On the strengthening of three-leaf stone masonry walls

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ABSTRACT: This paper is devoted to the experimental characterization of the structural behaviour of three-leaf stone masonry walls. The first part of the experimental results described here was presented during the last SAHC Conference (Oliveira et al. 2006). In total ten walls, plain and strengthened resorting to transversal tying, injection and both techniques applied simultaneously, were tested aiming at capturing the detailed structural behaviour. Globally, all strengthening techniques described here showed to be effective in different ways.

1 INTRODUCTION

The multi-leaf typology is very common in historical masonry constructions in the urban centres of Europe, particularly three-leaf stone walls. The latter walls are composed by two external leaves made of stone masonry, using the most abundant stone of the region, and a poor mortar. The inner leaf is usually made of rubble masonry or just an infill of a very weak material (like earth or construction residues), characterized by a substantial presence of voids (Binda et al., 1999). The collapse of this kind of walls is 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 (Valluzzi et al. 2004, Anzani et al. 2004).

To preserve these constructions and to avoid their continuous deterioration, intervention works are often required. However, given their cultural importance and historical value, such interventions must observe certain requirements, such as the use of materials mechanically, physically and chemically compatible with the original ones in order to assure effectiveness and durability of the strengthening and repair interventions, see Modena (1997), ICOMOS (2001) and Binda (2006) for further details. When these recommendations are not taken into account, the works carried out may result in wrong and ineffective interventions (Binda 2006). Most of the times, these problems are related to the lack of knowledge on the material and structure's behaviour, which must be enlightened with extensive research.

Currently, the most used and investigated strengthening techniques, due to the good accomplishment of many of the requirements pointed above, are injection, repointing or deep repointing and transversal tying.

Injection is the most used technique in repair and retrofitting of three-leaf walls mainly because of the simplicity of its application and the effectiveness of its use. The aims of the injection technique are the reduction of the weakness of the internal core, by filling the existing voids and cracks, and the improvement of its adherence to the external leaves, by filling the gaps between leaves. Several studies have been performed in the last years concerning this technique (Binda et al. 1994, Vintzileou et al. 1995, Toumbakari 2002, Valluzzi et al. 2004), however, special attention with regard to material compatibility is needed, which limits the grout selection (Binda, 2006).

A good grout selection depends mostly of the knowledge of the wall to be injected, which determinates the properties required for the repair grout. Nowadays the trend is to use a grout mixture mainly based on lime with a low percentage of cement, in particular when dealing with restoration works in historical constructions. Injection is typically performed by injecting the grout starting from the bottom part of the wall and reaching progressively the top. Usually, for three-leaf walls the injection pressure is very low, not exceeding 50-100 kPa to avoid the undesired detachment of the external leaves.

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. injection).

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 structures with creep problems (Valluzzi et al. 2005). Experimental works with this technique have showed an improvement of the compressive strength.

The transversal tying technique is aimed at improving the connection among leaves, in particular between the external ones, in order to reduce the transverse deformation. 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 improve this last anchoring mechanism, a local grout injection around the tie can be applied instead (Oliveira et al, 2006). 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.

The work presented here deals with the strengthening of three-leaf stone masonry walls, using different strengthening techniques: transversal tying by means of GFRP bars, injection and combination of the two previous techniques. The main objectives of this research are: characterization of the behaviour of three-leaf walls under different strengthening configurations and development of a suitable numerical model able to interpret and explain the structural behaviour of such type of walls. This paper presents the experimental results concerning the testing of three series of walls (ten walls), where the three aforementioned strengthening techniques were applied. Strengthening was applied without any previous induced damage. The test program is summarized in Table 1.

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.

Information about the materials used and mechanical properties of masonry components (external and inner leaves) is also provided.

The experimental results described in a previous paper (Oliveira et al. 2006) are here summarized and all new developments made are described in detail.

2 CHARACTERIZATION OF WALL COMPONENTS

The mechanical characterization of some of the components has been already provided in a previous paper (Oliveira et al, 2006), but for the sake of simplicity, it will be briefly repeated here.

2.1 *Stone*

A locally available granite stone was used to build all walls. Its mechanical characterization was performed in cylindrical specimens of dimensions $\varnothing 100\times200$ mm^2, where the following average values were obtained: compressive strength of 52.2 N/mm^2, Young's modulus of 20.6×10^3 N/mm^2 and Poisson's ratio of 0.24.

