

TOPIC 3 – Repair procedures

Three-leaf stone masonry repair and strengthening

R.A. Silva^{1,a}, D.V. Oliveira^{2,b} and P.B. Lourenço^{3,c}

^{1,2,3}*ISISE*, University of Minho, Portugal

^aruisilva@civil.uminho.pt, ^bdanvco@civil.uminho.pt, ^cpbl@civil.uminho.pt

Keywords: three-leaf masonry; strengthening, grouting; transversal tying.

Abstract. This paper summarizes the results of an extensive test campaign over three-leaf stone masonry walls, aiming at studying the behavior of these kind of walls under compressive loading and the effects introduced by the most common strengthening techniques used for structural rehabilitation of heritage buildings. A total of ten three-leaf stone (granite) masonry walls were tested, plain or strengthened resorting to transversal tying with GFRP rods, injection of a lime based grout and both techniques applied simultaneously. In addition, it is also presented the characterization of the materials and of the three-leaf walls components (external and inner leaves). The results show that the strengthening techniques used in this work were effective in different ways.

Introduction

A significant part of the ancient constructions is made of masonry, where the three-leaf stone masonry wall typology is quite common, especially in some urban centres of European cities, and so they are considered as part of the heritage constructions. These walls are currently constituted by two external leaves with weak mortar joints and an inner leaf, usually, made of rubble masonry or just an infill of a very weak material, like earth, characterized by a substantial quantity of voids [1].

One of the structural main problems of this kind of walls is the lack of connection between these leaves, which, usually, leads to the wall collapse, characterized by the formation of brittle collapse mechanisms, which consist essentially on the detachment of the external leaves and the out-of-plane material expulsions, both under compression and shear-compression loading [2, 3].

In order to preserve the constructions built with this masonry wall typology, due to its cultural importance and historical value, specific repair approaches are required. In fact, intervention on this kind of buildings requires a multidisciplinary approach [4], which makes this process rather complex, where both image and substance of the historical constructions should be preserved after any kind of structural intervention [5]. These values defy the exigencies of the current codes for new structures, which cannot be applied to ancient structures without heavy interventions, damaging permanently their identity [4].

In a structural intervention on ancient masonry, aspects such as the structural effectiveness, durability and compatibility must be taken in account, where the chosen intervention materials have an important role, in order to be observed certain requirements, fundamental for a good intervention, such as the mechanical, physical and chemical compatibility between the original and intervention materials [4, 6, 7]. When all these aspects are not considered or are simply forgotten, the works carried out may result in wrong and ineffective interventions [7], which eventually may result in a damage state worst than the previously and in durability problems, leading to economical consequences in a new repair intervention and to losses in the structure heritage identity.

However, most of the times these approaches are hard to be applied, mainly, due to the lack of knowledge on the material and structure's behaviour, which must be enlightened with extensive research.

Among the most used and investigated strengthening techniques are the grouting, the joints repointing or deep repointing and transversal tying of the external leaves. Normally, these techniques accomplish most of the principles recommended by ICOMOS for heritage structures repair and strengthening [4], which explains the last years research and developments in these techniques procedures and materials, taken all over Europe.

From the three techniques aforementioned, grouting is the most used in repair and retrofitting of three-leaf walls, mainly because of the simplicity of its application and the effectiveness of its use. In a grouting intervention on this kind of masonry walls, it is aimed to reduce the weakness of the internal core, by filling the existing voids and cracks, and to improve its adherence to the external leaves, by filling the gaps between leaves, promoting to the walls a overall better behavior. Several studies have been performed in the last years concerning this technique [3, 8-10], however, special attention with regard to material compatibility is needed, which limits the grout selection [7].

A good grout selection depends mostly of the knowledge of the wall to be injected, which determinates the properties required for the repair grout, where the material compatibility takes an important role in durability field. Nowadays the trend is the use of a grout mixture mainly based on lime and pozzolanic materials with a low percentage of cement, in particular when dealing with restoration works in historical constructions [10], materials which can be easily found in ancient mortar compositions.

Grouting is typically performed by injecting the grout starting from the bottom part of the wall and reaching progressively to the top. Usually, for three-leaf walls the injection pressure is very low, not exceeding $0.5-0.1 \text{ N/mm}^2$ to avoid the undesired detachment of the external leaves, the undesired flow of the original materials through the walls voids or undesired grout leakages. However the pressure value decision is an issue which depends mostly of the masonry injectability characteristics, and so it should be evaluated carefully and specifically for the masonry to be grouted.

Besides the problem in choose a suitable grout mixture, the unexpectability in the grouting procedure and the quality control of the grouting as the unknown of the grout quantity needed represents also a drawback in this technique. Since the quantity of grout needed for full injection of a masonry wall of an heritage structure is almost unpredictable and, in general, is always underestimated, due to possible grout leakages and to the unknown of its quantity of voids and its interconnection, which normally leads to the unplanned grouting of parts of other walls before the full wall injection being achieved, highly increasing the intervention costs. Also due to the result of this technique being almost unseen, creates doubts in its quality, which consequently brings uncertainties in the structural behavior. In this matter, inspection tools, like sonic and ultra-sonic tests and also the Ground Penetration Radar (GPR) may have, in the future, one important role, in the prediction of the needed grout quantity and in the grouting quality control.

The repointing or deep repointing technique consists in the removal of part of the old mortar of the joints, which is then replaced by a new mortar with improved properties. It can be applied simultaneous with other strengthening techniques (e.g. grouting). This technique is normally used in brick masonry with regular joints, which allows to introduce steel or FRP rods in the bed joints, constituting a good strengthening solution for masonry structures with creep problems [11]. Experimental works with this technique have showed a slight improvement of the compressive strength. However the major role of this intervention technique is taken in the transversal deformation field, by reducing it [11]. Also in this technique, the choice of suitable materials for the new mortar composition has an important role in the success of the intervention, for the many reasons here already mentioned.

In what concerns with the transversal tying of the external leaves technique, this is aimed to improve the connection among leaves, in particular between the external ones, in order to reduce the

transverse deformation and so counter the typical collapse mechanism of this kind of walls, decreasing its fragility. For this purpose, stainless steel bars or FRP bars can be used. The bars are inserted into drilled holes through the thickness of walls and then anchored. In case of FRP bars, the anchoring 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 accomplish this last anchoring mechanism, a local grout injection around the tie can be applied, if also bars with treated surface for friction increase be used [12]. This technique can also be applied in combination with other techniques.

Note that the aforementioned techniques try to solve a problem of localized behavior, i.e. at the element level, and not a global behavior problem, i.e. at level of the structural global behavior (connections between walls, floors, etc.) that require the application of other strengthening techniques, which are out of the scope of this paper.

Hence, the current work deals with the strengthening of three-leaf stone masonry walls, using two different strengthening techniques and their combination: grouting and transversal tying by means of GFRP rods and local grouting. The main objectives of this research are: characterize the behavior of three-leaf walls under different strengthening configurations and provide an experimental base for the development of a suitable numerical model able to interpret and explain the structural behaviour of such type of walls. So in this paper are presented the experimental results concerning the testing of three series of walls (ten walls in the total), where the three aforementioned strengthening techniques were applied. Should be noticed that the strengthening was applied without any previous induced damage, not following the procedure taken by others researchers [9-11]. The test program is summarized in Table 1, where it can be seen that the experimental program has been developed through the constructions of three series of walls, only strengthened in the second and the third series. During these last two series, also a single plain wall was tested, as a reference of each series. Information about the used materials and mechanical properties of masonry components (external and inner leaves) is also here provided.

Table 1: Testing of three-leaf walls.

Wall	Wall series	Strengthening technique
1W1	1	U
1W2	1	U
2W1	2	U
2W2	2	T
2W3	2	T
2W4	2	T
3W1	3	U
3W2	3	I
3W3	3	I
3W4	3	T+I

U – Unstrengthened wall / T – Transversal tying. / I – Injection.

