JURE RADIĆ
VLATKA RAJČIĆ
ROKO ŽARNIĆ

EDITORS

HERITAGE PROTECTION

CONSTRUCTION ASPECTS

INTERNATIONAL CONFERENCE
PROCEEDINGS

EUROPEAN CONSTRUCTION
TECHNOLOGY PLATFORM

CONTENTS

Keynotes

1. Assesment, monitoring, diagnosis

2. Materials for heritage protection

3. Intervention techniques

4. Energy and environmental aspects

5. Management, exploatation and maintenance

6. City and territorial aspects

HL1 Education, training & Ethics

HL2 Technical Standards and Specification

HL3 Preservation of artworks

HL4 Socio-Economic Aspects

HL5 Disaster Prevention and Risk Management

HL6 Communication and Dissemination

CONFERENCE AND BROKERAGE EVENT
THE CONSTRUCTION ASPECTS OF BUILT HERITAGE PROTECTION
Dubrovnik, Croatia, 14 – 17 October 2006

EXPERIMENTAL BEHAVIOUR OF THREE-LEAF STONE MASONRY WALLS

D. V. Oliveira* & P. B. Lourenço**

*Assistant Professor, University of Minho, Portugal
danvco@civil.uminho.pt

**Associated Professor, University of Minho, Portugal
pbl@civil.uminho.pt

Key words: Three-leaf masonry walls, FRP strengthening

Abstract: *A major part of historical structures, currently in European urban centres, is built with stone masonry walls, often constituted by multiple leaves. A common typology encountered is the three-leaf stone masonry wall, which is characterized by a substantial presence of voids in the inner leaf and prone to brittle collapse mechanisms. Nevertheless, the knowledge of the mechanical behaviour of three-leaf masonry walls and guidelines for proper design and control of the interventions are limited. A comprehensive experimental study on the structural behaviour of three-leaf stone masonry walls has been planned at University of Minho, considering different strengthening techniques using GFRP (glass fibre reinforced polymer) materials, pozzolana-lime based mortar and lime-based grout. In the paper the first experimental results on materials and three-leaf stone masonry walls are presented and discussed.*

EUROPEAN CONSTRUCTION TECHNOLOGY PLATFORM

Structural Engineering Conferences

University of Zagreb
Faculty of Civil Engineering

University of Ljubljana
Faculty of Civil and Geodetic Engineering

1. INTRODUCTION

A large part of historical structures, currently in the European urban centres, was built with stone masonry walls, frequently constituted by multiple leaves having little or no connection between them, and built with various materials, different types of stones and usually poor mortars. The common typology encountered is the three-leaf masonry wall, which is characterized by a substantial presence of voids in the inner leaf[1] and prone to brittle collapse mechanisms. The mechanisms consist in the detachment of the external leaves and the out-of-plane material expulsions, both under compression and shear-compression loading[2, 3].

Nevertheless, the knowledge of the mechanical behaviour of three-leaf masonry walls and guidelines for proper design and control of the interventions are limited. Such limitations lead to rehabilitation design of masonry buildings performed with inadequate reliable studies. Moreover, for conservation purposes an increased sensitivity in the choice of consolidation materials is required. The materials should be mechanically, physically and chemically compatible with the original ones to assure effectiveness and durability of the strengthening and repair interventions[2, 4].

A comprehensive experimental study on the structural behaviour of three-leaf stone masonry walls has been planned at University of Minho. The experimental campaign consists in sixteen stone masonry walls designed for compressive tests in different strengthening conditions: transversal connections of the external leaves by GFRP (glass fibre reinforced polymer) ties, bed joint structural repointing with GFRP rods and a combination of the two previous techniques. Further developments will consist in the application of the injection technique with lime-based grout applied both individually or combined with the previous strengthening techniques. The aims of the planned research are to characterize the behaviour of the stone masonry three-leaf walls under different strengthening configurations and developing a suitable contribution for analytical models and design guidelines. In the paper the experimental work plan and the first experimental results on materials and three-leaf stone masonry walls are presented and discussed.

2. ADOPTED STRENGTHENING TECHNIQUES

A brief description regarding the three main different reinforcing techniques adopted in the present work is hereafter given.

