Testing, Analysis and Building Technology for Industrialized Reinforced Masonry Shells

Paulo B. Lourenço, Joaquim O. Barros, Juliana T. Oliveira
Universidade do Minho, Guimarães, Portugal

Abstract

This paper addresses briefly the research carried out at University of Minho, regarding an industrialized solution for reinforced masonry shells. The aspects of material characterization are presented, together with a contribution for a full prefabrication process. Aspects related to numerical analysis and structural design can be found in [1-3].

Introduction

Usage of clay tiles for reducing the weight of structural concrete slabs is traditional in the South of Europe. These elements are less usual in shells and the technological process of shell construction itself is expensive today due to intensive labor and special formwork requirements. Nevertheless, vaulted or shell construction is appealing from the point of view of architectural heritage and shape. A possible solution to regain market for masonry vault construction is the inclusion of reinforcement and the use of innovative technologies based in semi- of full prefabrication processes. The solution encountered within the framework of the ISOBRICK project is based in a stacked configuration of masonry units, with reinforcement in the joints, with a reinforced concrete or mortar screed on top.

The present paper contributes to the aforementioned objective by characterizing experimentally the components of the ISOBRICK shells and by detailing a successful attempt to develop a full prefabrication strategy for masonry vaulted construction.

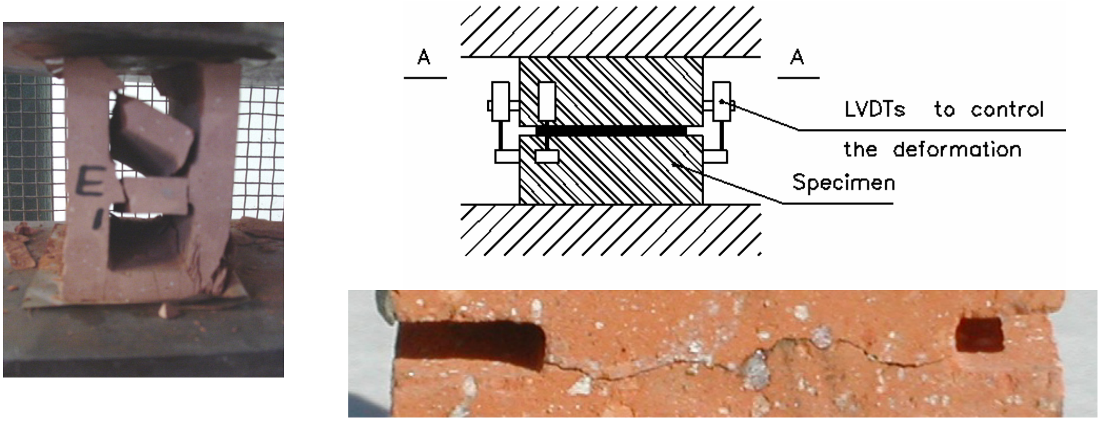
2. Experimental testing

The experimental testing carried out at University of Minho included the following aspects: (a) compression and tension of bricks; (b) shear of masonry joints; (c) out-of-plane testing of masonry plates; (d) tension tests of expanded metal sheet [4].

The clay units have been produced by J. Monteiro & Filhos (Portugal) for this research project. The dimensions are $215 \times 100 \times 65$ mm^3, with two longitudinal holes of 25×25mm^2. The possibility of a full prefabrication process was sought in Portugal, and the joints were filled with micro-concrete made of cement, sand, gravel (size 5-10mm) and a superplastifier.

2.1 Uniaxial compression and tension of bricks

Figure 1 presents the failure mechanisms of bricks, see [5] for details. Figure 2 presents typical stress-elongation diagrams from uniaxial tensile tests. The response exhibits softening characterized by a gradual decrease of mechanical resistance under a continuous increase of deformation, defined by the fracture energy G_f necessary to open a unitary area of crack.



(a) (b)

Figure 1 – Testing of bricks: (a) uniaxial compression in full size specimens with ground faces; (b) uniaxial tension in small samples with notches.