Characterization of the walls materials and components

Granite

A locally available granite stone, from a Mondim de Basto (North of Portugal) quarry, was used to build all walls. Used as unity in the external leaves masonry and as granite scabblings in the inner leaf. Its mechanical characterization was performed in six cylindrical specimens of dimensions $\text{Ø}100 \times 200 \text{ mm}^2$, tested under uniaxial compression, where the following average values were obtained: compressive strength of 52.2 N/mm^2 , Young's modulus of $20.6 \times 10^3 \text{ N/mm}^2$ and Poisson's ratio of 0.24.

Mortar

In order to use a representative mortar in the construction of the walls, a 1:3 binder/sand ratio and a 0.8 water/binder ratio were selected for the compositions of the mortar (all ratios in weight). The binder was composed by 25% of hydrated lime and 75% of metakaolin (pozzolanic material). In addition, a pozzolanic drier (10% on binder weight) was used to obtain a faster mortar drying and, therefore, to improve the construction procedure of the walls.

The mechanical behavior of mortar was assessed using cubic specimens of $50 \times 50 \times 50 \text{ mm}^3$, sampled during the construction of the walls and tested under uniaxial compressive loading at the ages of 7, 28 and 90 days. The cure conditions of these specimens were the same of the constructed walls. The average compressive strengths computed for the aforementioned ages were 0.5 N/mm^2 , 2.9 N/mm^2 and 2.2 N/mm^2 , respectively.

Strengthening materials: GFRP rods and grout

The transversal tying technique was applied by means of GFRP rods placed transversally to the wall in holes previously drilled and anchored along the thickness of the external leaves, by means of a localized injected grout.

Due to technical limitations, it was not possible to present valid tensile tests on the GFRP rods. Some test were done following a similar procedure to the traditionally adopted for test steel rod to tensile, but the specimens always failed due to crushing of the rod in the grips zones. However the low stress state together with the high tensile strength of the GFRP bar (a value of 760 N/mm^2 was provided by the manufacturer) excluded its brittle tensile failure from the collapse hypothesis of the walls strengthened with transversal tying. Furthermore the bond strength between the rods, the grout and the masonry was considered enough to transmit the load from the external leaf to the GFRP rods.

A commercial lime-based grout was used (Mape-Antique I), for both wall injection and bonding of the GFRP rods to masonry. Its mechanical behavior was assessed by means of cubic specimens of $50 \times 50 \times 50 \text{ mm}^3$ sampled during injection and cured under lab ambient conditions. For the walls strengthened with transversal tying in the second series, the grout samples provided an average compressive strength of 17.6 N/mm^2 and an average tensile strength of 0.3 N/mm^2 , this last one assessed through direct tensile tests. For the walls injected in the third series, grout specimens reached an average compressive strength of 13.7 N/mm^2 (no tensile tests were performed).

External leaf

The mechanical behaviour of the external leaf was characterized through a set of representative stone masonry prisms consisting of three stones and two horizontal joints [12] (see Fig. 1a). These prisms were built during the walls construction, and so the same cure conditions were given. The specimens were tested under uniaxial compressive loading at a displacement control rate of $10 \text{ }\mu\text{m/s}$. An average compressive strength of 9.21 N/mm^2 and a coefficient of variation of 19% were computed for specimens coming from the three series.

Inner leaf

Also representative core specimens were built, using granite scabblings poured into alternate layers with mortar, in a typical concrete cylindrical mould, without any compaction, aiming at representing the construction procedure followed for the walls inner leaf. During the construction of all walls series, a total of ten cylindrical specimens of dimensions $\text{Ø}150 \times 300 \text{ mm}^2$ were built and cured under the same ambient conditions (see Fig. 1b). The specimens were tested under uniaxial compressive loading at a displacement control rate of $5 \text{ }\mu\text{m/s}$. An average compressive strength of 0.3 N/mm^2 and a coefficient of variation of 45% were obtained. As expected, a very low strength was achieved, being the strength of the external leaves 30 times superior.

Injected inner leaf

In order to also characterize the injected inner leaf of the walls, seven prisms were sampled from the inner leaf of all the injected walls, during the dismantling procedure, see Fig 1c. The samples were extracted with average dimensions of $80 \times 80 \times 160 \text{ mm}^3$ (h/d ratio of 2) in order to obtain, as much as possible, dimensionally representative inner leaf specimens.

The specimens were tested under uniaxial compressive loading at a displacement control rate of $2.5 \mu\text{m/s}$. An average compressive strength of 4.1 N/mm^2 was attained with a variation coefficient of 12%. The improvement observed was of about 14 times the strength of the plain inner leaf, diminishing drastically the strength differences between the external and inner leaves, being this last one only 2.25 times inferior. In addition the low variation coefficient shows that injection allowed for a homogenization of the inner leaf strength.

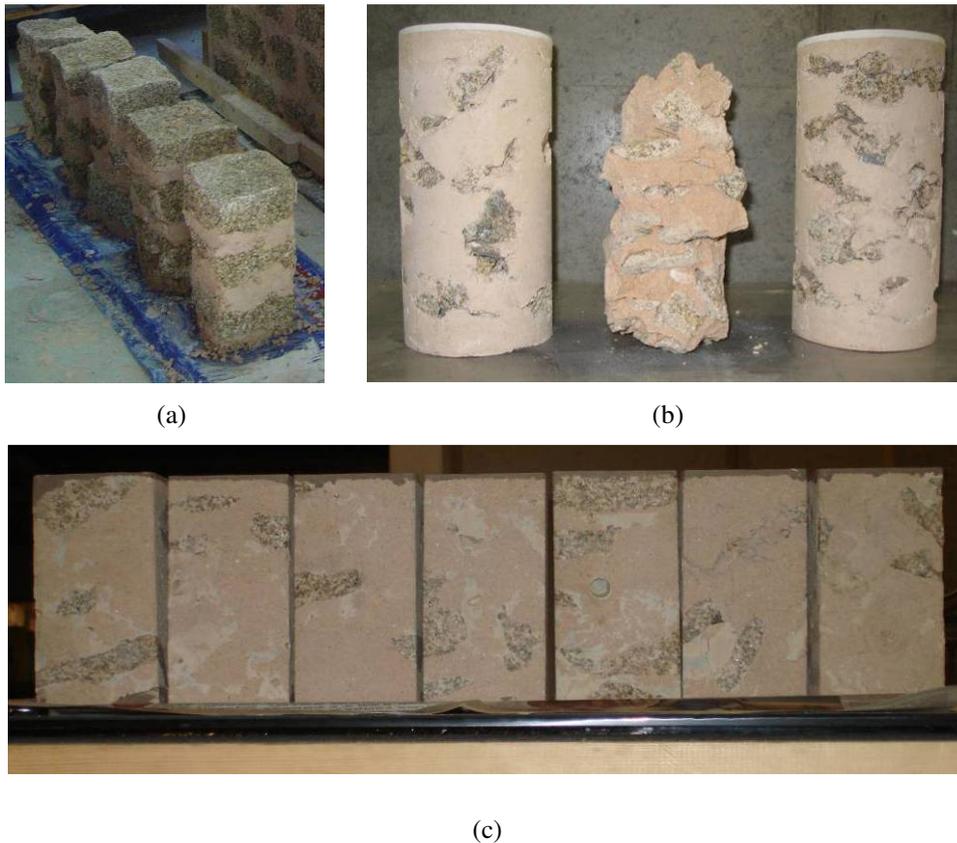


Figure 1: Walls components: (a) external leaves specimens; (b) inner leaf specimens; (c) injected inner leaf specimens.

Walls construction

In the three series of walls tested, were built a total of ten walls, with two granite masonry external leaves and an inner leaf built by simple pouring alternated granite scabblings and mortar layers, without any compaction (see Fig. 2), aiming at obtaining an amount of voids, representative of this kind of walls and able to allow injection. This inner leaf execution procedure was originally followed by Vintzileou et al. [9], in order to obtain an inner leaf void percentage of 30% to 40%.

