Study of the Structural Behaviour of Traditional Adobe Constructions

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Abstract

In Aveiro, Portugal, adobe can be found with abundance in rural and urban buildings. Many of these buildings present, however, an important level of structural damage. To face the lack of information concerning the mechanical properties and structural behaviour of adobe masonry, it was developed an experimental campaign at University of Aveiro. The mechanical behaviour of adobe units, mortars and small wallets was studied. Laboratory and *in situ* tests on full-scale walls were performed. Test results reveal the behaviour and structural fragilities of adobe elements, and will help in the assessment of existing constructions, and in the strengthening strategy definition.

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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 in littoral centre, especially in Aveiro district (Oliveira and Galhano 1992; SAT 1992). 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. 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 architectural recognized value, belonging some of them to the "Art Nouveau" style. A more detailed description of the predominant constructive typologies can be found in (Varum et al. 2006a:41-45).

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 concern the seismic safety. Rehabilitation and strengthening of existing adobe constructions have also been disregarded during decades. These constructions are thus not properly reinforced to resist to seismic actions, suffering of various structural anomalies and deficiencies. Structural rehabilitation of the existing adobe constructions is demanded, and constitutes an urgent matter. 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 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 (Hernandez, Barrios, and Pozas 2000: 33-45).

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

For the experimental testing campaign, it was selected a set of adobe samples units representative of different existing adobe construction typologies. Samples 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 adobe samples units. These cylindrical cores had a height of approximately two times the diameter.

A total of 101 cylindrical specimens, 51 proceeding from houses and 50 from land dividing walls, were submitted to mechanical tests: 83 specimens were submitted to compression; and 18 to splitting tests (fig. 2a, fig. 2b, fig. 3).

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 (Varum et al. 2007a).

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. 2c, fig. 2d, fig. 4). 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 (Varum et al. 2007b).

2.5 Tests on full-scale adobe masonry walls

2.5.1 Introduction

It were conducted tests on adobe masonry wall specimens, one in laboratory and another *in situ* conditions, to characterize the mechanical behaviour of this masonry when subjected to cyclic actions , as those induced by earthquakes.

The wall tested in laboratory 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 (fig. 5). During the test, displacements were measured at four points on each side of the wall.

The wall tested *in situ* 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 (fig. 6, fig. 7).

The detailed description of the procedures and of the obtained results can be found in (Varum et al. 2006b).

2.5.2 Laboratory test results

The wall tested in the laboratory was constructed with units taken from an existing construction and with a mortar having a composition similar to the one traditionally used. The boundary conditions at the base of the wall avoid lateral displacements and rotations.

The natural frequencies in the two horizontal directions (transversal and longitudinal) were measured with a seismograph. A frequency of 10.94Hz in the transversal direction was measured and, from it, an average modulus of elasticity of 316MPa was estimated. Subsequently, it was applied a vertical load of 2.86kN on the top of the wall, and in-plane horizontal forces were imposed, in cycles of increasing amplitude, till the collapse was reached. 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.

2.5.3 In situ tests results

The wall tested in situ conditions was firstly subjected to dynamic tests. A frequency of 2.20Hz in the transversal direction was measured and, from it, an average modulus of elasticity of 101MPa was estimated.

For the cyclic tests on the wall it was not applied an additional vertical load. Initially, in-plane horizontal cyclic forces were imposed, in cycles of increasing amplitude. In a second phase, 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. A maximum horizontal force of 10.7kN was applied in-plane. This force was not raised to a higher level in order to allow performing the out-of-plane test. A maximum horizontal force of 0.69kN was applied out-of-plane. The failure mode observed is characterized by a rotation at the base, with damage spread through the wall height.

3. Work in development and final considerations

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.

The work presented in this paper is part of a project focused in the rehabilitation and strengthening of the adobe constructions 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.

In addition to the work presented, the following tasks are presently in development.

i) Detailed survey of the existing constructions and of the commonest structural and non-structural pathologies.

With this task it is intended to characterize the adobe constructions in Aveiro district. It includes a study of the spatial distribution of the constructions (creation of maps with the distribution of the adobe constructions in the district); a historical characterization of the buildings (investigation of construction dates, rehabilitation or other interventions, or abandonment dates, and identification of the constructions that are still currently in use); an architectonical characterization (analysis of the geometry of constructions, thickness of walls, dimensions of adobes, wall openings dimensions and relative position, etc.); a brief structural characterization (identification of roofing and foundation systems, characterization of the quality of the connections between structural elements, structural irregularities, etc.); a characterization of the current conservation state of the existing adobe constructions.

ii) Study of adobe arches mechanical behaviour.

Three adobe arches, with the same span and different geometries, were built in laboratory, with prismatic blocks extracted from adobe units taken from an existing construction and with a mortar with a composition similar to the traditionally used. Each arch was, initially, submitted to vertical symmetrical loading, followed by vertical non-symmetrical loading and, finally, by vertical punctual loading, till collapse was reached. The obtained results are currently under analyze.

iii) 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.

4. Acknowledgments

The authors express their acknowledgments to Tiago Martins, Henrique Pereira, João Almeida and Hugo Rodrigues, for their collaboration in the experimental work here summarily presented, to CIVILRIA, S.A. for the transport of adobe units to the laboratory, to MARTIFER, S.A. for offering the reaction steel frames used in the cyclic tests on adobe walls, and to all persons that kindly opened their own homes for samples collecting and testing on adobe constructions.

