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1

STRUCTURAL ANALYSIS OF HISTORICAL CONSTRUCTIONS

Possibilities of numerical and experimental techniques

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Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Experimental Investigation on the Structural Behaviour and Strengthening of Three-Leaf Stone Masonry Walls

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ABSTRACT: A large part of historical structures, currently in the European urban centres, is built with stone masonry walls, frequently 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. As support for the rehabilitation design phase, some analytical approaches are available in literature. 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 experimental plan and the first experimental results on materials and three-leaf stone masonry walls are presented and discussed.

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 (Binda et al. 1999) 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 (Valluzzi et al. 2004, Anzani et al. 2004).

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 (Valluzzi et al. 2004, Modena 1997).

As support for the rehabilitation design phase, some analytical approaches are available in literature concerning unstrengthened and injected walls. They are based on simplified formulations, which depend on few parameters easily detected by in situ survey and/or experimental tests (Valluzzi et al. 2004, Toumbakari et al. 2004).

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 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 combination of these techniques can provide useful information in order to evaluate the different strengthening configurations that can be applied to restore the masonry deficiencies noticeable on site. The subsequent repair of the tested wall specimens is also an approach under consideration whenever possible.

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 in detail.

A preliminary bibliographic study was also performed, both on the geometrical characteristics of the three-leaf walls and on the constitutive materials used (Valluzzi et al. 2004, Valluzzi 2000, Toumbakari 2002, Binda et al. 1999, Rodrigues et al. 2003, Bartos et al., 1999) in order to produce masonry specimens representative enough of the existing three-leaf stone masonry walls. For that, an experimental investigation has been done in order to select adequate materials that correctly simulate the historical three-leaf stone masonry in laboratory conditions. Granite stone and pozzolanic mortars, for bed joints and repointing purposes, were selected to build the walls. Aiming at representing as much as possible the traditional construction techniques still in use, a professional mason was hired to build all the specimens.

Furthermore, experimental tests on specimens reproducing the external and the internal leaves have also been performed.

2 STRENGTHENING TECHNIQUES

A brief description regarding the three main different reinforcing techniques adopted in the project is hereafter given. These techniques aim to solve specific structural deficiencies of three-leaf stone masonry walls, as follows:

- lacking of the connection among the leaves;
- reduction of the horizontal dilation due to creep damage;
- weakness of the internal core.

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 transverse deformation. For this purpose, stainless steel bars or FRP bars can be used. The bars can be easily inserted into drilled holes through the thickness of the walls and then anchored. In case of steel bars, the anchoring phase is achieved by bending the bar from the outside into a mortar joint previously grooved and then refilled with new mortar, whereas the anchoring of FRP bars is slightly more complicate because usually these bars can not be bent without their failure. In this last case, the anchorage can be achieved by using special anchoring elements (like angle bars or connector developed on purpose) or relying on the bond behaviour between the FRP bar and the mortar, developed along the thickness of the external leaf. In order to improve this last anchoring mechanism, a local grout injection around the tie can be applied instead.

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 (Valluzzi et al. 2005). 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 technique is performed by removing an external layer of the horizontal joints (up to about 6-8 cm), and placing into the groove one or two small diameter reinforcing bars (stainless steel or FRP bars can be adopted). In the case of multi-leaf walls, transversal short links can be inserted into drilled holes successively sealed to improve the confining action of the bars and to tie the external leaf of the wall.

The injection is aimed to improve the weakness of the internal core, filling the voids in the inner core, 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 mechanically, physically and chemically compatibility (Valluzzi 2000, Toumbakari 2002, Binda et al. 1994).

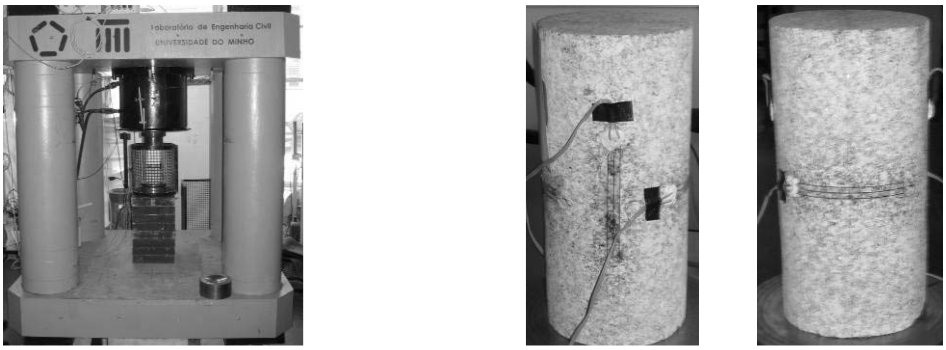
Nowadays the trend is using grout mainly based on lime, in particular when the restoration works deal with historical constructions. The injection is typically performed injecting the grout starting from the bottom of the wall and reaching progressively the top. Usually, for three-leaf walls the used pressure is very low and not exceeding 50-100 kPa to avoid the undesired detachment of the external leaves.