All the stones before being placed were wetted, including the granite scabblings, in order to avoid the mortar water absorption and consequently the shrinkage phenomena's associated. With the same objective, after the specimens being built, they were covered with a wet tissue during 2 weeks, after which the specimens stayed under the lab ambient conditions.

The walls were built representing 1/2 scaled models of real ones, with the global dimensions of 600 mm long, 300 mm thick and 1100 mm high, being the adopted thickness of all leaves equal and

of about 100 mm (see Fig. 3), similar to dimensions found in previous experimental works, see Table 2.

During the walls construction, no intentional connection between the leaves was intended, in order to simulate the worst condition, typically, found in the heritage buildings and to provide similar interfaces between leaves from wall to wall.

Table 2: Other researcher’s walls geometry.

Researchers	Walls aproximated dimensions (mm ³)	Leaves thickness (mm)		
		External (each one)	Inner	Ratio
Valluzzi et al. [3]	600x400x1200	130	140	0.54
Vintzileou et al. [9]	800x500x1400	180	140	0.39
Toumbakari [10]	600x400x1200	90	220	1.22
Pina-Henriques [13]	310x510x790	170	170	0.50

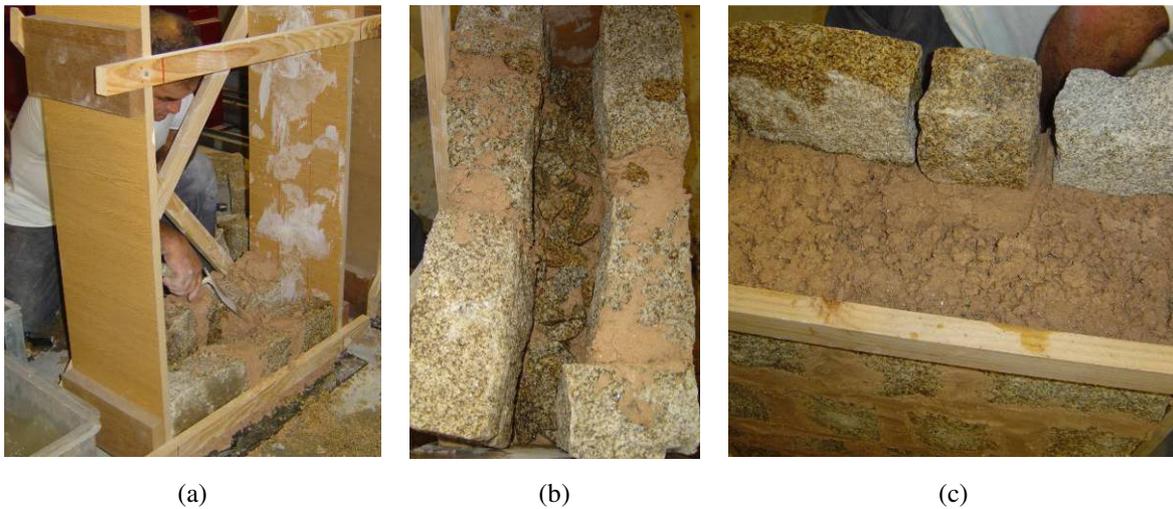


Figure 2: Walls construction: (a) external leaves first layer execution; (b) inner leaf granite scabblings layer; (c) inner leaf mortar layer.

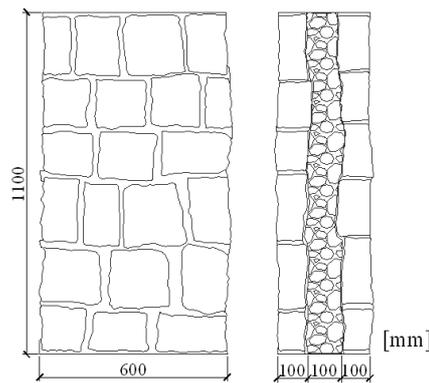


Figure 3: Walls geometry.

Walls strengthening

Transversal tying

The transversal tying technique was applied and tested individually only in the second series, and in combination with grouting in the third. This strengthening technique was done by means of two GFRP rods connecting the leaves, placed at one third and two thirds of specimen’s height, see Fig. 4a. The connection between the rods and leaves was granted through a localized injection of a

commercial grout (see section 2.3). The appliance of this strengthening technique involved the subsequent procedure:

- Drilling two holes with 20 mm of diameter to set the GFRP rods;
- Cleaning the holes with compressed air, for remove the dust resulted from the drilling;
- Set of the GFRP rods;
- Sealing the holes using silicone and transparencies, and at the same time, applying the injection tube and the air purge tubes (see Fig. 4b and c);
- Water injection through the injection tubes, for wet the wall materials and to remove any remaining dust resulted from the drilling process;
- Preparation of the grout following the procedure recommended by the manufacturer, being then filtered and placed in the deposit of the gravity injection device;
- Gravity injection of the influence area of the lower rod (see Fig. 4d). Injection of the influence area was considered completed when the grout went out through the two purge tubes;
- Following the same injection procedure for the influence area of the top rod.

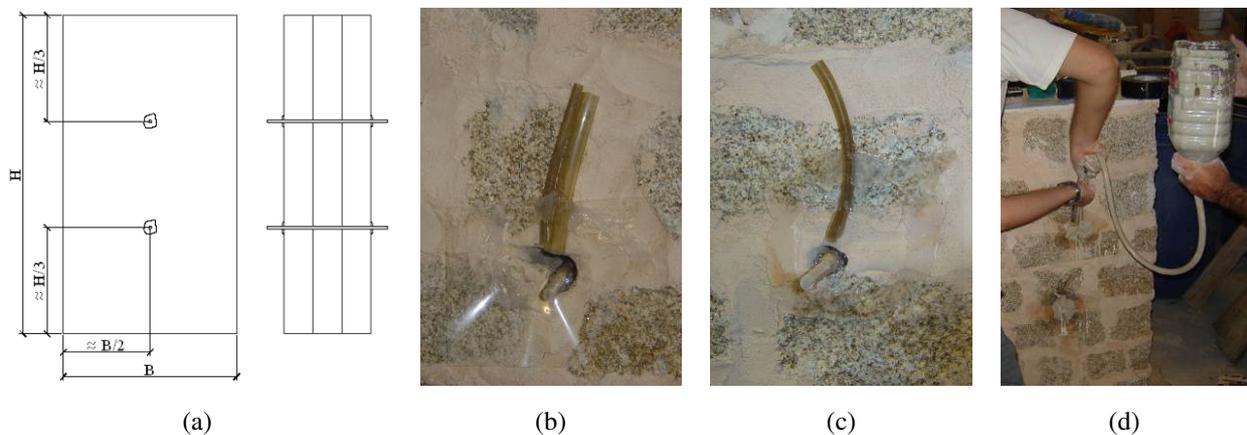


Figure 4: Transversal tying strengthening: (a) reference position of the GFRP rods; (b) hole seal detail (injection side); (c) hole seal detail (opposite side); (d) gravity injection.

To avoid damaging considerably the walls, during the holes drilling, by the vibration of the drilling equipment, the transport scheme was mounted in the walls, applying on it a compression stress state, doing so allowed minimizing cracks formation during this process. For the same reason the holes were drilled through the horizontal mortar joint.

During the injection of the influence area of the rods, the voids interconnection was observed, by the leakage of grout through the transversal faces of the walls, which needed to be stopped in order to accomplish this operation, by blocking the gaps with pieces of journal paper or textile residues.