The transversal tying through the thickness of multi-leaf walls is aimed to improve the connection among the leaves, in particular between the external leaves, in order to reduce the transversal deformation. For this purpose, stainless steel bars or FRP bars can be used.

The bed joint structural repointing has been recently considered for the strengthening and repair of historic brick structures exhibiting horizontal dilation due to creep damage[5]. When stone masonry walls show a regular bond arrangement of the units with aligned horizontal bed joints, this technique can also be applied on such walls.

The injection is aimed to improve the weakness of the internal core, filling its voids, and to improve its adherence to the external leaves. Several studies have been performed in the last years concerning the feasibility of this technique and its mechanical, physical and chemical compatibility[6, 7]. Nowadays the trend is using grout mainly based on lime, in particular when the restoration works deal with historical constructions.

3. CHARACTERIZATION OF THE WALL COMPONENTS

3.1. Stone

The major part of ancient buildings located in the North of Portugal is made of granite. Therefore, in order to assure an effective representativeness, a granitic stone, locally available, was used in all tests concerning the behaviour of three-leaf walls. Aiming at characterizing its mechanical behaviour, six cylindrical stone specimens of ∅100×200 mm^2 were tested. A monotonic compressive load was applied under displacement control in a static fashion until the complete loss of strength capacity was attained. In order to assess the Young's modulus and Poisson's ratio, four strain gauges attached to each specimen, equally spaced around the perimeter and placed at mid-height, were used.

Considering all stone specimens tested, an average compressive strength of 52.2 MPa was obtained, whereas for the mechanical properties, averages values of 20.6 GPa and 0.24 (assessed within the [30%–60%] stress range) were computed for the Young's modulus and the Poisson's ratio, respectively. These values can be considered typical of the material[8]. For all the three measured parameters, coefficients of variation around 20% were observed, which can be considered perfectly acceptable given the nature of the material used.

3.2. Mortar

For a reliable experimental simulation of the structural behaviour of ancient masonry components, the selection of an appropriate mortar is a key issue in the sense that ancient mortars and binders were completely different from the ones used nowadays. Aiming at obtaining a low strength compressive mortar and representative of old existing mortars, a pozzolana-lime based mortar was used to build the prisms and walls. Based on a preliminary composition study developed by the authors, a binder/sand ratio equal to 1:3, and a water/binder ratio equal to 0.8 were selected (all ratios in weight), see Oliveira et al.[9] for further details. In addition, a pozzolanic drier (10% on binder weight) was used to improve the construction procedure of the walls. In order to assess the mechanical behaviour of mortar, cubic specimens of 50×50×50 mm^3 were sampled during the construction of the walls and tested under compressive loading at the age of 7, 28 and 90 days. Average compressive strengths of 0.5 MPa, 2.9 MPa and 2.2 MPa were observed at the aforementioned ages, respectively. Each value was obtained considering the average of three specimens. Considering the available data in literature, the adopted mortar composition can be considered representative of ancient mortars in terms of compressive strength.

3.3. External leaf

In order to obtain a good insight into the structural behaviour of each one of the leaves, a set of prisms representing both the external and internal layers were built. The stone masonry prisms were composed of three stones and two masonry joints, built carefully in order to simulate as much as possible the external leaves. During the construction of the walls, in both series a total of nine prisms with average dimensions of 150×150×320 mm^3 (height/width ratio of 2.1) were built and tested under uniaxial compressive loading and at a displacement control rate of 10 μm/s. The prisms were tested after about 60 days of curing.

An average compressive strength of 7.7 MPa and a coefficient of variation of 28% were computed. As reported in the literature, see Oliveira et al.[10] and others, the use of several stone pieces assembled in one prism is likely to originate lower maximum strength values in comparison to the monolithic stone specimens.

Here, a reduction of 85% was observed when shifting from stone specimens to stone masonry prisms. However, the high coefficient of variation found, caused by different average values rising from the two series, seems to indicate that such a reduction is also due to the workmanship effect and that more research is needed in order to assess the effect of mortar joints.