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, see Fig. 1a. 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, see Fig. 1b.

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, see Vasconcelos (2005) for details. 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.



(a) (b)

Figure 1 : Testing setup: (a) testing equipment; (b) strain gauges arrangement.

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 (Klrca, 2004). 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. (2006a) 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 10μm/s, see Fig. 2a. The prisms were tested after about 60 days of curing.

(a) (b)

Figure 2 : Prisms representative of the external leaf: (a) prisms prior testing; (b) typical failure pattern.

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. (2006b) 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. The typical failure pattern observed is dominated by the formation of vertical cracks that progressed through the entire prism, see Fig. 2b.

3.4 Internal leaf

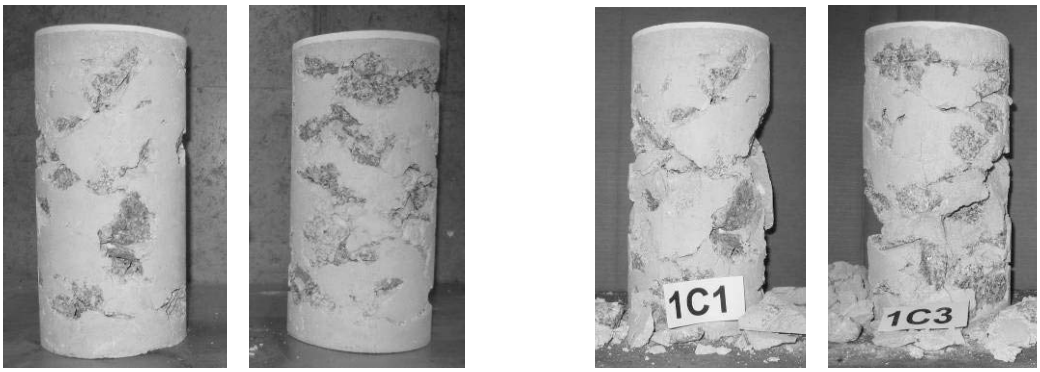
Typically, the internal leaf of multi-leaf walls is composed of poor materials, as wastes obtained from the rough-shaping of the stones placed in the outer leaves, and mortar.

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 ∅150×300 mm^2 were built following the same procedure used for the internal layers leaves, see Fig. 3a.

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. This idea is further validated by the failure pattern found, characterized by the partial disintegration of the specimen, see Fig. 3b.

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.



(a) (b)

Figure 3 : Specimens representative of the internal leaf: (a) specimens prior testing; (b) typical failure modes.

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.

As aforementioned, 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 50×50×50 mm^3 were sampled during the injection of the holes and tested 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.

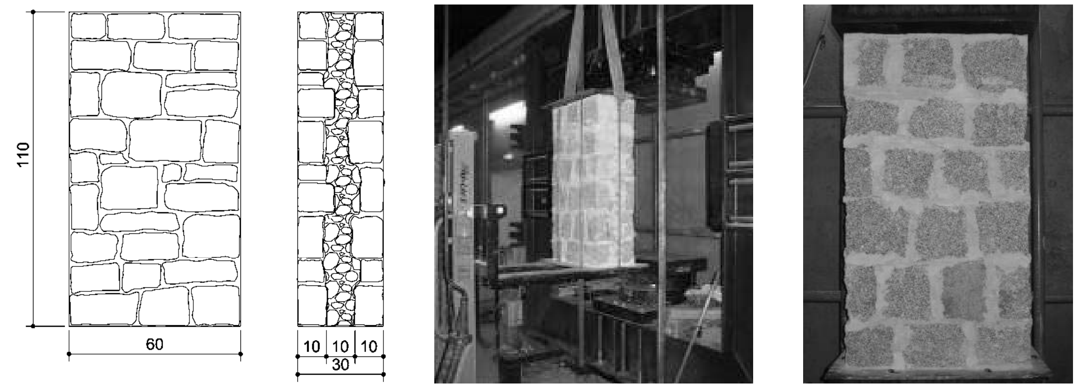
4 EXPERIMENTAL TESTS ON THREE-LEAF WALLS

4.1 *Test specimens*

Wall specimens of 600 mm long, 300 mm thick and 1100 mm high have been designed, see Fig. 4a. 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. 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 Figs. 4b and 4c.



