First South Asia Conference on Earthquake Engineering (SACEE'19)
21-22 February 2019, Karachi, Pakistan

KEYNOTE PAPER

STRUCTURAL ASSESSMENT AND SEISMIC RETROFITTING OF EXISTING ADOBE CONSTRUCTIONS

Humberto Varum, Dora Silveira
University of Porto, Porto, Portugal
hvarum@fe.up.pt

KEYWORDS
Adobe, Earthen Construction, Built Heritage, Mechanical Properties, Structural Behaviour, Rehabilitation, Seismic Retrofitting

1. INTRODUCTION

Earth is one of the oldest building materials, having been used throughout the world since ancient times until the present day (Houben and Guillaud 1994). Nowadays, a significant percentage of the world population still lives in earthen buildings (Minke 2012). There is also a vast earthen built heritage, with many examples inscribed in UNESCO's World Heritage List (Gandreau and Delboy 2012).

In Portugal, adobe, which is one of the most common earthen building techniques, was very used until the mid-twentieth century. At present, there are still many adobe buildings in use, some of which with great cultural and architectural value (Silveira et al. 2013, Oliveira et al. 2013).
Earthen constructions have many advantages, such as low cost and reduced environmental impact (Morton et al. 2005, Shukla et al. 2009). However, these constructions, if not effectively designed and strengthened, may perform very poorly when subjected to seismic loads, as has been observed in recent earthquakes (Blondet 2008, Elnashai et al. 2010, Gautam et al. 2016).

Knowledge on the mechanical properties and structural behaviour of these constructions is thus fundamental to support their adequate rehabilitation and strengthening. In order to contribute to this knowledge, research on the existing adobe constructions in Aveiro district, Portugal, has been developed in the last decade. A brief overview of some of the studies carried out is presented in the following sections.

2. CHARACTERIZATION OF IN-PLANE BEHAVIOUR OF ADOBE MASONRY

A full-scale adobe wall and a full-scale adobe house model were subjected to in-plane cyclic tests (Figure 1). The wall had a double-T horizontal cross-section, representing a wall of a one-storey dwelling connected to two transversal walls. The house model represented a one-storey dwelling with three openings (two doors and one window).

In both cases, a vertical load was distributed along the top of the walls, simulating dead and quasi-permanent live loads. Horizontal cyclic displacements with increasing amplitude were imposed at the top of the structures – in the plane of the web of the double-T shaped wall and in the plane of two parallel walls of the model. For the house model, a monotonic test was conducted first.

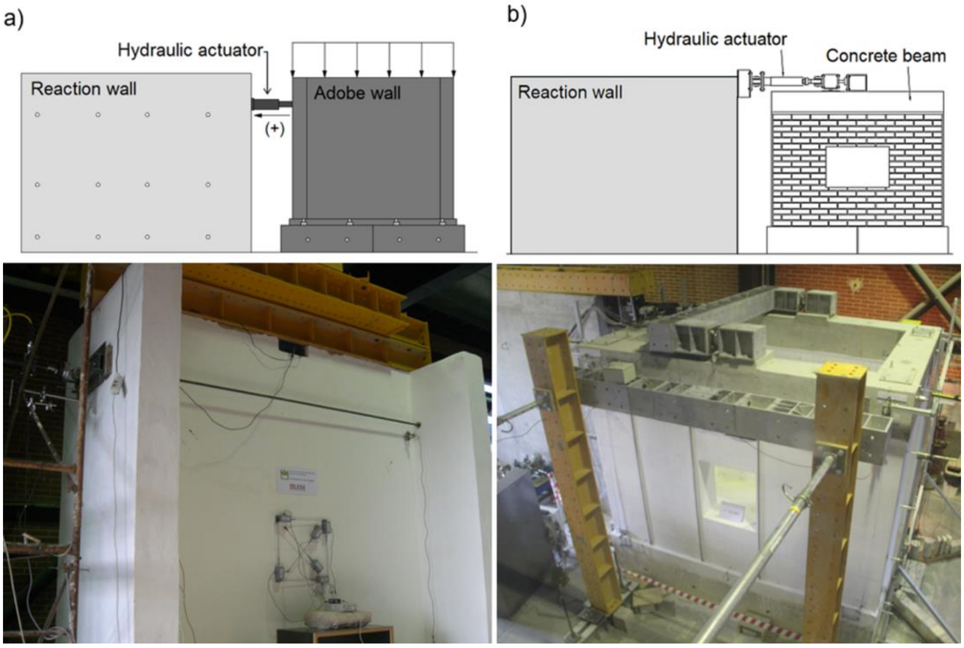

Figure 1: Test setups for: (a) double-T shaped adobe wall (adapted from Silveira et al. (2018)); (b) adobe house model (Varum et al. 2018)

Figure 2: (a) Injection of hydraulic lime into the cracks; (b) application of polymer mesh (Figueiredo et al. 2013)

For the double-T shaped wall, a maximum shear stress at the base of 57.3kPa was reached for a drift at the top of the wall of 0.03%. The initial tangent shear stiffness was 738MPa. For the house model, a maximum shear stress of 45.2kPa for a drift of 0.06% was obtained. In both structures, cracks with an X shape were formed in the walls subjected to in-plane demands. Fragile failure was observed in both cases.

