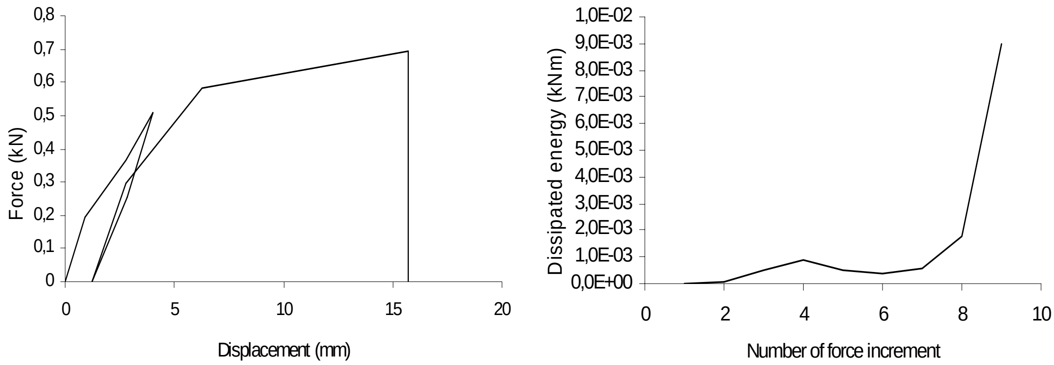


Figure 6. In situ out-of-plane cyclic testing layout: wall; horizontal displacement transducers; and horizontal loading system.



a) b)

Figure 7. Out-of-plane cyclic in-situ test results: a) applied horizontal force vs top-displacement; b) dissipated energy evolution.

3 WORK IN DEVELOPMENT AND FINAL CONSIDERATIONS

The work presented in this paper is part of a project focused in the rehabilitation and strengthening of the adobe constructed park of Aveiro district. In this project, the following methodology is being followed: i) detailed survey of the existing constructions and of the commonest structural and non-structural pathologies; ii) material mechanical characterization; iii) structural characterization and evaluation of structural safety; iv) development of non-structural rehabilitation and structural strengthening solutions. Even though this research is focused in adobe constructions of Aveiro district, it may have repercussions in all regions of Portugal where earth construction appears with a significant expression (namely in Beira Litoral, Algarve and Alentejo), and also in other parts of the World with similar constructive systems.

The most relevant results obtained from the work developed and summarily presented in this paper are: i) strength and stiffness of adobe units and mortars; ii) strength, stiffness, energy dissipation capacity and common collapse mechanisms of adobe masonry walls. These results contribute for the enrichment of a basis of knowledge which can support the interpretation of observed structural pathologies, calibration of numerical models, structural safety assessment, design of strengthening solutions adequate for existing adobe constructions, and even support the design and construction of new edifications.

In addition to the work that has been developed for the mechanical characterization of adobe masonry walls, it has also been initiated work on the study of adobe masonry strengthening solutions. The wall tested in laboratory, presented in section 2.5.1, was strengthened with a wrapping polymeric mesh and coated with a mortar layer with composition similar to the traditionally used in the existing constructions (Fig. 8). The structural response of the strengthened wall when subjected to imposed horizontal cyclic displacements is currently under investigation. The behaviour improvement achieved with the applied strengthening solution will then be evaluated. This analysis is just the first step of a larger work that aims to develop effective strengthening solutions for the existing adobe constructions.

Figure 8. Strengthening of the wall with a wrapping polymeric mesh, and with plaster mortar.

4 ACKNOWLEDGMENTS

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