3.4. Internal leaf

Typically, the internal leaf of multi-leaf walls is composed of poor materials, as wastes obtained from the rough-shaping of the stones placed in the outer leaves, and mortar.

In this work, the internal leaves, as well as the specimens aimed to describe the structural behaviour of these leaves, were built with granite scabblings poured into alternate layers with mortar and avoiding any compaction in order to create a certain amount of internal voids. During the construction of the walls, a total of six cylindrical specimens of $\varnothing 150\times300$ mm^2 were built following the same procedure used for the internal leaves.

After a period of approximately 60 days of curing, the specimens were tested under uniaxial compressive loading at a displacement control rate of 5μm/s. From the tests, an average compressive strength of 292 kPa and a coefficient of variation of 46% were obtained. As expected, a very low strength was achieved given the weak bond between mortar and granite scabblings. As happened with the prisms representative of the external leaf, the average compressive strength of the specimens representative of the internal leaf found in each series shows an important variation (405 kPa and 178 kPa), which justifies the high coefficient of variation. In addition, the coefficient of variation found in each series was below 25%, which seems to indicate that within a same series the mason followed a same procedure. These differences are most likely due to differences in the construction process, which again stresses the important role of workmanship. Considering the aforementioned average values, the compressive strength of the internal leaf is approximately 4% of the external leaf compressive strength. This clearly indicates that in the multi-leaf walls, most of the load is transmitted by the external layers.

3.5. FRP bars and injection material

The wall strengthening, to be discussed later in the paper, was achieved by means of transversal tying of the external walls by resorting to GFRP bars anchored along the thickness of the external leaves. This means that the bond between the bar and the injected grout was considered enough to transmit the load from the leaf to the GFRP rod. In addition, the tensile strength of the GFRP bar (a value of 760 MPa was provided by the manufacturer) is high enough to prevent its brittle tensile failure.

The holes drilled to insert the GFRP bars were injected with a commercial lime-based grout able to fill in the hole as well as the surrounding voids. In order to assess the mechanical behaviour of the grout injection, cubic specimens of $50\times50\times50$ mm^3 were sampled during the injection of the holes and tested separately under uniaxial tensile and compressive loading. The grout specimens were tested after approximately 30 days of curing, raising an average compressive strength of 17.6 MPa and an average tensile strength of 291 kPa.

4. EXPERIMENTAL TESTS ON THREE-LEAF WALLS

4.1. Wall specimens

Wall specimens of 600 mm long, 300 mm thick and 1100 mm high have been designed. The external layers have a thickness of approximately 100 mm and they are made of roughly shaped granite stones bonded with lime-based mortar and aligned bed joints, see Figure 1. No transversal connection between the external layers by means of stone blocks was provided. The granite used to build the specimens is from a quarry in the Northern part of Portugal and the mortar is composed by a binder of lime and pozzolana. The mechanical properties of these materials have been discussed in detail in section 3.

4.2. Test program

The test program on walls is summarized in Table 1, being based on compressive tests on sixteen three-leaf walls, strengthened by resorting to different techniques: transversal tying with GFRP rods, bed joint structural repointing with GFRP rods and the combination of the two previous techniques. During the experimental program, the strengthening techniques are not applied consecutively on fixed series of walls, but they will be spread over the series of walls in order to minimize the influence of the construction phase, instead. In fact, the first two series of walls (see Table 2) have concerned a first characterization of the behaviour of plain and transversal tied three-leaf stone masonry walls. After approximately 60 days of curing the walls were placed between two steel plates lightly post-tensioned by means of steel bars and transported to the testing frame, see Figure 1(a).

(a) (b) (c)

Figure 1: Three-leaf walls: (a) transport of the wall to the testing frame; (b) transversal tying; (c) wall 2W3 under compressive loading.

Type of strengthening	Number of walls to be tested	Number of walls tested
Unstrengthened (U)	4	3
Transversal tying (T)	4	3
Bed joint structural repointing (B)	4	0
Combination of transversal tying and bed joint structural repointing (T+B)	4	0

Table 1: Experimental campaign, walls designed for compressive testing.