These experimental works provide a contribution to the understanding of the in-plane behaviour of adobe masonry and are presented in more detail in Silveira et al. (2018) and Carvalho (2013).

3. TESTING OF SEISMIC STRENGTHENING SOLUTION FOR ADOBE MASONRY

A damage repair technique and seismic strengthening solution were used on the double-T wall and house model previously tested. To repair the adobe masonry, hydraulic lime grout was pressure-injected into the cracks (Figure 2). Afterwards, the original plaster was removed, and a polymer mesh was applied to the surface of the walls (Figure 2). The walls were then plastered again with lime mortar. The polymer mesh was chosen because it is easily available in the market, low-cost, non-corrosive and flexible.

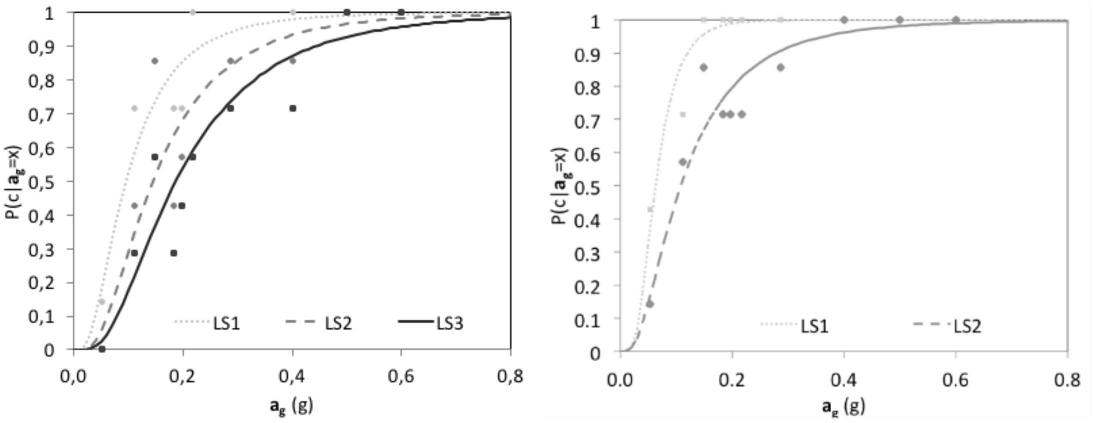

Figure 3: Fragility curves: (a) 'House 28' and (b) 'House 32' (Sarchi et al. 2018)

The double-T wall and house model were then tested again, using the same procedure as in the first test phase. After repair and strengthening, it was observed that

a) The maximum capacity increased 23% for the wall and 14% for the house model;
b) The maximum drift was approximately twice the maximum drift on the unstrengthen structures;
c) There was a significant increase of the energy dissipation capacity;
d) For the double-T wall, it was possible to recover completely the initial stiffness; for the house model, this recovery was almost complete;
e) The reduction of stiffness was smoother than for the original structures.
f) Thus, it can be concluded that the repair and strengthening solutions led to significant behaviour improvements for both structures. The work regarding the strengthening of the double-T wall is presented in more detail in Figueiredo et al. (2013).

4. NUMERICAL MODELLING OF STRUCTURAL BEHAVIOUR OF ADOBE CONSTRUCTION

Two existing buildings in Aveiro district, Portugal, were numerically modelled in order to estimate their structural behaviour when subjected to seismic loads. The material properties of adobe masonry were calibrated with the support of the experimental results obtained in the cyclic in-plane test conducted on the double-T adobe wall, previously described. The method adopted to characterise the adobe masonry and model its nonlinear behaviour followed a total strain crack-based macro-modelling approach, and a pushover analysis was conducted to simulate the experimental test.

The method adopted was effective in characterizing and modelling the behaviour of adobe masonry, since the experimental and numerical results showed a good agreement. Based on the calibrated numerical model, fragility curves for the two selected buildings were determined, using real records selected and scaled to seven intensity measure levels (Figure 3). Two to three damage limit states were considered. A well-known and previously validated nonlinear static procedure

(N2) was used for demand estimation. This work, which brought further insight on the seismic fragility of adobe constructions, is presented in more detail in Sarchi et al. (2018).

