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Procedia Engineering 114 (2015) 714 – 721

Procedia Engineering

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1st International Conference on Structural Integrity

Behaviour characterization and rehabilitation of adobe construction

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Abstract

Earth construction is one of the oldest and most widespread construction system. Around 30% of world population lives in earth buildings. About 50% of population in developing countries, including the majority of rural areas, and at least 20% of urban and marginal urban areas, lives in earth buildings.The main general objectives of this study are the behaviour characterisation of adobe and rammed earth constructions along with the research for the development of retrofitting and seismic performance enhancement solutions, considering the relevant earthen heritage built in Portugal. In fact,until the first half of the last century, earth was commonlyadopted as a construction material in Portugal. Adobe was used in almost all types of constructionin littoral centre, particularly in Aveiro region.
The consolidation of the knowledge on this technique and on the mechanical behaviour of adobe masonry will play a fundamental role on the preservation of the earthen built heritage. In addition, it maycontribute to the development of innovative earth construction solutions for new buildings, following current concerns but also respecting structural safety demands, which will allow accommodatingthe increasing interest on this type of building solutions.
The mechanical properties of adobe units and mortars were studied and a series of tests for the characterization of the adobe masonry behaviour were carried out, in the Department of Civil Engineering of the University of Aveiro, namely: (i) bond strength and (ii) joint shear tests. Additionally,a full-scale adobe building model was subjected to monotonic and cyclic horizontal lateral loads until failure. The present paper present the main results and conclusions of the experimental campaign developed.

Peer-review under responsibility of INEGI - Institute of Science and Innovation in Mechanical and Industrial Engineering

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*Keywords:*Adobe masonry, Mechanical characterization, structural behaviour characterization

Peer-review under responsibility of INEGI - Institute of Science and Innovation in Mechanical and Industrial Engineering
doi:10.1016/j.proeng.2015.08.015

Nomenclature

f_m Compressive strength
f_{voi} Initial shear strength
E_m Elasticity modulus
f_{pi}Pre-axial compression strength
f_{vok} Characteristic shear strength

1. Introduction

The earth construction is one of the oldest and most widespread construction system. Around 30% of World population lives in earth buildings. About 50% of population in developing countries, including many rural areas, and at least 20% of urban and marginal urban areas, lives in earth buildings. The main general objectives of this study are the behaviour characterization of adobe earth constructions along with the research for the development of retrofitting and seismic performance enhancement solutions, considering the relevant earthen heritage built in Portugal. In fact, until the first half of the last century, earth was also a commonly adopted construction material in Portugal. Adobe was used in almost all types of construction in littoral Centre, particularly in Aveiro region.

In a recent study developed at the Department of Civil Engineering of the University of Aveiro adobes from existing structures fated to demolition were gathered. The mechanical, physical and chemical properties of adobes and mortars were studied and a series of tests for the characterization of the interface between the adobes and the mortar joints were carried out, namely: (i) bond strength and (ii) joints shear strength tests, as illustrated in Fig. a and Fig. b, respectively. The description of the testing setup and campaign, as well as the experimental results are presented and discussed.Additionally,a full-scale adobe building model was constructed and tested for horizontal monotonic and cyclic lateral loading conditions until its failure.

a) b)

Fig. –Adobe masonry mechanical characterization tests: a) bond strength and b) shear strength.

2. Mechanical characterization of adobe masonry specimens

Adobe unitsand mortar samples were collected in existing structures and tested at the laboratory of the Department of Civil Engineering of the University of Aveiro. Tests to access mechanical, physical and chemical properties of the adobe units and of the mortar were carried out. The traditional method of adobe' production n and the composition of adobe units and mortars were studied. Masonry specimens with different dimensions were built to test the behavior of masonry systems under different demands. To represent the characteristics of the masonry in traditional existing constructions[1]: (i) hydraulic lime mortar similar to the one used in the constructions of Aveiro district has been used; (ii)adobe units collected in existing structures were used, and (iii) adobe masonry samples have been constructed according to the traditional layout and construction methods.

Acid dissolution for the determination of binder/aggregate ratio, wet and dry sieving for the determination of particle size distribution, capillary water absorption and drying tests were carried out [2]. The results obtained by Velosa and Varum (2013) revealed a clear influence of the binder and aggregate on the mortar properties.

To determine the mechanical properties of adobe units and mortars, compressive, flexural and tensile strength and modulus of elasticity tests were carried out [1, 3].A summary of the mechanical properties of the collected adobes and mortars samples from ancient constructions in Aveiro district are given in Table .