Grouting

The grouting technique was only applied in the third series of walls, either individually or in combination with transversal tying. Due to the low wall thickness, injection was applied just in one side of the walls. For that, the subsequent procedure was followed:

- drilling of slightly inclined holes with 14 mm diameter and about 200 mm deep in to the wall;
- introduction of small plastic tubes with a diameter of 10 mm in the holes (see Fig. 4a);
- sealing of holes and major mortar joint absences, caused by the drilling process, with silicone to prevent grout leakage;
- injection of water to verify which tubes were active and to wet the inner leaf, at least 24 hours before grouting;

- sealing of the transversal sides with polyurethane foam to prevent grout leakage (see Fig. 4b);
- preparation of the grout according with the manufacturer demands and injection under a low pressure of around 0.1 N/mm^2 with a pressure pot (see Fig. 4c).

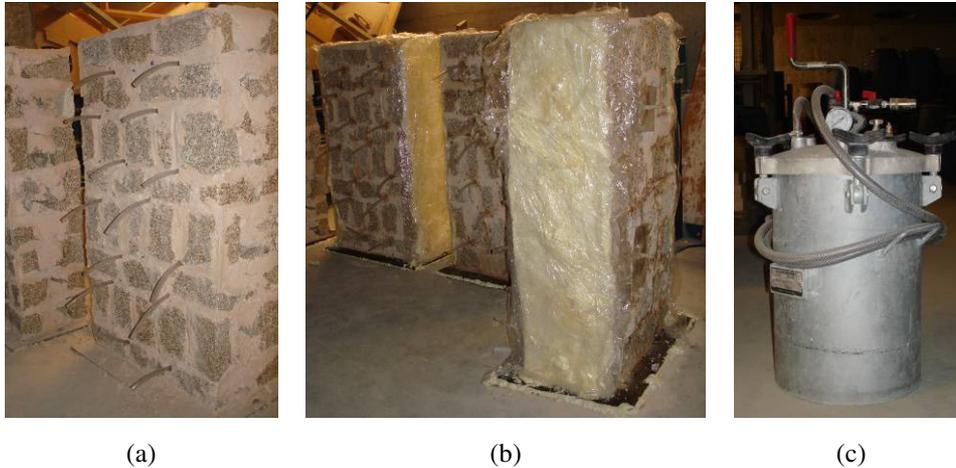


Figure 5: Walls grouting set up: (a) injection tubes detail; (b) transversal faces sealed with polyurethane foam; (c) pressure pot.

Also to the drilling of the holes for the wall grouting, a compressive stress was applied with the transport scheme, in order to minimize the caused damage by the vibration of the drilling equipment. This scheme also had an important role during the injection under pressure, where the compressive stress applied helped preventing the opening of major cracks due to tensile stress applied in the masonry. The holes were also drilled in to the mortar joints, with variable distances between them of about 100 to 200 mm vertically and 250 to 300 mm horizontally, but following a triangular geometrical distribution in the wall façade.

The use of the polyurethane foam as a material to seal the transversal faces of the walls, intended to not adding any stiffness to the walls due to its resilient properties. By the same reason the silicone was used, to seal the major cracks in the wall resultant from the drilling or shrinkage phenomena's, with high probably for grout leakage.

The grouting of each wall started from the bottom row of injection tubes till the top row being reached, in agreement with the good practices of this technique. In Fig. 5 are illustrated some phases of the grouting process.



Figure 6: Walls grouting

Combination of transversal tying and grouting

The combination of transversal tying and grouting was only applied in the wall 3W4 of the third series. This wall had as objective, the evaluation of the potential of this two techniques applied simultaneously, serving as a starting point for future works. To apply the two techniques it was followed the same procedures taken to apply the two techniques individually, described above.

Walls test procedure and test setup

The walls were tested under monotonic compressive loading, using a 2 MN closed-loop servo-controlled testing machine (see Fig. 7a). The tests were performed under displacement control at a displacement increment rate of $3 \mu\text{m/s}$, being stopped during the softening branch when specimens were about to fail, in order to prevent the total collapse of the walls. At the end, whenever possible, walls were dismantled in order to check the efficiency of the strengthening procedure.

The measurements of the displacements of the walls were done by means of LVDTs strategically disposed in the walls, according with two distinct setups, an internal and an external. The internal setup was composed by LVDTs connected directly to specimens and measuring vertical, horizontal and transversal displacements [12] (see Fig. 7b). This setup had an important role in the determination of the elastic properties of the walls. The external setup was constituted by the control LVDT that measured the displacement between the machine plates. This last setup was used to control the test and to obtain the plot of the post-peak force-displacement curve, which was not possible by the internal setup, due to the influence of crack pattern and collapse mechanism in the transducers readings, especially in the vertical displacements.

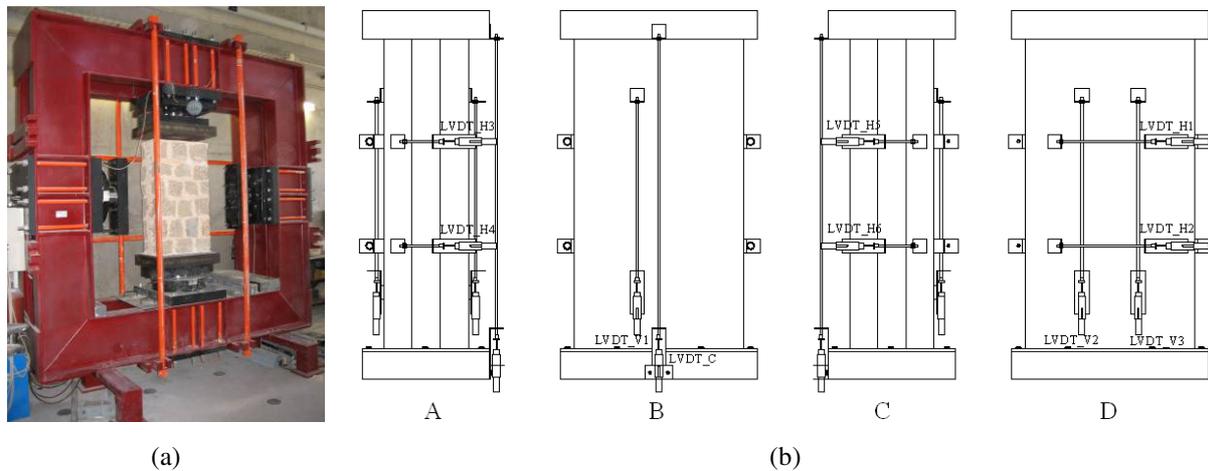


Figure 7: Walls test setup: (a) testing machine; (b) position of the displacement transducers.

Walls tests results

Plain walls

In the Table 3 are summarized the results from the compressive tests on the four unstrengthened walls (associated with the three series) in terms of compressive strength ($f_{c,w}$), peak axial strain ($\epsilon_{a,p}$), peak lateral strain ($\epsilon_{l,p}$), initial Young's modulus (E_0) computed between 0% and 20% of the wall's compressive strength and Young's modulus computed between 30% and 60% of the wall's compressive strength ($E_{[30-60]\%}$). The two stress intervals used to compute the Young's modulus have as objective, evaluate the stiffness degradation with the increasing of the stress levels.

The scattering found in all parameters computed is considerable, mainly for the deformability parameters. This may be due to the influence of workmanship and the variability of natural and handmade materials.

Comparing the two Young's modulus computed, the stiffness drop is evident. On average the drop is of about 44%.

Table 3: Summary of results of the unstrengthened walls.