5. WORK IN PROGRESS AND FINAL COMMENTS

Some studies on the structural assessment and seismic retrofitting of existing adobe constructions, focused particularly on Portuguese adobe masonry, were briefly presented. This research, however, is an ongoing process, and more work is currently under progress, including:

a) In-situ joint shear tests;
b) In situ out-of-plane tests on adobe walls using airbags;
c) Shaking table tests on a full-scale adobe house model.

The knowledge obtained from research on this topic is fundamental to support the assessment, rehabilitation and seismic retrofitting of adobe constructions, contributing to their protection and safety.

ACKNOWLEDGMENTS

The authors express their acknowledgments to: all the persons who kindly opened their homes for the collection of adobes; Câmara Municipal de Aveiro and Câmara Municipal da Murtosa; the staff of the Civil Engineering Laboratory of the University of Aveiro; and the Laboratory of Earthquake and Structural Engineering (LESE) of the Faculty of Engineering of the University of Porto.

This work was developed within the framework of the project “SafEarth: Seismic protection of earthen construction heritage”, with reference POCI-01-0145-FEDER-016737 (PTDC/ECM-EST/2777/2014), financed by FEDER funds through “Programa Operacional Factores de Competitividade” (COMPETE) and by National Funds through “Fundação para a Ciência e a Tecnologia” (FCT). The funding provided is kindly acknowledged.

REFERENCES

Blondet M. (2008) *Behavior of earthen buildings during the Pisco Earthquake of August 15, 2007,* Earthquake Engineering Research Institute, Oakland.

Carvalho R. (2013) *Caracterização de comportamento de estruturas em alvenaria de adobe*. M.S. dissertation, University of Aveiro, Aveiro.

Elnashai A.S., Gencturk B., Kwon O.S., Al-Qadi I.L., Hashash Y., Roesler J.R. et al. (2010) *The Maule (Chile) earthquake of February 27, 2010: consequence assessment and case studies, MAE Center Report No.10-04*, Mid-America Earthquake Center, Urbana.

Figueiredo A., Varum H., Costa A., Silveira D., Oliveira C. (2013) Seismic retrofitting solution of an adobe masonry wall. *Mater Struct*, 46(1-2), 203-219.

Gandreau D., Delboy L. (2012) *World heritage inventory of earthen architecture – 2012 WHEAP, World Heritage Earthen Architecture Programme,* T. Joffroy, ed., CRAterre-ENSAG, Grenoble.

Gautam D., Rodrigues H., Bhetwal K. K., Neupane P., and Sanada Y. (2016) Common structural and construction deficiencies of Nepalese buildings. *Innovative Infrastructures Solutions*, 1(1).

Houben H., Guillaud H. (1994) *Earth construction: a comprehensive guide*, ITDG Publishing, London.

Minke G. (2012) *Building with earth: Design and technology of a sustainable architecture*, Birkhauser Verlag AG, Basel.

Morton T., Stevenson F., Taylor B., Smith N. C. (2005) *Low cost earth brick construction. 2 Kirk Park, Dalguise: Monitoring & Evaluation*, Arc, Chartered Architects, Fife.

Oliveira C., Varum H., Costa A. (2013) Adobe in Art Noveau constructions in Aveiro. *Proc., Art Noveau & Ecology, Aveiro Historical Lab*, Aveiro, 26 January 2013.

Sarchi L., Varum H., Monteiro R., Silveira D. (2018) Seismic behavior of two Portuguese adobe buildings: Part II - Numerical modelling and fragility assessment. *Int J Archit Herit*, 12(6), 936-950.

Shukla A., Tiwari G.N., Sodha M.S. (2009) Embodied energy analysis of adobe house. *Renew Energ*, 34(3), 755-761.

Silveira D., Varum H., Costa A., Lima E. (2013) Levantamento e caracterização do parque edificado em adobe na cidade de Aveiro. *digitAR*, 1, 102-108.

Silveira D., Varum H., Costa A., Pereira H., Sarchi L., Monteiro R. (2018) Seismic behavior of two Portuguese adobe buildings: Part I - In-plane cyclic testing of a full-scale adobe wall. *Int J Archit Herit*, 12(6), 922-935.

Varum H., Silveira D., Costa A., Vicente R., Fonseca J. (2018) Characterisation of existing adobe constructions and development of effective repair and seismic retrofit solutions. *Transsylvania Nostra Journal*, 45, 6-19.