2.2 *Mortar*

A 1:3 binder/sand ratio and a 0.8 water/binder ratio were selected (all ratios in weight) in order to obtain a representative mortar composition. 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 behaviour of mortar was assessed using cubic specimens of $50\times50\times50$ mm^3 sampled during the construction of the walls and tested under compressive loading at the ages of 7, 28 and 90 days. Average compressive strengths of 0.5 N/mm^2, 2.9 N/mm^2 and 2.2 N/mm^2 were measured at the aforementioned ages, respectively.

2.3 *GFRP bar and grout*

The transversal tying technique was applied by means of GFRP bars placed transversally to the wall and anchored along the thickness of the external leaves, by means of injected grout. The bond strength between the bar, the grout and the masonry was considered enough to transmit the load from the external leaf to the GFRP bar. Furthermore, 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.

A commercial lime-based grout was used, for both wall injection and bonding of the GFRP bars to masonry. Its mechanical behaviour was assessed by means of cubic specimens of $50\times50\times50$ mm^3 sampled during injection. For the walls strengthened with GFRP bars within series 2, 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. For the walls injected within series 3, grout specimens reached an average compressive strength of 13.7 N/mm^2 (no tensile tests were performed).

2.4 *External leaf*

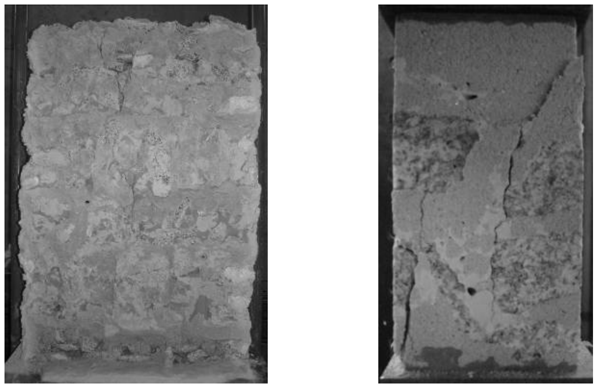
The mechanical behaviour of the external leaf was characterized through a set of representative stone masonry prisms (see Oliveira at al. 2006). An average compressive strength of ~~8.6~~9.21 N/mm^2 and a coefficient of variation of ~~27~~19% were computed for specimens coming from the three series.

2.5 *Inner leaf*

Representative core specimens were also built using granite scabblings poured into alternate layers with mortar and avoiding any compaction, aiming at representing the construction procedure followed for the walls. During the construction of the walls, a total of ten cylindrical specimens of dimensions $\varnothing150\times300$ mm^2 were built. The specimens were tested under uniaxial compressive loading at a displacement control rate of 5 µm/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.

2.6 *Injected inner leaf*

The injected inner leaf was also characterized. For that, seven prisms were sampled from the inner core of the injected walls (3W2 and 3W3) during the dismantling procedure, see Figure 1a. The samples were extracted with average dimensions of 80x80x160 mm^3 (h/d ratio of 2) in order to obtain representative core specimens.
The specimens were tested under uniaxial compressive loading at a displacement control rate of 2.5 µm/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. The low variation coefficient shows that injection allowed for a homogenization of the inner leaf strength.
In Figure 1b it is shown the crack pattern of a tested prism, where it is possible to observe cracks contouring the stone elements.



(a) (b)

Figure 1. Injected inner leaf: (a) general view of a wall's inner leaf; (b) crack pattern of a sampled specimen after testing.

3 WALL TEST PROCEDURES

3.1 *Wall specimens*

As exposed above, the entire ten wall specimens were built with three leaves, two granite masonry external leaves and an inner leaf built with granite scrabblings and mortar, without any compaction, aiming at obtaining an amount of voids representative of this kind of walls, able to allow injection. The average thickness of each leaf was about 100 mm, which wasn't always possible, due to the variable size and shape of the stones used. This feature also influenced the number of courses, which ranged from six to eight courses. The global dimensions adopted for all wall specimens were 600 mm long, 300 mm thick and 1100 mm high, similar to dimensions found in previous works (Vintzileou et al. 1995, Toumbakari 2002, Valluzzi et al. 2004) and aiming at representing 1/2 scaled models of real walls. It is worth to mention that no stones connecting the external leaves were used, in order to both assure the worst conditions found in ancient buildings and provide leaf interfaces for all specimens as similar as possible.