Wall	$f_{c,W}$ (N/mm ²)	$\varepsilon_{a,p}$ (mm/m)	$\varepsilon_{l,p}$ (mm/m)	E_0 (N/mm ²)	$E_{[30-60]\%}$ (N/mm ²)
1W1	2.3	6.81	3.52	3246	780
1W2	1.7	2.86	4.10	2087	1889
2W1	1.4	9.37	2.69	1422	711
3W1	2.6	3.87	7.85	1733	1351
Average	2	5.73	4.54	2122	1183
CV (%)	27	51	50	38	47

In Fig. 8 are represented the axial stress - axial strain curves of the unstrengthened walls. There, it can be observed two distinct stiffness degradation zones, which seems to be associated to the detachment of the external leaves, which looks to be very fragile, due to instantaneous change of slope of the curves. Moreover, it happens to lower stress levels, of about 25% to 35% of the peak load of the walls. However, this behavior was not observed in wall 1W2 (see also Fig 9 and Table 3), probably due to an unexpected improved connection between leaves, resulting from the construction process of the wall, like the overlapping of some stones of the external leaves into the inner leaf.

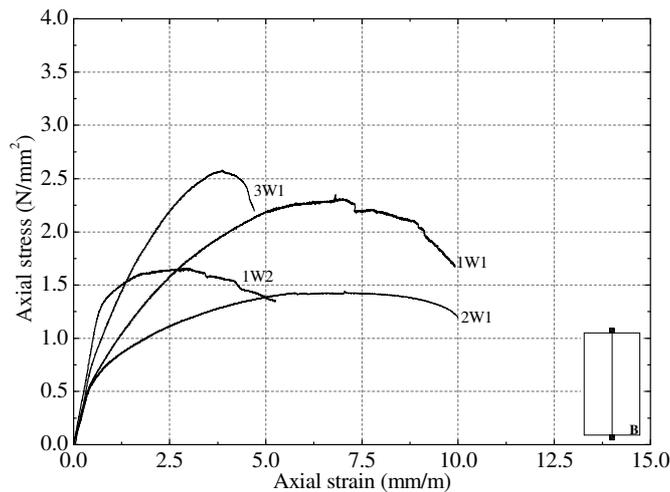


Figure 8: Axial stress - axial strain curves of the unstrengthened walls.

Like in most of experimental works about three leaf masonry walls [3, 9, 10], the observed failure modes of the unstrengthened walls showed that the collapse mechanism of these is governed by the out-of-plane rotation of the external leaves.

In order to evaluate this feature, the adimensional parameter λ is now introduced. This parameter was calculated for each wall using the Eq. 1, and it is an indicator of the state of damage of the walls associated to the development of that typical collapse mechanism. The parameters needed in Eq. 1 are illustrated in the Fig. 9.

$$\lambda = \frac{\sum_{i=1}^4 \frac{\Delta l_i}{h_i}}{4} \quad (1)$$

The relationship between the λ parameter and the axial compressive stress is given in Fig. 10 for the unstrengthened walls. This figure allows to identify the beginning of leaves separation and to better recognize the atypical behaviour of wall 1W2.

Experiments also showed that the out-of-plane rotation of the external leaves was caused by the development of three hinges along bed joints, close both to plates and the middle height of the wall. Vertical cracks contouring the masonry stones are also visible, see Fig. 11. In this figure also can be seen that, cracks are, essentially, concentrated near the developed middle height horizontal hinges, which indicates a non mobilization of all strength available in the external leaves, so the collapse may attributed exclusively to the second order effects of the external leaves.

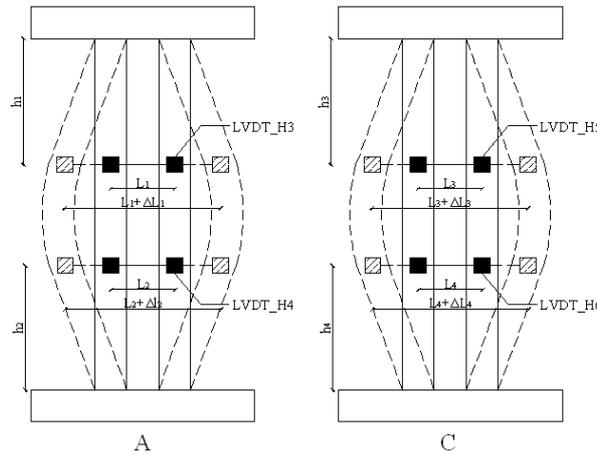


Figure 9: Representation of the typical collapse mechanism of the three-leaf walls.

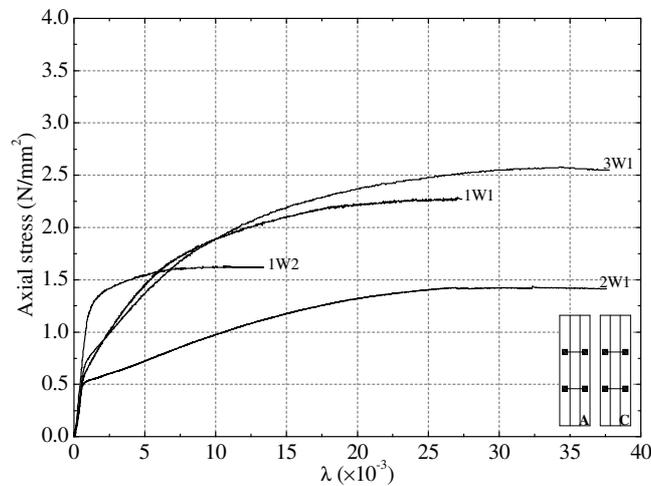


Figure 10: Unstrengthened walls: evolution of the λ parameter with regard to the axial stress.

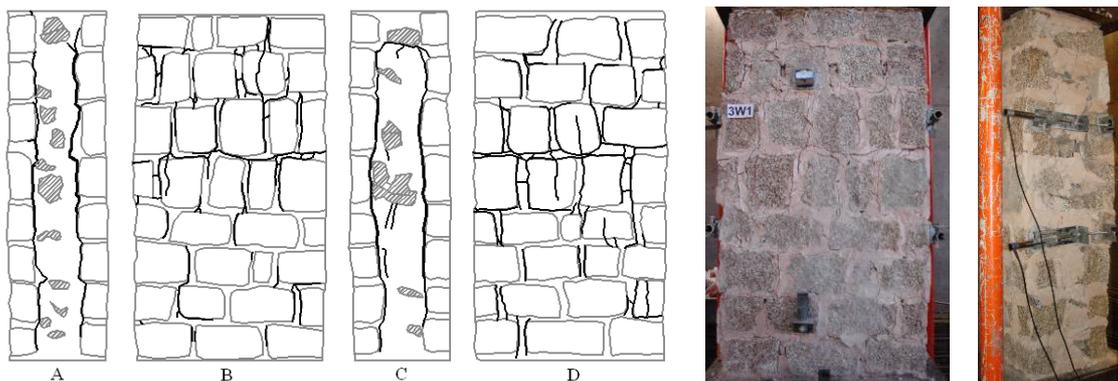


Figure 11: Crack pattern of the unstrengthened wall 3W1.

Walls strengthened with transversal tying

In the Table 4 are shown the summary of the results concerning the three walls strengthened with transversal tying tests.

Also in these results the scattering is considerable, showing again the intrinsic variability of ancient masonry structures.

The transversal tying strengthening allowed a 55% increase of the average compressive strength in relation to the unstrengthened walls. Comparing also the Young's modulus computed, an unexpected lower average values were obtained. This may be due to differences associated to the distinct series, however, the hypothesis of damage induced by the drilling procedure cannot be totally excluded. Though, if the deformability parameters strengthened walls are compared with the ones of the unstrengthened wall of their series (reference wall), an increase of the computed Young modulus E_0 of about 13% can be observed. In the other hand $E_{[30-60]\%}$ had a decrease of 6%.

In what concerns with the Young's modulus drop, the existence of the transversal ties does not prevent the important stiffness reduction observed previously, by the contrary it was higher, at about 59%.

Table 4: Summary of results of the walls strengthened with transversal tying.