Series	Number of walls	Type of strengthening	Wall's label
I	2	U×2	1W1, 1W2
II	4	U×1 and T×3	2W1 and 2W2, 2W3, 2W4

Table 2: Three-leaf stone masonry walls tested.

Walls 1W1 through 2W4 were tested under monotonic compressive loading, using a 2 MN steel frame. All the tests were performed under displacement control at a displacement increment rate of 3 μm/s. Ten displacement transducers (lvdt's) were used to measure the relevant displacements.

4.3. Transversal tying

The walls 2W2, 2W3 and 2W4 were strengthened by means of two GFRP bars of 10 mm diameter. For that, two holes of 20 mm diameter were drilled at specimens' third high, as illustrated in Figure 1(b, c). The holes were made coincident as much as possible with bed joints. Afterwards, the bars were inserted through the thickness of the wall and the holes were injected with a lime-based grout in order to anchor the strengthening. All walls were strengthened after a period of 30 days curing.

The voids adjacent to holes were injected as well and the absence of compaction in the inner core allowed the leakage of grout though the lateral sides during the injection process. This implies that some parts of the inner core had their weakness improved.

4.4. Test results

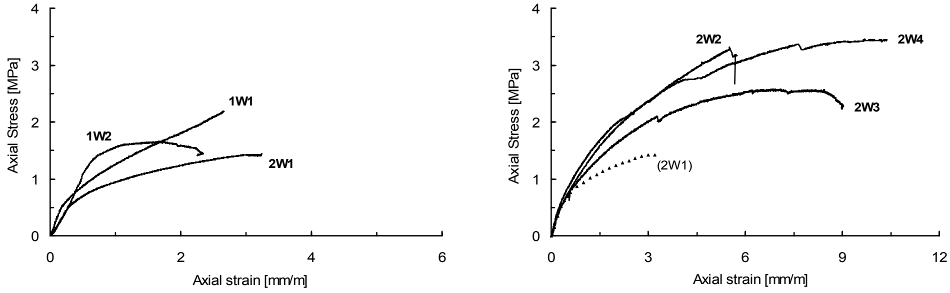
In this section, the main results concerning the testing of the three-leaf walls (three plain and three strengthened by transversal tying) are discussed. Table 3 presents the compressive strength of all walls (the coefficient of variation is indicated inside brackets). The unstrengthened walls present an average compressive strength of 1.8 MPa, whereas for the strengthened walls an average compressive strength of 3.1 MPa is achieved. This increase in strength, of about 71% in average terms, is mostly due to the confinement effect produced by the GFRP bars.

Wall's label	f_c (MPa)
1W1	2.4
1W2	1.7
2W1	1.4
average	1.8 (26%)

Wall's label	f_c (MPa)
2W2	3.3
2W3	2.6
2W4	3.5
average	3.1 (15%)

Table 3: Compressive strength of the unstrengthened and strengthened walls (the coefficient of variation is given inside brackets).

Figure 2 illustrates the axial stress-strain curves computed for the walls. The plain walls (Figure 2a) present a similar behaviour. The response is characterized by two localized stiffness degradation zones, the first occurring at a stress level of approximately 0.6 MPa, most probably related to the initial separation of the external leaf, and the second close to the peak load, although in wall 1W2 the separation of the external layer seems to be happened for a higher stress level.
Figure 2(b) shows that the strengthened walls present analogous stress-strain curves, characterized by progressive stiffness degradation along with the increase of normal stress, although wall 2W2 failed prematurely in a brittle fashion, most likely caused by some construction defect. Figure 2 seems also to indicate that the value of the elastic modulus of the strengthened walls is not markedly affected by the presence of the two GFRP bars.



(a) (b)

Figure 2: Axial stress-strain diagrams: (a) unstrengthened walls; (b) strengthened walls (the 2W1 curve is also represented).