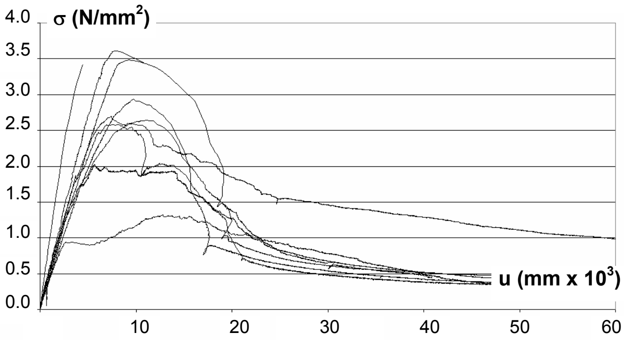
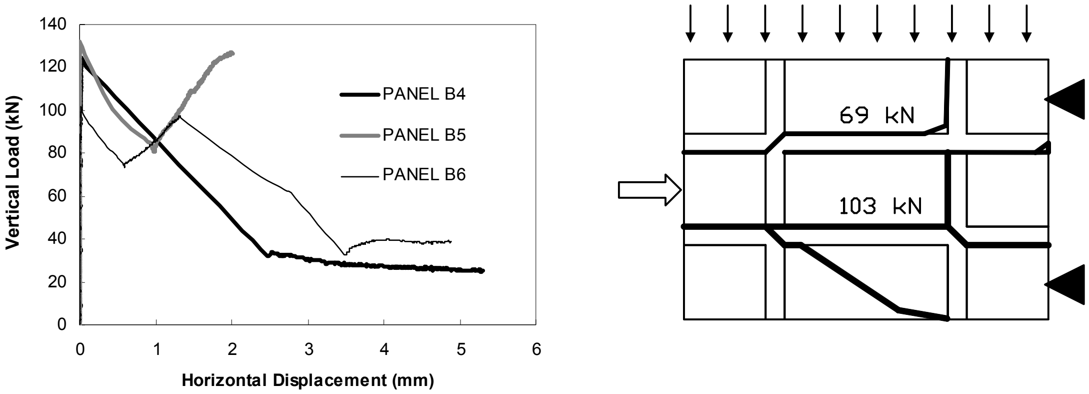


Figure 2 – Typical stress-elongation response for bricks under uniaxial tension.

Due to the difficulties of ensuring material and geometric homogeneity amongst brick specimens, a large scatter on the tensile strength and fracture energy was obtained. A tensile strength of about 3 N/mm^2 and a fracture energy of about 0.08N/mm was obtained. Slightly higher strength was obtained in the extrusion direction.

2.2 Shear

The triplet test was used successfully to assess the shear behavior of stack-bonded masonry with micro-concrete joints. Standard masonry bond is the running bond, which results in discontinuous vertical joints. Typical failure modes were obtained and the shear strength seems to adequately follow Coulomb friction law. Therefore, both the use of a stacked configuration and the use of micro-concrete for the joints are acceptable. The mechanical strength parameters that characterize the interface of the joints are a cohesion of 1.39 N/mm^2 and a tangent of the friction angle of 1.03. Additional information can be obtained from [6].



(a) (b)

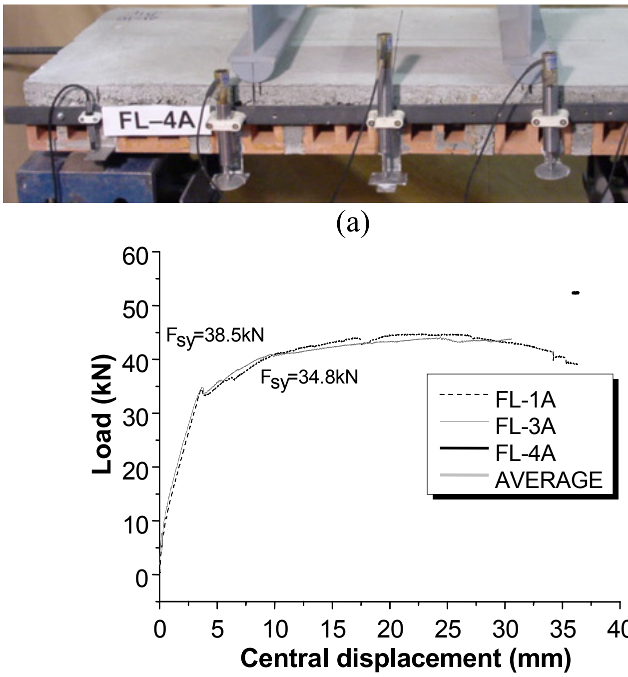
Figure 3 – Typical results for triplet test in stacked bond masonry: (a) force-displacement response; (b) failure mechanism.

2.4 Flexural tests

To assess the flexural behavior of reinforced masonry shells submitted to positive and negative bending moments, four-point bending tests on representative panels were carried out, see Figure 4a and [7] for full details.