Wall	$f_{c,w}$ (N/mm ²)	$\varepsilon_{a,p}$ (mm/m)	$\varepsilon_{l,p}$ (mm/m)	E_0 (N/mm ²)	$E_{[30-60]\%}$ (N/mm ²)
2W2	3.3	9.35	11.05	1954	722
2W3	2.6	5.93	2.97	1707	603
2W4	3.5	9.37	8.26 ^(*)	1160	675
Average	3.1	8.21	7.01 ^(**)	1607	667
Cv (%)	27	51	81 ^(**)	25	9

Note: ^(*) – value corresponding to 99% de $f_{c,w}$, since it was not possible take measurements till peak load being reached.

^(**) – do not include the wall 2W4.

In Fig. 12 are displayed the axial stress - axial strain curves of the walls strengthened with transversal tying. These curves shows a smooth and continuous stiffness degradation with the increasing applied load and not a fast change of slope, dividing them into two distinct zones, as observed for the unstrengthened walls. This means a gradual separation of the leaves controlled by de GFRP rods.

For the walls strengthened with transversal tying the evolution of the λ parameter with respect to the applied stress is displayed in Fig. 13. A sudden increase of the variation rate of λ took place for a stress level close to the peak, while for the unstrengthened walls, this sudden change occurred much sooner.

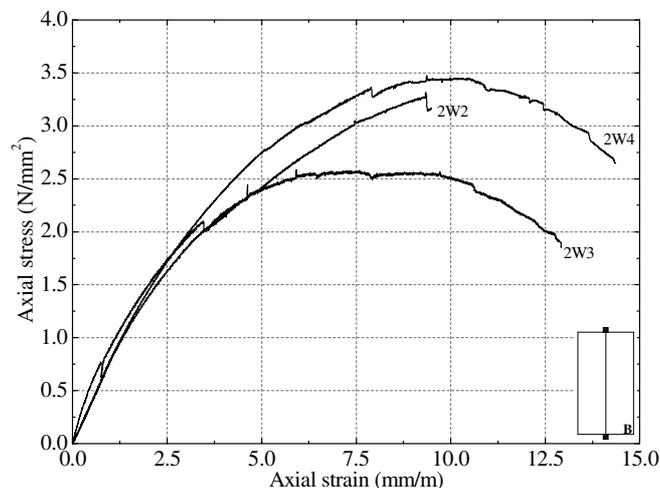


Figure 12: Axial stress - axial strain curves of the walls strengthened with transversal tying.

From above, it can be concluded that the transversal tying technique does not prevent stiffness degradation but makes it happen in a more smooth way, by controlling the external leaves depart before and after the peak load.

The crack pattern for a near-collapse condition is showed in Fig. 14 for the wall 2W4, where can be observed that the vertical cracks are dominant and an absence of important horizontal cracks, showing that transversal tying is able to prevent the formation of the “middle hinge” necessary to the development of the out-of-plane collapse mechanism. Instead of global collapse mechanism due to the external leaves instability, failure happened due to localized instability related to the detachment of parts of the leaves.

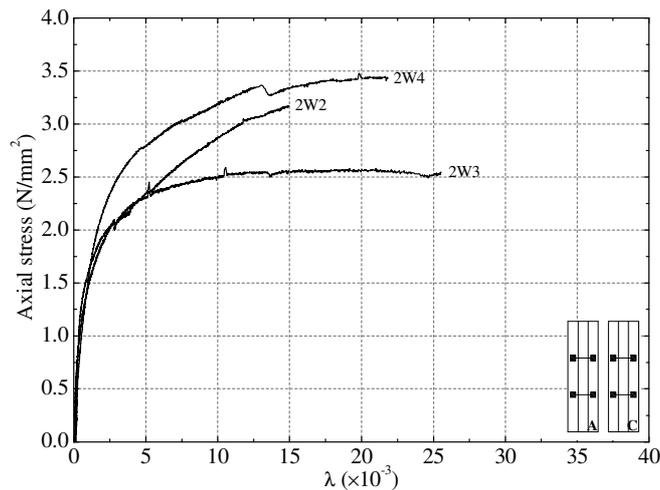


Figure 13: Walls strengthened with transversal tying: evolution of the λ parameter with regard to the axial stress.

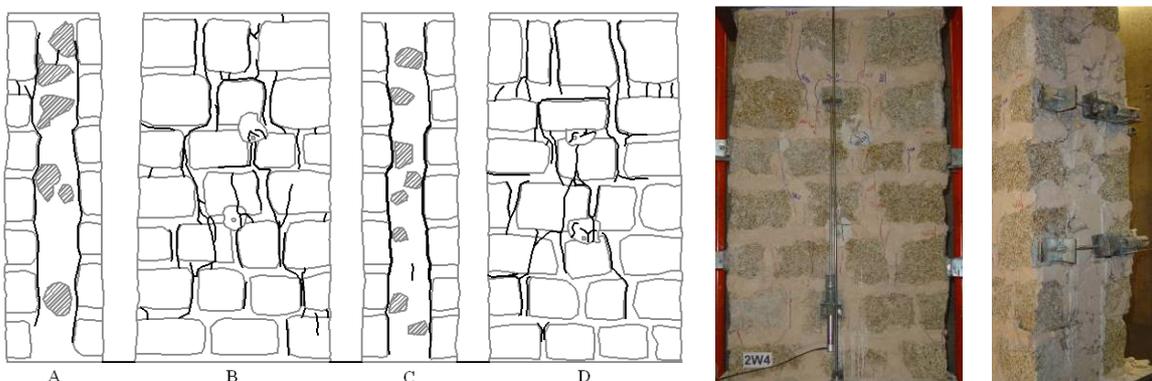


Figure 14: Crack pattern of the wall 2W4, strengthened with transversal tying.

Walls strengthened with grout injection

Table 5 summarizes the main results regarding the injected walls. Now a low scattering was obtained, probably due to a homogenization effect provided by the injection, but the reduced number of tests also influenced it, so this possible effect of the grouting should be evidenced with a new test campaign.

Moreover, the grout injection technique allowed an increase of the compressive strength of about 80% and 16%, when compared with the plain and the tied walls, respectively. Also, comparing the two Young's modulus computed, with the ones of the reference wall of the series (3W1), an increase on both was registered. The modulus E_0 had an increase of 16% and $E_{[30-60]\%}$ an increase of 1%. These increases are due to the addition of a new material (grout), which seems to greatly raise the stiffness of the inner leaf, and so, the stiffness of the walls is slightly increased.

The drop between the two modulus was of about 32%, being inferior to the one obtained for the unstrengthened walls.

According to Toumbakari [10], the injection improves the tensile strength of the walls, which can be confirmed in these walls by the lower lateral peak extension obtained comparatively to the reference unstrengthened walls.

Table 5: Summary of results of the walls strengthened with grout injection.

Wall	$f_{c,w}$ (N/mm ²)	$\epsilon_{a,p}$ (mm/m)	$\epsilon_{l,p}$ (mm/m)	E_0 (N/mm ²)	$E_{(30-60)\%}$ (N/mm ²)
3W2	3.9	7.00	4.74	2172	1604
3W3	3.3	6.87	3.77	1844	1114
Average	3.6	6.93	4.26	2008	1359
Cv (%)	11.0	1	16	12	26

The Fig. 15 shows the axial stress - axial strain curves concerning the injected walls. Like in the curves of the walls strengthened with transversal tying, also here a continuous stiffness degradation zone was observed. However the degradation is less pronounced, maybe due to the homogenization promoted by the injection. The λ parameter near peak of the injected walls shows a considerable increase (see Fig. 16), which means that close to this point the injection technique did not prevent the detachment of the external leaves in the same effective way as when the walls strengthened with transversal tying were tested, still in the before peak phase, the injection greatly controls the detachment.