(a) (b) (c)

Figure 4 : Three-leaf wall specimens: (a) schematic geometry (units in *cm*); (b) ; transport of the wall to the testing frame; (b) wall before testing.

Walls 1W1 through 2W4 were tested under monotonic compressive loading, using a 2 MN steel frame, see Fig. 5a. All the tests were performed under displacement control at a displacement increment rate of 3 μm/s. In order to prevent the total collapse of the walls, tests were stopped during the softening branch when specimens were about to fail. Ten displacement transducers (lvdt's) were adopted according to Fig. 5b. Applied displacements and corresponding loads were duly recorded at a frequency of 1 Hz.

Table 1 : Experimental campaign, walls designed for compressive testing

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

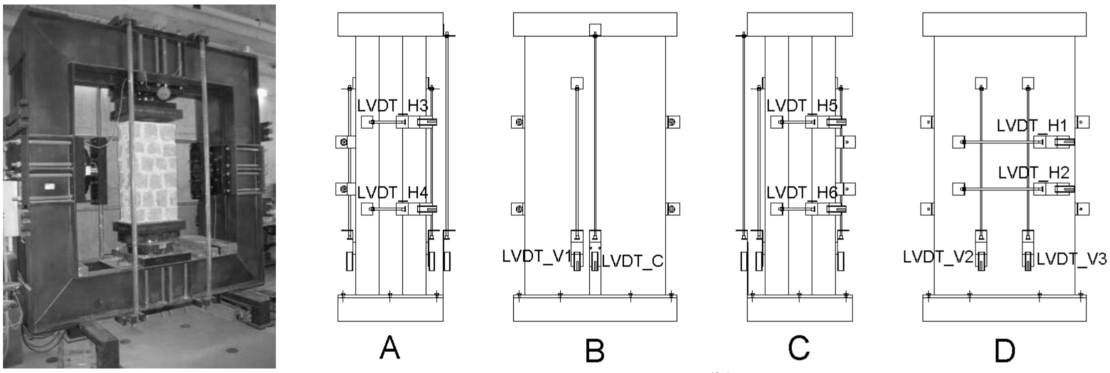
Table 2 : Three-leaf stone masonry walls tested

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

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 Figs. 6a and 6c. 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. The 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, as shown in Fig. 6b. This implies that some parts of the inner core had their weakness improved.



(a) (b)

Figure 5 : Testing setup: (a) Testing frame; (b) displacement transducers used.

(a) (b) (c)

Figure 6 : Transversal tying of a multi-leaf wall: (a) injection of the holes; (b) leakage of grout; (c) wall 2W3 under compressive loading.

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.

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

Wall's label	f_c (MPa)	Wall's label	f_c (MPa)
1W1	2.4	2W2	3.3
1W2	1.7	2W3	2.6
2W1	1.4	2W4	3.5
average	1.8 (26%)	average	3.1 (15%)

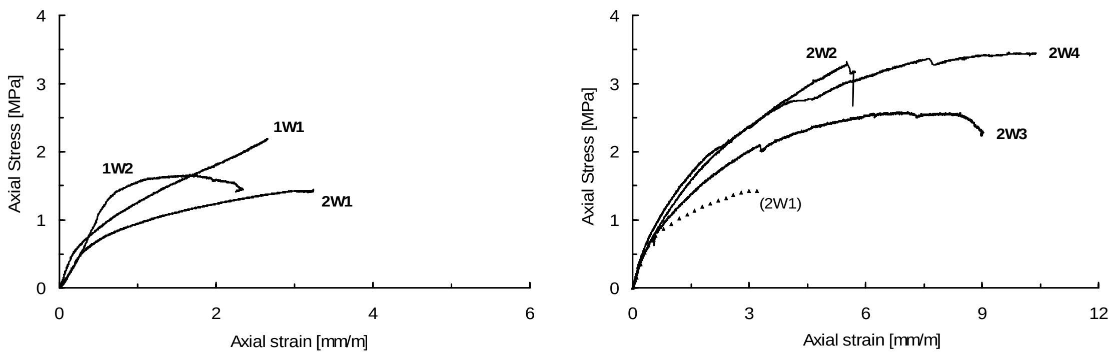
Fig. 7 illustrates the axial stress-strain curves computed for the walls. The plain walls (Fig. 7a) present a similar behaviour. The response is characterized by two localized stiffness degradation zones, the first occurring at a stress level of approximately 0.6 MPa, most probably related to the initial 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.