3.2 *Strengthening*

The transversal tying technique was applied and tested in the second and third series of walls. After drilling two holes with a diameter of 20 mm, through the entire wall thickness, at one third and two thirds of specimen's height, GFRP bars with 10 mm diameter were placed and the holes were injected with the aforementioned grout.
The injection technique was applied only in the third series of walls. Due to the low wall thickness, injection was applied just in one side of the walls. For that, the subsequent procedure was followed (see Figure 2): (a) drilling of slightly inclined holes with 14 mm diameter. Their distance varied between 100 mm and 200 mm, depending on the location of

masonry joints; (b) introduction of small plastic tubes with a diameter of 10 mm in the holes; (c) sealing of holes and major mortar joint absences, caused by the drilling process, with silicone to prevent grout leakage; (d) injection of water to verify which tubes were active and to wet the inner leaf; (e) sealing of the transversal sides with polyurethane foam to prevent grout leakage and without adding extra stiffness to walls; (f) preparation of the grout and injection under a low pressure of around 0.1 N/mm^2.

(a) (b) (c)

Figure 2. Wall injection procedure: (a) sealing of transversal sides with polyurethane foam; (b) injection equipment; (c) injection works.

3.3 *Test procedure and test setup*

All walls were tested under monotonic compressive loading, using a 2 MN closed-loop servo-controlled testing machine. 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. Whenever possible, walls were dismantled in order to check the efficiency of the strengthening procedure.

For the measurements of the displacements, an internal setup and an external setup were used. The internal setup was composed by LVDTs connected directly to specimens and measuring vertical, horizontal and transversal displacements (see Oliveira et al. 2006 for further details). 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.

4 WALL TEST RESULTS

4.1 *Plain walls*

Table 2 summarizes the test results for the four unstrengthened walls (associated with the three series) in terms of compressive strength (f_c), peak axial strain ($\varepsilon_{a,p}$), 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 ($E_{[30\text{-}60]}$). The computation of the Young's modulus was performed according to two different criteria in order to assess its degradation with increasing stress levels.

The considerable scattering computed mainly for the deformability parameters is essentially due to the influence of workmanship and the variability of natural and handmade materials.

Table 2. Summary of results of the unstrengthened walls.

Wall	f_c (N/mm^2)	$\varepsilon_{a,p}$ (mm/m)	E_0 (N/mm^2)	$E_{[30\text{-}60]}$ (N/mm^2)
1W1	2.3	6.81	3246	780
1W2	1.7	2.86	2087	1889
2W1	1.4	9.37	1422	711
3W1	2.6	3.87	1733	1351
Average	2.0	5.73	2122	1183
CV (%)	27	51	38	47

Figure 3 represents the axial stress - axial strain curves of the unstrengthened walls. Two distinct stiffness degradation zones can be observed, which seem to be associated to the detachment of external leaves. However, this behaviour was not observed in wall 1W2 (see Figure 3 and Table 2), probably due to an unexpected improved connection between leaves, originated during the construction of the wall.

The observed failure modes of the unstrengthened walls showed that the collapse mechanism of these walls 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. Here, λ is given by the average value of the four rotation angle tangents of the external leaves. This parameter can be seen as a damage measurement of the out-of-plane behaviour. The relationship between the λ parameter and the axial compressive stress is given in Figure 4 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 showed also 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 Figure 5.

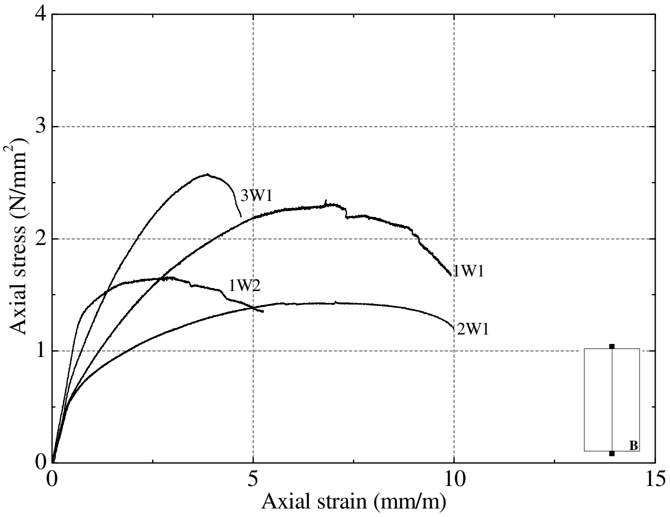


Figure 3. Axial stress - axial strain curves of the unstrengthened walls.