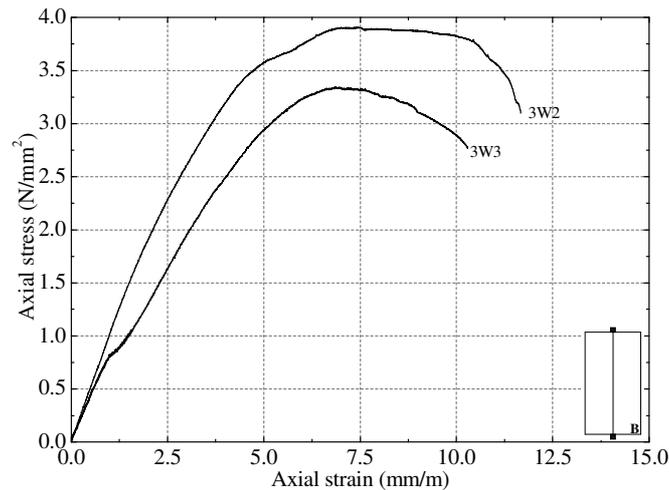


Figure 15: Axial stress - axial strain curves of the grouted walls.

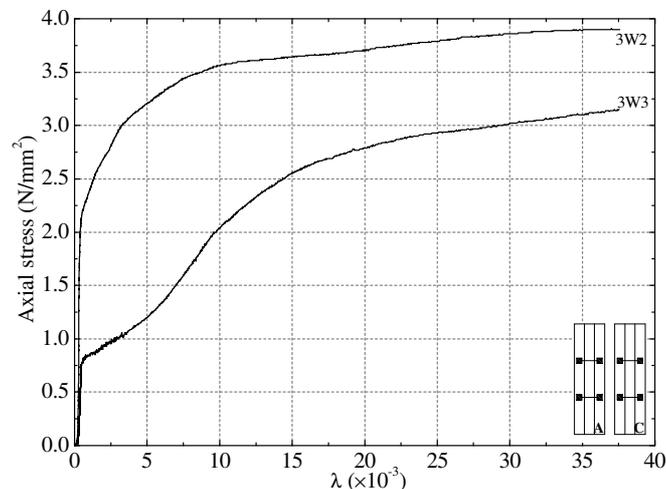


Figure 16: Walls strengthened with grout injection: evolution of the λ parameter with regard to the axial stress.

The odd behavior exhibited by wall 3W3 is most probably due to a deficient injection procedure, leading to the existence of non-injected voids in the core, as found out during the dismantling of the wall, performed after testing. This resulted in a premature and unexpected local detachment of the external leaves, with direct consequences in the compressive strength. This shows the importance in control the quality of this kind of structural strengthening intervention.

The crack pattern near-collapse condition of the wall 3W3 presented in Fig. 17, shows a crack pattern composed mainly by vertical cracks, despite some horizontal cracks started to appear mostly at the end of the test, indicating the incipient onset of an out-of-plane mechanism, which in these walls never reached the development level achieved by the unstrengthened walls.

The Fig. 17 also shows a greatly diffuse crack pattern in the walls façades, being the cracks spread all over its area and predominantly vertical. So injection technique caused a more diffuse crack distribution when compared with the crack pattern from the previous walls, leading also to the development of important cracks in the inner leaf, detected during dismantling. This shows a greater contribution of this leaf in the wall response.

Like for the walls strengthened with transversal tying the failure of the injected walls was due to localized stone cracking and instability, followed by the detachment of stones or parts of the external leaves. The injection technique prevented the full external leaf detachment from happen, but it allowed partial detachments.

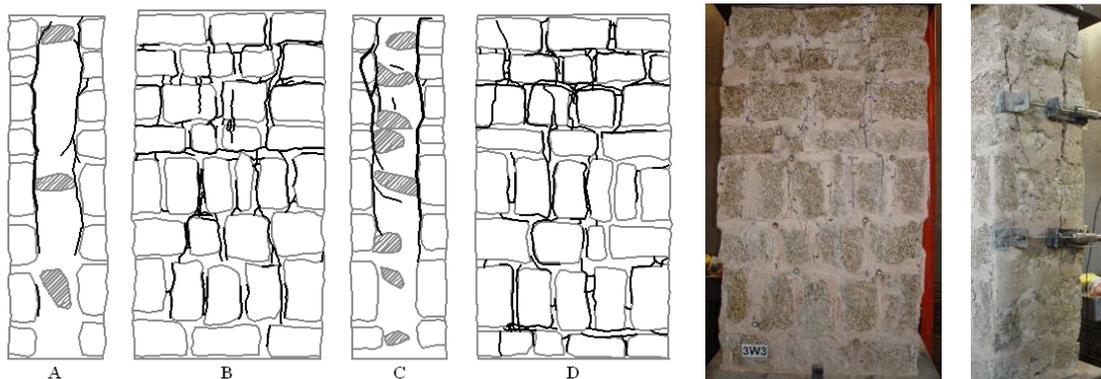


Figure 17: Crack pattern of the wall 3W3, strengthened with grout injection.

Walls strengthened with combination of transversal tying and grout injection

The summary of the results obtained from the tests on the wall strengthened with combination of transversal tying and grouting are presented in Table 6. It must be noted that the number of tested specimens is insufficient to validate the comments provided hereinafter.

In what concerns the compressive strength, the application of the two techniques in simultaneous provided a similar value, on average terms, to the ones reached by the injected walls and slightly higher than the value obtained for the tied walls. Compared with the average value of the unstrengthened walls for this parameter, an increase of 90% was observed.

Also for the young's modulus an increase was registered when compared with the series reference unstrengthened wall. For E_0 the increase was of about 104% and of 37% for $E_{[30-60]}$ %. Such higher increase of these parameters was not expected, however the single wall do not allows clarify if this is a variability problem.

The drop between the two Young's modulus computed was of about 48% which is higher than the obtained for the unstrengthened walls, still the values involved are much superior, besides the variability problem of testing a single wall.

Like for the injected walls, the lateral peak extension was inferior to the obtained for the reference wall, reinforcing the idea that the grouting allows an improvement of the tensile strength of the walls.

Table 6: Summary of results of the wall strengthened with combination of transversal tying and grout injection.

Wall	$f_{c,w}$ (N/mm ²)	$\epsilon_{a,p}$ (mm/m)	$\epsilon_{l,p}$ (mm/m)	E_0 (N/mm ²)	$E_{[30-60]\%}$ (N/mm ²)
3W4	3.8	4.86	1.43	3539	1849

Figure 18 shows the axial stress - axial strain curve of the wall 3W4. This figure allows identifying a smooth and continuous stiffness degradation. This feature is further confirmed by Fig. 19, where the evolution of the leaves' opening (λ parameter) with stress level is represented. These results seem to indicate that the simultaneous use of both strengthening techniques is beneficial in the sense that a better global structural behavior was reached, namely in terms of stiffness degradation and control of the out-of-plane movement of the external leaves, either in the before and post peak phases.

The crack pattern of wall 3W4 observed near collapse is illustrated in Fig. 20. Visible cracks are mainly vertical, which may go trough some stones, with a diffuse crack pattern distribution, spread all over the wall façades area. The wall failure was due to localized stone instability located in the edge of the wall, far from the relatively localized effect of the tie rods. During the wall dismantling huge vertical cracks crossing the entire inner leaf were observed, showing again the greater contribution of the injected inner leaf in the wall response.

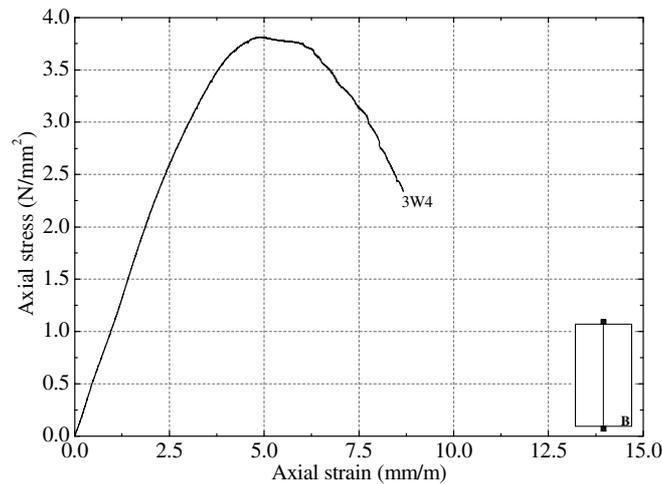


Figure 18: Axial stress - axial strain curves of the walls strengthened with combination of transversal tying and grouting.