Fig. 7b 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.

Fig. 7 seems also to indicate that the value of the elastic modulus of the walls is not markedly affected by the presence of the two GFRP bars.

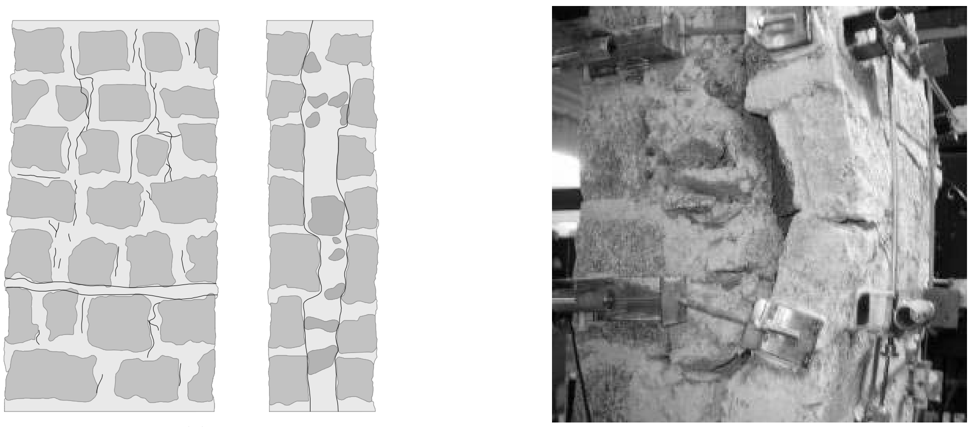
Besides the compressive strength increment, the strengthening originated also an increase in the axial deformation prior to failure. This has been made possible by the existence of the transversal GFRP bars that changed the failure pattern. In fact, the failure of the plain walls was dominated by the development of horizontal plastic hinges along bed joints, leading to the formation of a mechanism, as illustrated in Fig. 8, 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, see Fig. 9. 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.



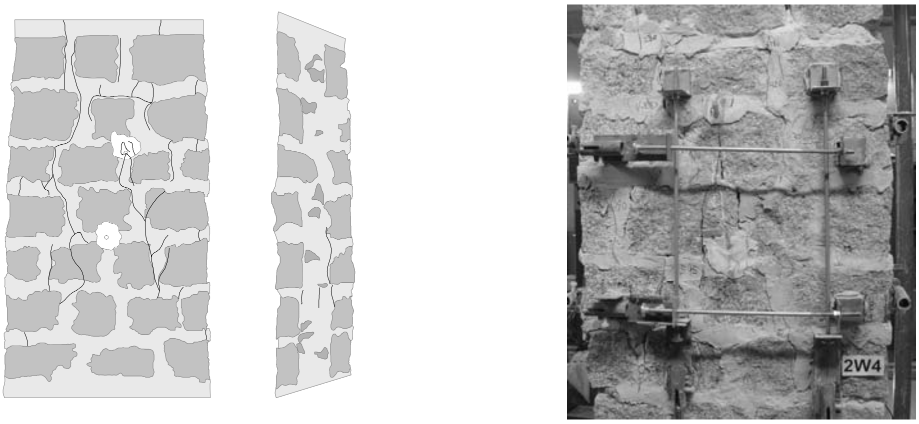
(a) (b)

Figure 7 : Axial stress-strain diagrams: (a) unstrengthened walls; (b) strengthened walls (the 2W1 curve is also represented).



(a) (b)

Figure 8 : Failure of wall 2W1 (unstrengthened): (a) crack pattern close to failure; (b) rotation of the external leaf.



(a) (b)

Figure 9 : Failure of wall 2W4 (strengthened): (a) crack pattern close to failure; (b) relevant vertical cracking.

5 CONCLUDING REMARKS

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, bond 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.

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