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Varum Fig. 1

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Varum Fig. 2a

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Varum Fig. 2b

Color

Varum Fig. 2c

Color

Varum Fig. 2d

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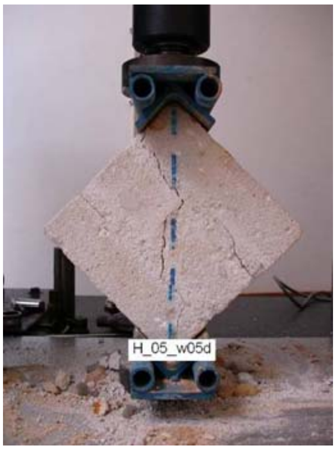

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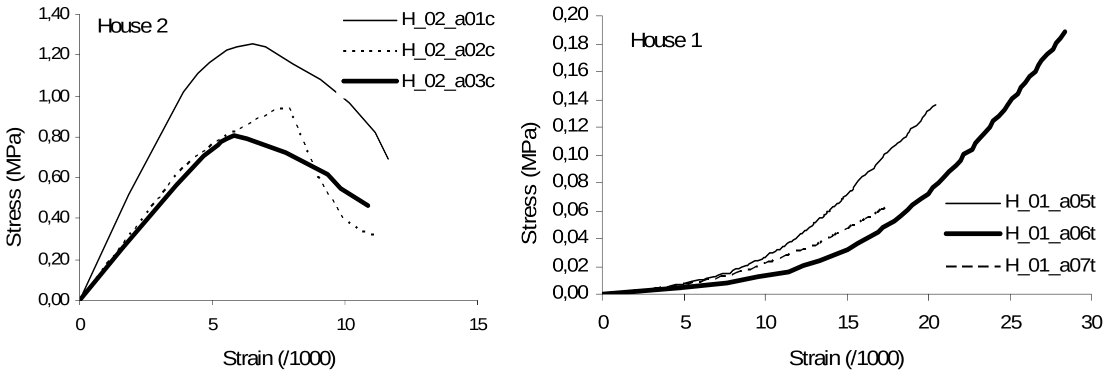

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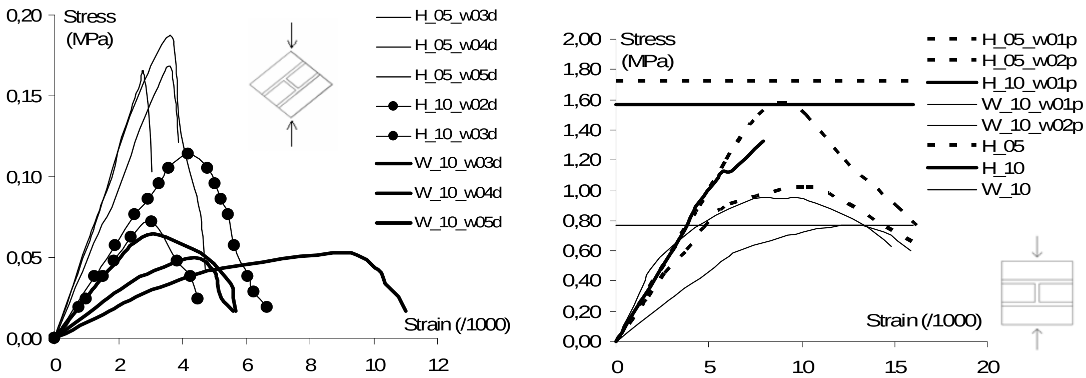

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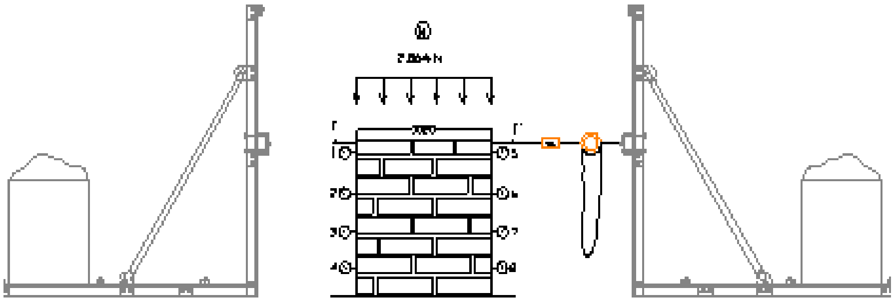

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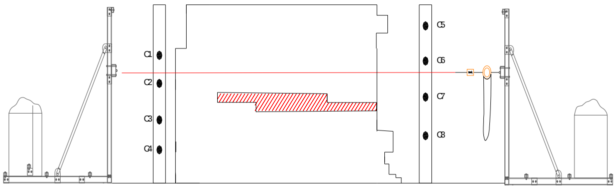

Varum Fig. 7

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Figure 7. *In situ* out-of-plane testing layout: wall; horizontal displacement transducers; and horizontal loading system.

Varum Fig. 8

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

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Figure Captions and Credits

1. Examples of existing adobe constructions in Aveiro district. Photos: University of Aveiro.

2. Simple compression test (a), and splitting test (b) on adobe specimens. Compression test, perpendicular to the bed joints (c), and compression test, diagonal to the bed joints (d), on wallets. Photos: University of Aveiro.

3. Stress vs strain relations obtained in simple compression and splitting tests. Graphs: University of Aveiro.

4. Stress vs strain relation obtained in compression tests on small wallets, diagonal, and perpendicular to the bed joints. Graphs: University of Aveiro.

5. Laboratory testing layout: wall specimen; reaction frames; horizontal displacement transducers; dynamometer; and horizontal loading system. Drawing: University of Aveiro.

6. *In situ* in-plane testing layout: wall; reaction frames; horizontal displacement transducers; dynamometer; and horizontal loading system. Drawing: University of Aveiro.

7. *In situ* out-of-plane testing layout: wall; horizontal displacement transducers; and horizontal loading system. Photos: University of Aveiro.

8. Strengthening of the wall with a wrapping polymeric mesh, and with plaster mortar. Photos: University of Aveiro.

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