Besides the compressive strength increment, the strengthening originated also an increase in the axial deformation prior to failure. This has been made possible by the existence of the transversal GFRP bars that changed the failure pattern. In fact, the failure of the plain walls was dominated by the development of horizontal plastic hinges along bed joints, leading to the formation of a mechanism and the typical detachment of the external leaves (global mechanism). However, for the strengthened walls, the GFRP bars provided a effective connection of the external leaves allowing the wall to behave approximately as a single layer, as illustrated by the visible vertical cracks registered close to failure and the absence of significant horizontal cracks. For the strengthened walls, failure occurred at a local level caused by the instability of one or more stone units (local mechanism).
In the strengthened walls, failure occurred always before the loss of bond between the GFRP bars and the injected grout. Since a high GFRP-grout bond strength can hardly be expected, this behaviour indicates that the GFRP is most likely submitted to low stress levels.

5. MAIN CONCLUSIONS

This paper presents the first results of an experimental program concerning the structural assessment of three-leaf stone masonry walls. The mechanical characterization of the wall's materials and components has been performed in order to better understand the global behaviour of the walls. Given the remarkable difference in terms of load capacity, the external leaves of the three-leaf stone masonry walls under analysis carry most of the applied load. The use of transversal GFRP ties through the wall thickness, bonded to the external leaves by means of a lime-based grout, has shown to be an effective strengthening technique. The average compressive strength was increased about 71% with regard to the plain walls.

The typical failure mode was shifted from out-of-plane movement of the external leaves, due to the development of horizontal plastic hinges (global mechanism), to the formation of a dominant vertical cracking pattern and the localized loss of equilibrium at some stone units (local mechanism).

Finally, the results presented in the paper show that the influence of workmanship and the variability of natural and handmade materials should be considered when dealing with ancient building constructions.

6. ACKNOWLEDGEMENTS

The authors want to acknowledge companies Fradical, Mapei and Augusto de Oliveira Ferreira & Ca. Lda for providing raw materials and workmanship.

The financial support provided by the Portuguese Science and Technology Foundation through the POCI/ECM/58987/2004 project is gratefully acknowledged.

REFERENCES

[1] Binda, L., Baronio, G., Penazzi, D., Palma, M. and Tiraboschi, C. 1999. Characterization of stone masonry walls in seismic areas: data-base on the masonry sections and materials investigations. L'ingegneria Sismica in Italia, 9th National Conference, Turin, Italy, 14 pp., on CD-ROM (only available in Italian).

[2] Valluzzi, M.R., da Porto, F. and Modena, C. 2004. Behaviour and modeling of strengthened three-leaf stone masonry walls. Materials and Structures, Vol. 37, April 2004, pp. 184-192.

[3] Anzani, A., Binda, L., Fontana, A. and Pina Henriques, J. 2004. An experimental investigation on multiple-leaf stone masonry. 13th International Brick and Block Masonry Conference, Amsterdam, July 4-7, 2004, 10 p., on CD-ROM.

[4] Modena C. 1997. Criteria for cautious repair of historic building. A valuation and strengthening of existing masonry structures. Binda L. and Modena C., Ed. RILEM.

[5] Valluzzi M.R., Binda L. and Modena C. 2005. Mechanical behaviour of historic masonry structures strengthened by bed joints structural repointing. Construction and Building Materials, Vol. 19, pp. 63-73.

[6] Valluzzi M.R. 2000. Mechanical behaviour of historic masonry walls consolidated with lime-based materials and techniques. Ph.D. Thesis, University of Trieste, Trieste, Italy, 276 pp. (only available in Italian).

[7] Toumbakari, E.E. 2002. Lime-pozzolan-cement grouts and their structural effects on composite masonry walls. Ph.D. Thesis, Katholieke Universiteit Leuven, Heverlee, Belgium, 364 pp.

[8] Vasconcelos, G. 2005. Experimental investigations on the mechanics of stone masonry: Characterization of granites and behavior of ancient masonry shear walls. Phd Dissertation, Universidade do Minho Guimarães (available from www.civil.uminho.pt/masonry).

[9] Oliveira, D.V., Silva, R. and Garbin., E. 2006. Behaviour of ancient multi-leaf masonry walls, Report 06-DEC/E-14 (in portuguese), Universidade do Minho Guimarães, Portugal.

[10] Oliveira, D.V., Lourenço, P.B. and Roca, P. 2006. Cyclic behaviour of stone and brick masonry under uniaxial compressive loading, Materials and Structures, 39(2), 2006, pp. 219-227.