Table - Mechanical properties of adobe and mortar specimens [3-5]

	Compressive strengthf_m (MPa)	Flexural strength (MPa)	Tensile strength (MPa)	Modulus of Elasticity E_m(MPa)
Adobe units (from houses)	0.70 to 2.15	-	0.13 tot 0.4	87 to 448
Mortar	1.19	0.4	-	128 to 251

Mechanical characterization of masonry walls was performed on specimens built in the laboratory and tested under different loading demands, namely: (i) compressive strength test, according to BS E 1052-1 [6], on six walls with 0.9x0.9m^2(3 plastered and 3 without plaster); (ii) diagonal tensile strength test, according to RILEM LUMB6[7], on five plastered walls with 0.9x0.9m^2; (iii) out-of-plane flexural strength tests, parallel and perpendicular to bed joints, according to EN 1052-2 [8], on 10 walls (5 tested for flexural demands parallel to the bed joints, and 5 for perpendicular). The obtained test results on masonry specimens are given in
Table .

Table - Mechanical properties of masonry specimens [3-5].

Compression strength (MPa)	0.79 (plastered)
	0.59 (non-plastered)
Shear modulus of elasticity (MPa)	1365 (plastered)
	1086 (non-plastered)
Flexural strength perpendicular to bed joints (MPa)	0.23
Flexural strength parallel to bed joints (MPa)	0.16

The interface between the adobe units and bed mortar joints were also studied, namely in terms of flexural and shear behaviour. Thus, (i) bond strength tests were performed following the bond wrench test method, according to RILEM LUMB3 [9]; and (ii) shear tests were developed to study the interface between the adobe units and bed mortar, according to RILEM LUMB5 [10]; (iii) determination of initial shear strength (f_{voi}) was made, according to BS EN 1052-3 [11]. The setups used for the three tests stated above are shown inFig. .

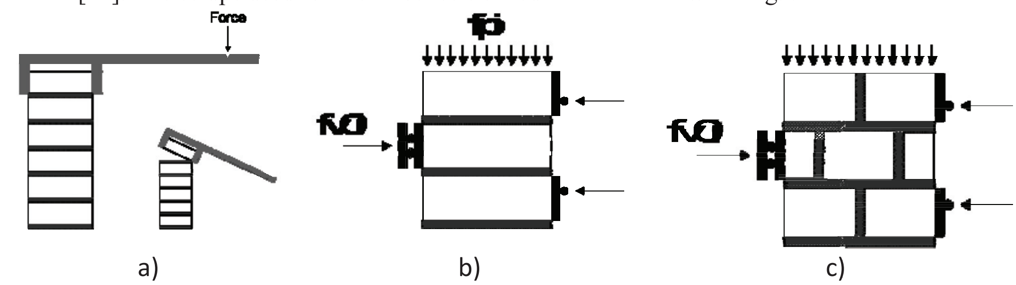


Fig. -Test setup for bond and shear strength, according to: a) RILEM LUMB3 [9]; b) EN1052-3 [12]; c) RILEM LUMB5 [10].

2.1. RILEM Lumb3

In the first phase, one wall of 11 adobe units high wasbuilt with adobes from a land-dividing wall, in the city of Aveiro, with average dimensions of 28x42cm^2, and 11cm thick. The ultimate mean bond strength achieved was 61kPa [1], from a set of 8 valid test results. In a second phase, three other walls of 15 adobe units high were built, using adobes collected in the village of Arcos, municipality of Anadia, district of Aveiro. These adobe units had average dimensions of 32x42cm^2, and a thickness of 11cm. The ultimate mean bond strength achieved was 57kPa for wall 2, 76kPa for wall 3 and 55kPa for wall 4. These average results were obtained from experimental results sets of 9, 6 and 11 adobes,for wall 2, 3 and 4, respectively. The same proportionmortars 1:1:2 (hydrated lime, earth, sand) were used in the construction of all specimens. The average bond strength resulting from all valid tests was 61kPa, as illustrated in Fig. .

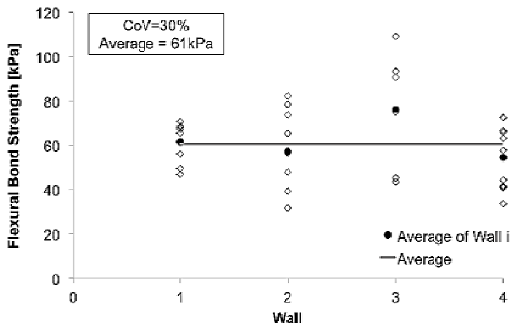


Fig. –Ultimate flexural bond strength.