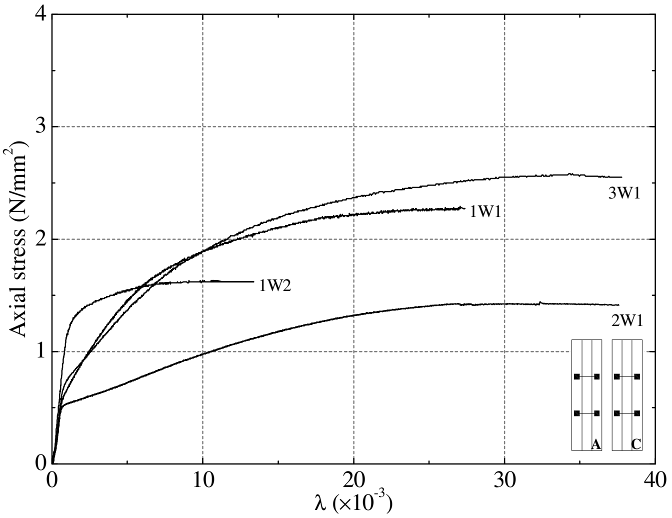


Figure 4. Unstrengthened walls: evolution of the λ parameter with regard to the axial stress.

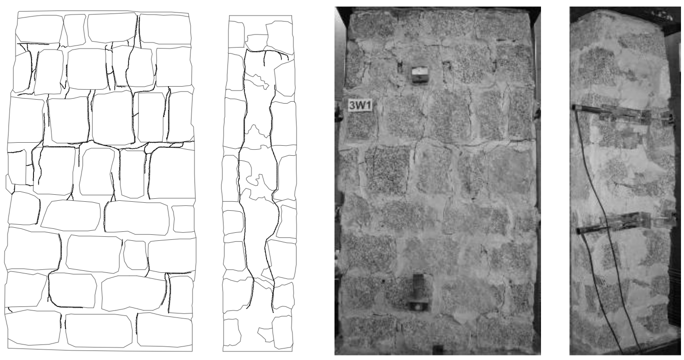


Figure 5. Crack pattern of the unstrengthened wall 3W1 (The top and bottom hinges are not represented).

4.2 *Walls strengthened with transversal tying*

Results concerning the three walls strengthened with transversal GFRP bars are summarized in Table 3.

The presence of the ties allowed a 55% increase of the average compressive strength in relation to the unstrengthened walls. It is believed that the lower value of the Young modulus of the tied walls (using both criteria) is due to differences associated to distinct series, however, the hypothesis of damage induced by the drilling procedure cannot be totally excluded. This feature will be later discussed.

Table 3 also shows that the existence of the transversal ties does not prevent the important stiffness reduction observed previously.

Table 3. Summary of results of the walls strengthened with transversal tying.

Wall	f_c (N/mm²)	$\varepsilon_{a,p}$ (mm/m)	E_0 (N/mm²)	$E_{[30-60]}$ (N/mm²)
2W2	3.3	9.35	1954	722
2W3	2.6	5.93	1707	603
2W4	3.5	9.37	1160	675
Average	3.1	8.21	1607	667
CV (%)	27	24	25	9

The axial stress - axial strain curves of the tied walls are displayed in Figure 6. For these walls it is possible to observe smooth and continuous stiffness degradation with increasing applied load.

The evolution of the λ parameter with respect to the applied stress is displayed in Figure 7 for the tied walls. A sudden increase of the variation rate of λ occurs for a stress level close to the peak, while for the unstrengthened walls, this sudden change occurred much sooner.

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.