In panels with micro-concrete layer at top surface, the highest stiffness and maximum load carrying capacity occurred in panels with the higher number of longitudinal concrete joints and steel bars of larger yield and ultimate stress. In these panels, with brick holes in the panel longitudinal direction, interlock due to micro-concrete penetration into the extremities of these holes provided higher resistance to crack propagation in the interfaces, which resulted in cracks crossing the bricks. In the other panels, the cracks were initiated at the interfaces between bricks and transversal concrete joints. Both series of this type of panels failed in a bending ductile mode, see Figure 4b. As micro-concrete was applied without external compacting energy, it had low compacity, which resulted in sliding between reinforcing bars and surrounding concrete. This indicates that, with concrete joints of 25 mm width, it is difficult to ensure good bond properties for the reinforcement, mainly in joints with steel bars of ϕ8 mm.

The panels with the concrete layer at panel bottom surface had a low load bearing capacity and a more fragile failure mode. This means that loading configurations inducing negative moments are the most unfavorable for the proposed shell structural system. The results also indicate that brittle shear failure modes have low probability to occur.



(a)

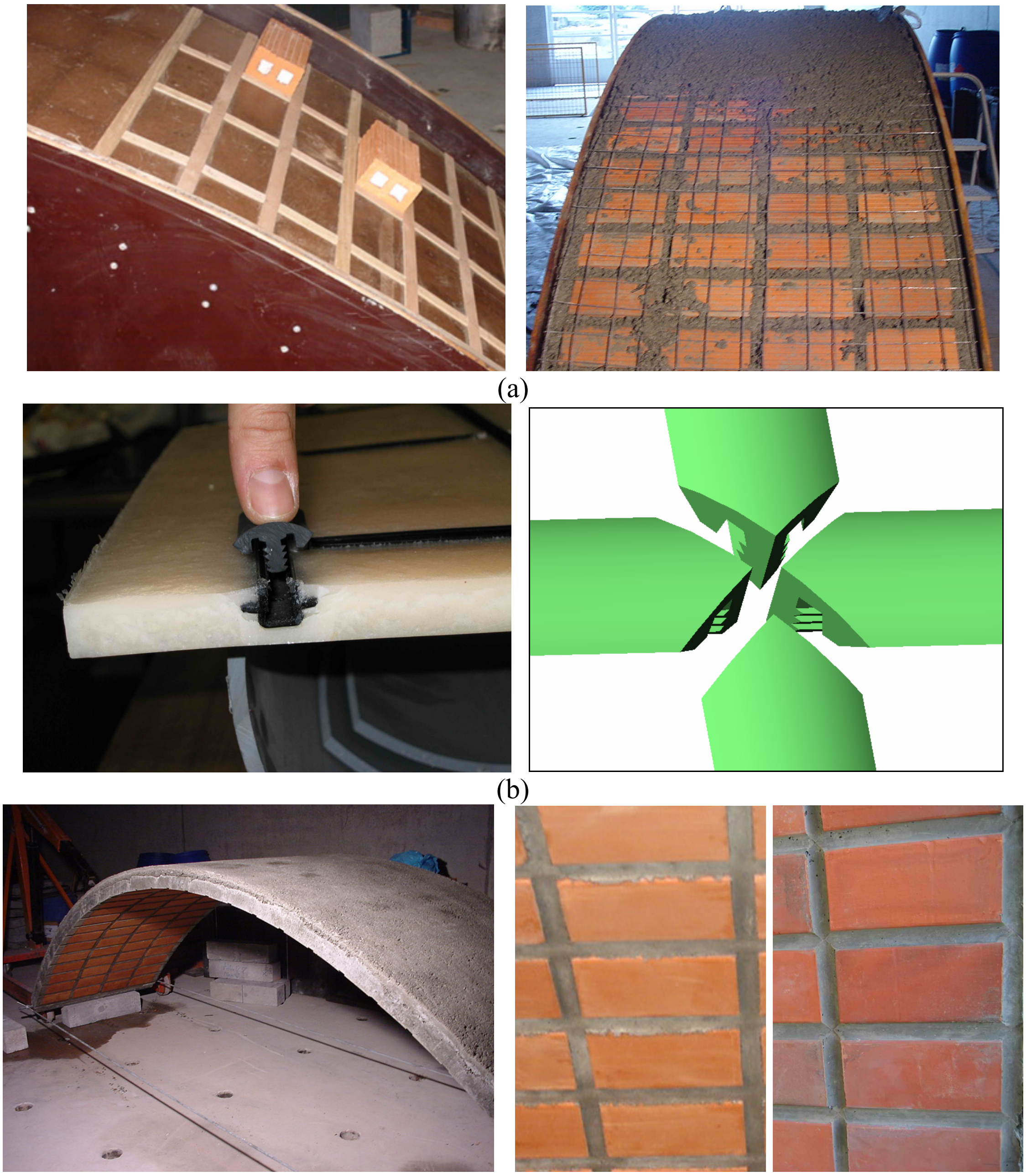
(b)