For wall 2 and wall 3 some of the results were considered not valid, since: (i) the first adobes on wall 2 were used to verify and calibrate the testing setup, (ii) on wall 3 some specimens were damagedby the clamp and the two steel plates used in the tests or (iii) by applying tension on the loading straps, used to stabilize the wall.

After each bond test developed in wall 2, 3 and 4, the failure mode was registered, as shown in

Table . In 84.6% of the cases, the failure occurs at lower brick-mortar interface, for 11.5% at both brick-mortar and for 3.8% at the upper brick-mortar interface. Failure in tension at the mortar joints was never observed. This suggests that the mortar used possess adequate mechanical properties [13].

Table – Type of failure observed in the tests according with EN 1052-5 [14].

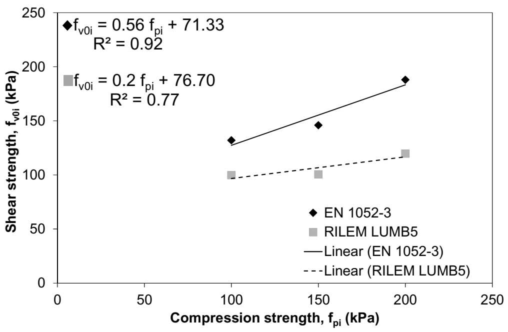
Type of failure	Wall 2	Wall 3	Wall 4
At upper brick-mortar interface	-	-	1
At lower brick-mortar interface	9	4	9
At both brick-mortar interface	-	2	1
Tension failure within mortar	-	-	-

The average flexural bond strength obtained was 61kPa. This testing protocol is very simple and expedite, considering the construction, the execution and data analysis. Although the results shown a pronounceddispersion (CoV=30%) and even if adobes were used from two different sources, the failure mode observed was quite consistent.

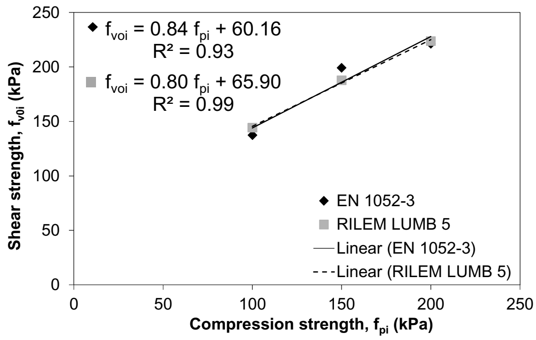
In the literature, namely in VenuMadhava Rao *et al*. [15], it is presented a work using various types of blocks and mortars, and it was obtained an average flexural bond strength of 0.132MPa. These authors concluded that the flexural bond strength increases with the mortar strength, independently of the type of masonry unit used. The moisture content of the masonry unit (at the time of casting) has a significant influence on the flexural bond strength. An optimum moisture content is identified, that leads to a maximum bond strength. Also,Pavia and Hanley [13] concluded that the water retention is the parameter that more influences the bond strength, followed by the water content and, finally, by the hydraulic strength. Therefore, the bond strength is not determined uniquely by the hydraulic strength of the binder. As stated before, the bond strength of masonry is strongly governed by the mortar's water retention: the higher the water retention the strongest the bond.

2.2. RILEM Lumb5 and BS EN 1052-3

The shear strength tests for the characterization of the interface between the adobe units and bed mortar and the determination of initial shear strength (f_{voi}), were characterized in tests according to RILEM LUMB5 (RILEM, 1991a) and EN1052-3 (CEN, 2002) standards. This study was divided in two stages: (i) initially eighteen specimens were built, constructed in sets of 9, to be tested according each standard, and three levels of pre-axial stress were considered: 100, 150 and 200kPa (see Fig. a). The proportionof the mortar used was 1:1:2 (hydraulic lime, earth, sand); (ii) in a second stage,60 specimens were build, in sets of 30 for test following each standard. Again, the same three levels of pre-axial stress (f_{pi}) were considered (see Fig. b) and the mortar used was the same than for the first set of specimens. The specimens were equally divided,for testing, for each level of pre-axial stress. The obtained results, from the two shear tests series explained above, are given in Fig. .



a)



b)

Fig. – Shear strength results in accordance with RILEM LUMB5 (RILEM, 1991c) and EN 1052-3 (CEN, 2002) standards: a) initial test (18 specimens); b) second test (60 specimens).

For the first test series, Fig. a, the mean shear strength achieved according to RILEM LUMB5 [10], for each level of pre-stress was, respectively, 100, 101 and 120MPa. The initial shear strength (f_{voi}), according to BS EN 1052-3 [11], for each level of pre-stress was, respectively, 132, 146 and 188kPa. For the second test seriesFig. b, the mean shear achieved according to RILEM LUMB5 [10] was 144, 188 and 224kPa, and according to BS EN 1052-3 [11] 137, 199 and 221kPa, for each level of pre-stress adopted.