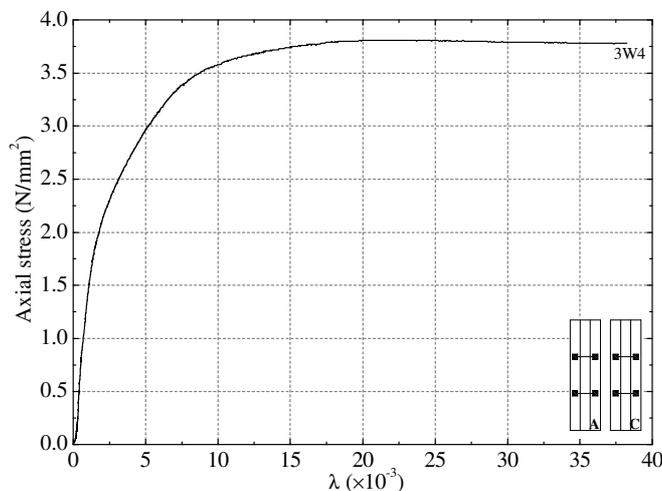


Figure 19: Walls strengthened with combination of transversal tying and grout injection: evolution of the λ parameter with regard to the axial stress.

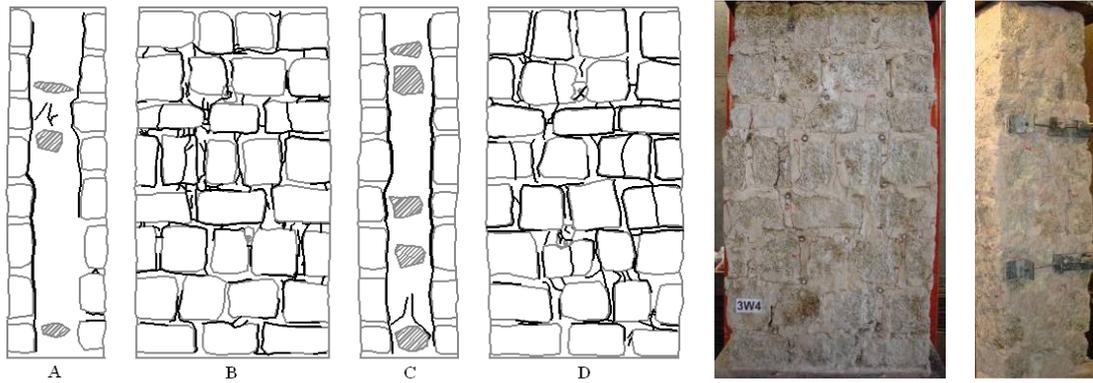


Figure 20: Crack pattern of the wall 3W4, strengthened with combination of transversal tying and grout injection.

Concluding remarks

All the strengthening techniques tested showed a compressive strength increase. The technique that allowed the higher improvement was the combination of injection and transversal tying, with an improvement of 90%, followed by the injection technique with 80% increase and finally the transversal tying with 55% increase of compressive strength.

One major aspect which was present in all results was scattering, mainly scattering between the different series. This influenced the comparison of the average values computed for Young's modulus between the strengthened and unstrengthened walls, which led to an anomalous Young's modulus decreased when shifting from plain to strengthened walls. However, when comparing the strengthened walls with the one unstrengthened built in the same series, it is possible to observe that, on average terms, strengthening usually causes an increase of the initial stiffness, around 13% for walls strengthened with transversal tying, 19% for injected walls and 127% for the combined strengthened wall. However, due to scattering, these figures need further support based on more experimental results.

The transversal tying technique promoted the leaves detachment control in the pre-peak and post-peak phases. In the pre- peak phase the transversal ties led to changes in the stiffness degradation evolution, while in the post-peak, it avoided the development of the typical collapse mechanism evidenced by the absence of major horizontal cracks.

In the same way, injection changed the behaviour of the walls, allowing all leaves to work together till near peak load, by increasing both the connection between leaves and the inner leaf strength, which was noticeable by the diffuse crack pattern and by the presence of big cracks in the inner leaf. In the other hand, after the peak the leaves detachment of the injected walls is not as efficient as in the previous technique.

The results obtained for combined strengthening seem to show that this technique gathered the benefits of both applied separately, however more tests are needed to confirm these aspects.

Acknowledgements

The authors would like to thank the technical staff at the Laboratory of Civil Engineering, University of Minho, for the help provided.

Acknowledgements are also due to the companies Fradical, Mapei and Augusto de Oliveira Ferreira 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] L. Binda, G. Baronio, D. Penazzi, M. Palma, C. Tiraboschi: *Characterization of stone masonry walls in seismic areas: data-base on the masonry sections and materials investigations* (in Italian), L'ingegneria Sismica in Italia, 9th National Conference, Turin, Italy, (1999), 14 pp., CD-ROM.
- [2] A. Anzani, L. Binda, A. Fontana and J. Pina Henriques: *An experimental investigation on multiple-leaf stone masonry*, 13th International Brick and Block Masonry Conference, Amsterdam, July 4-7, (2004), 10 pp., CD-ROM.
- [3] M.R. Valluzzi, F. da Porto and C. Modena: *Behaviour and modeling of strengthened three-leaf stone masonry walls*, Materials and Structures, Vol. 37, (2004), pp. 184-192.
- [4] ICOMOS: *Recommendations for the analysis, conservation and structural restoration of architectural heritage*, International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage, (2001).
- [5] R. Langenbach: *Architectural issues in the seismic rehabilitation of masonry buildings*, D. Abrams and G. Calvi (eds): US-Italy workshop on guidelines for seismic evaluation and rehabilitation of unreinforced masonry buildings. Technical report NCEER-94-0021, (1994).
- [6] C. Modena: *Criteria for cautious repair of historic building. Evaluation and strengthening of existing masonry structures*, Binda L. and Modena C., Ed. RILEM, (1997).
- [7] L. Binda: *The difficult choice of materials used for the repair of brick and stone masonry walls*, 1st International Conference on Restoration of Heritage Masonry Structures, Cairo, Egypt, (2006), CD-ROM.
- [8] L. Binda, C. Modena, G. Baronio and A. Gelmi: *Experimental qualification of injection admixtures used for repair and strengthening of stone masonry walls*, 10th International Brick/Block Masonry Conference, Calgary, Canada, Vol. 2, (1994), pp. 539-548.
- [9] E. Vintzileou and T.P. Tassios: *Three-Leaf Stone Masonry Strengthened by Injecting Cement Grouts*, Journal of Structural Engineering, (1995) pp.848-856.
- [10] E.E. Toumbakari: *Lime-pozzolan-cement grouts and their structural effects on composite masonry walls*. Ph.D. Thesis, Katholieke Universiteit Leuven, Heverlee, Belgium, (2002), 364 pp.
- [11] M.R. Valluzzi, L. Binda and C. Modena: *Mechanical behaviour of historic masonry structures strengthened by bed joints structural repointing*, Construction and Building Materials, Vol. 19, (2005), pp. 63-73.
- [12] D.V. Oliveira, P.B. Lourenço, E. Garbin, M.R. Valluzzi and C. Modena: *Experimental investigation on the structural behaviour and strengthening of three-leaf stone masonry walls*, Structural Analysis of Historical Constructions, New Delhi, (2006).
- [13] J. Pina-Henriques: *Masonry Under Compression: Failure Analysis and Long-Term Effects*, PhD dissertation, Universidade do Minho, Guimarães, (2005) (available from www.civil.uminho.pt/masonry).