Figure 4 – Results for the flexural tests: (a) test set-up; (b) typical load-displacement diagram.

3. Construction process

Two reinforced masonry shell models were built at Minho University, as a result of an attempt to define a full prefabrication process. For this purpose, a formwork of catenary shape with a span of 4 m and a rise of 1 m was built.

Two different strategies were considered for the shell construction with the aim of ensuring masonry joints of equal width, avoiding brick slipping and providing proper finishing of the joints: (a) timber strips with a cross section of 3 mm height and 25 mm width fixed to the base of the mould, see Fig. 5a; (b) a special developed polymer mould, see Fig 5b. In both cases, the final results were excellent with no stains in the facing units and masonry joints properly filled, see Fig. 5c. It is noted that tailored micro-concrete or mortar with a convenient slump or flow must be selected in all cases, see [8,9] for details. It is also noted that the mould with the timber strips can be re-used a low number of times, whereas the polymer mould can be re-used for hundreds of applications. The polymer mould has been designed with the following specifications, not fulfilled by commercial products: (a) allow different finishings of the joint; (b) accommodate large geometrical tolerances of the units (up to ± 3 mm). These requirements explain the need of a profile insert, see Fig. 5b, and control the stiffness and the material adopted for the insert.



(a)

(b)

(c)

Figure 5 – Full prefabrication technology for reinforced masonry shells: (a) mould with timber strips; (b) specially designed polymer mould; (c) final aspect of the shell.

Acknowledgements

The present work was partially supported by GROWTH project GROW-1999-70420 “ISO-BRICK” funded by European Commission. The third author gratefully acknowledges the PhD grant from the Portuguese Science and Technology Foundation (FCT).

References

[1] Palácio, K., Lourenço, P.B., Barros, J.O.B., Contribution to Design Criteria for Industrialized Masonry Vaults, Report 03-DEC/E-10, Universidade do Minho, 50 pp (2003). Available from www.civil.uminho.pt/masonry

[2] Lourenço, P.B., Palácio, K., Prieto, F., Implementation of a constitutive model for masonry shells as a stand-alone subroutine. Report 03-DEC/E-13, Universidade do Minho, 50 pp (2003). Available from www.civil.uminho.pt/masonry

[3] Palácio, K., Lourenço, P.B., Barros, J.O.B., Numerical Modeling of single shell roofs, Report 03-DEC/E-21, Universidade do Minho, 42 pp (2003). Available from www.civil.uminho.pt/masonry

[4] Oliveira, J.T., Barros, J.O., Lourenço, P.B., Marques Pinho, A., Uniaxial testing of expanded metal sheet, Report 02-DEC/E-11, Universidade do Minho, 31 pp (2002). Available from www.civil.uminho.pt/masonry

[5] Lourenço, P.B., Barros, J.O., Almeida, J.C., Characterization of masonry under uniaxial tension, Report 02-DEC/E-12, Universidade do Minho, 24 pp (2002). Available from www.civil.uminho.pt/masonry

[6] Lourenço, P.B., Barros, J.O., Oliveira, J.T., Shear testing of stack bonded masonry, Construction and Building Materials, 18, p.125-132 (2004)

[7] Oliveira, J.T., Barros, J.O., Lourenço, P.B., Bonaldo, E., Flexural behavior of reinforced masonry panels, Report 02-DEC/E-10, Universidade do Minho, 70 pp (2003). Available from www.civil.uminho.pt/masonry

[8] Barros, J.O., Lourenço, P.B., Torres, J.O., Bonaldo, E., Task T3.2 – Contribution for a full prefabrication approach of masonry reinforced shells, Relatório 03-DEC/E-05, Universidade do Minho, 15 pp (2003). Available from www.civil.uminho.pt/masonry

[9] Faria, P., Mould for the construction of architectural elements of brick/concrete, Report, Universidade do Minho, 31 pp (2004)