According to Eurocode 6 [16], the masonry characteristic shear strength (f_{vk}) for new constructions can be defined following the Mohr-Coulomb failure criteria $f_{vk}= f_{vk0}+ 0.4\ \sigma_d$, where $f_{vk0}$is the characteristic shear strength with zero compression stress and σ_d is the average compression stress for the respective normal load [17].The characteristic shear strength (f_{vk}) obtained from the specimens tested according with the RILEM LUMB5 [10], for the first and second testseriesare given in Equation 1 and 2, respectively, in kPa:

$$f_{vk} = 61.4 + 0.162\ \sigma_d \qquad \text{Equation 1}$$

$$f_{vk} = 53.0 + 0.816\ \sigma_d \qquad \text{Equation 2}$$

The characteristic shear strength (f_{vk}) obtained fromspecimens tested according with BS EN 1052-3 [11], for the first and second testserieswas, respectively, in kPa:

$$f_{vk} = 57.0 + 0.486\ \sigma_d \qquad \text{Equation 1}$$

$$f_{vk} = 48.1 + 0.890\ \sigma_d \qquad \text{Equation 2}$$

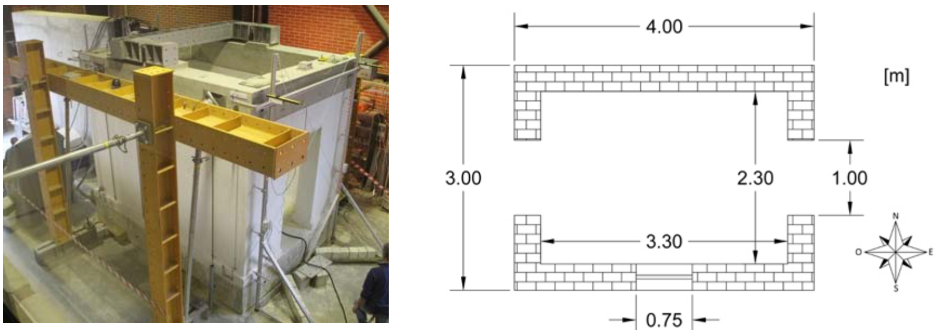
In the second testseries, a higher coefficient of friction was observed. For the tests performed according to RILEM LUMB5 [10] it was observed a difference of about 80% between the results for the first and second test series. Also, larger (45% difference) values were obtained for the second series of specimens tested according with the BS EN 1052-3 [11]. Zimmermann, et al. [18]compiled from the literature characteristic values,obtained by different authors,

of friction coefficient, ranging from 0.560 to 0.880.
The initial shear strength (f_{vk0}) of the masonry depends on the bond strength between the units and the mortar joints, which in turn depends on gluey properties of the mortar of the joint (adhesion), and on the surface quality of the units. Thus, the initial shear strength of the masonry depends on the following important factors: composition and strength of the mortar; workability and water absorption of the mortar; water absorption capacity of the units; the type and quality of the surface of the units being in direct contact with the mortar; the mortar curing conditions (ambient temperature, relative humidity); the age of the mortar at the testing; and shrinkage of the mortar [19]. A high shrinkage of mortar may induce high local stresses that may separate the mortar from the units in certain regions of the bed joints. This phenomenon reduces the adhesion properties. The appropriate selection of the optimum proportionfor the mortar (cement, aggregates and plasticizers) [20] will contribute for the adhesion of the mortar.The shear strength of masonry depends largely on the capacity in terms of friction forces that the horizontal joints can resist, on the tensile strength of the bricks, on the compressive strength of masonry and on the bond strength between bricks and mortar. For the adobe masonry studied, it was observed also that the normal stress level also influences largely the shear strength of the masonry.

3. Full-scale test of an adobe masonry model

3.1. Description of the model

A full-scale adobe model was built and tested for unidirectional (E-W) lateral demands. It was built with adobe units from a land dividing wall, using traditional methods of construction. Figure 4 shows the model and part of the instrumentation used, as well as the dimensions in plan. The model has a rectangular geometry in-plan, with dimensions 3.00x4.00m^2, 2.35m height and an average wall thickness (with plaster) of 0.35m (see Figure 4). The model has three openings: one window located on the south wall and two doors located on the east and west walls. The entire structure was fixed on a rigid foundation, connected to the strong reaction floor. On top of the walls, along the entire perimeter of the model, a reinforced concrete beam, with a total weight of approximately 60kN, was constructed and linked to the adobe walls in order to guarantee the distribution of the horizontal lateral loads and to simulate the other permanent loads (associated to the roof system and respective live-loads).The first bottom row of adobe blocks was laid perpendicular to the walls longitudinal direction and these blocks were linked with cement mortar in order to avoid possible sliding relatively to the concrete base. All subsequent rows of adobe bricks were build following the traditional techniques and using representative mortar for the joints and plaster. The mortar joints had 2cm thicknessand were prepared with a proportion1:1:2 (hydrated lime, earth, sand). An aluminum rigid frame, non-linked to the testing model, was mounted to support all external sensors. Other sensors were installeddirectly on the model in order to register the relative displacement in specific points to characterize the behavior of the model.The imposed lateral demands are applied in the horizontal East-West direction. To avoid global torsion of the model, steel reaction elements were mounted in the north and south walls, linked by rollers minimizing the friction forces (seeFig. a).

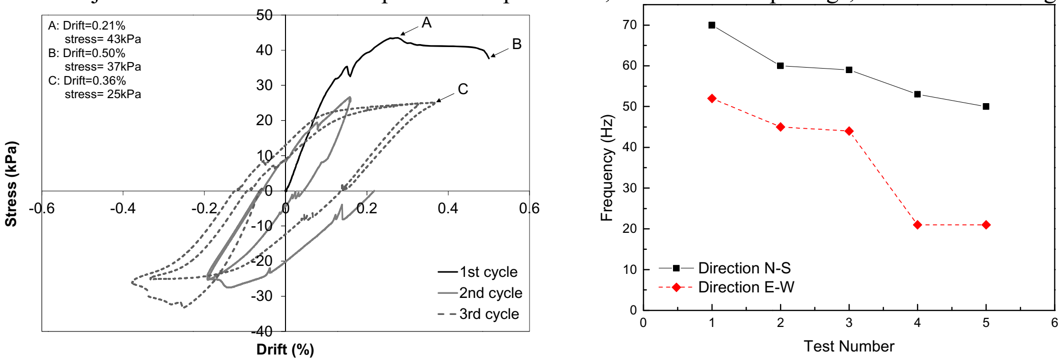


a) b)

Fig. –Full-scale adobe model: a) general view (south and east facade); b) plan view of the model.

3.2. Pushover and cyclic test

The test was performed in two phases: initially one monotonic test ("pushover") was performed followed by a cyclic test. The "pushover" test was developed until a considerable level of damage was installed in the structure, having been recorded a maximum shear strength at the base of 43kPa for a drift of 0.21%. The maximum lateral drift imposed was of 0.50% with a shear stress of approximately 37kPa. After the monotonic test, a cyclic test was performed, and at the 3rd cycle was yielded a shear strength of 25kPa for a drift of 0.36%. The results for both tests, in terms of strength versusdrift is shown in Fig. a.During the tests measurements of acceleration were performed, using an optical accelerometer located on top of the concrete beam, from which are estimated the frequencies of the structure. In Fig. bare represented theevolutions of the model natural frequency in the direction north-south (N-S) and east-west (E-W).The damage pattern observed in the modelrepresents the typical damage in adobe structures when subjected to seismic actions: in-plane X-shapedcracks, and cracks in openings, as illustrated in Fig. .



a) b)

Fig. – Experimental test results: a) Pushover and cyclic stress-drift; b) evolution of the first natural frequency (E-W and N-Z).

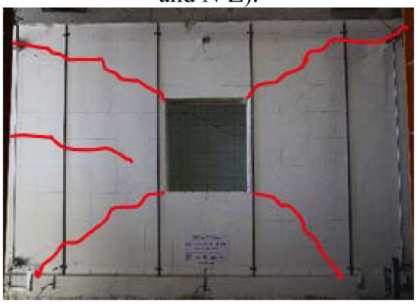


Fig. – Final damagestate.

4. Final comments

The mechanical characterization of the adobe masonry walls was performed in order to study the bond strength between adobe units and mortar using the bond wrench method;and to characterise the shear strength of the interface between the adobe unit and mortar.Also, a full-scale model was constructed and tested in the laboratory, from which it was possible to study the global structural behavior of typical adobe buildingssubjected to monotonic and cyclic lateral demands. It is noticeable that experimental results confirmed the brittle failure that structures with this type of materials tends to exhibit.

Acknowledgements

The work presented was developed within the Be+Earth project, with reference PTDC/ECM-EST/2396/2012, funded by the Foundation for Science and Technology (FCT), Portugal. The collaboration of the engineers Rodrigo Carvalho and Bruno Lobo is acknowledged in the preparation and development of the tests on the adobe model.

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