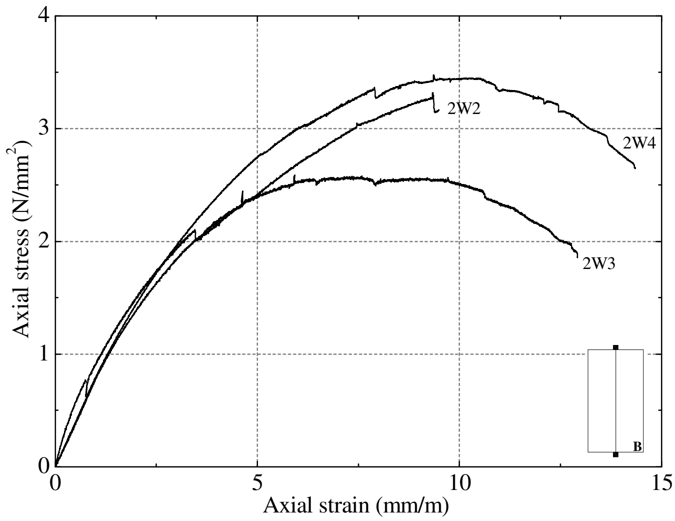


Figure 6. Axial stress - axial strain curves relative to the transversal tied walls.

The crack pattern for a near-collapse condition is showed in Figure 8 (wall 2W4), where vertical cracks are dominant. The absence of important horizontal cracks shows 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, failure happened due to localized instability related to the detachment of some stones.

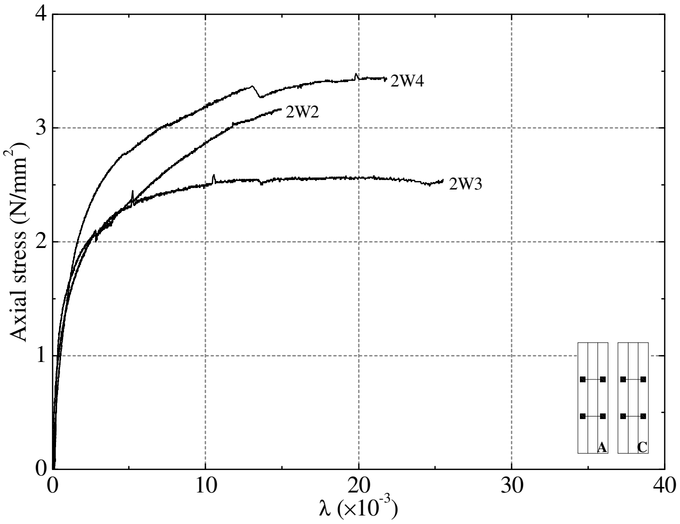


Figure 7. Walls strengthened with the transversal tying technique: evolution of the λ parameter with regard to the axial stress.

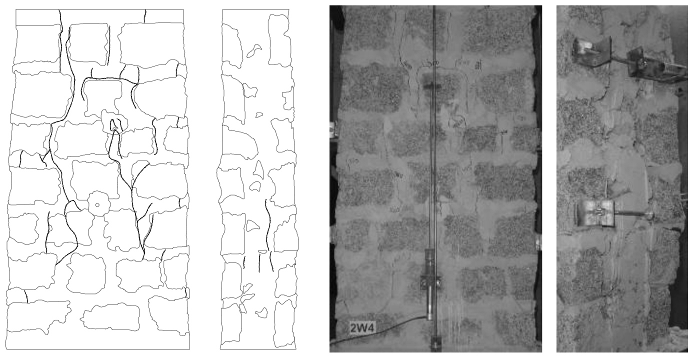


Figure 8. Typical crack pattern of a tied wall (wall 2W4).

4.3 *Injected walls*

Table 4 summarizes the main results regarding the injected walls. A low scattering was obtained, probably due to a homogenization effect provided by the injection, but the reduced number of tests also influenced it.

The injection technique allowed an increase of the compressive strength of about 80% and 16% when compared with the plain and the tied walls, respectively.

Table 4 seems also to indicate that the stiffness reduction with increasing stress is less pronounced for the injected walls.

Table 4. Summary of results of the injected walls.

Wall	f_c (N/mm^2)	$\varepsilon_{a,p}$ (mm/m)	E_0 (N/mm^2)	$E_{[30\text{-}60]}$ (N/mm^2)
3W2	3.9	7.00	2172	1604
3W3	3.3	6.87	1844	1114
Average	3.6	6.93	2008	1359
CV (%)	11.0	1	12	26

The axial stress - axial strain curves concerning injected walls are displayed in Figure 9. Like in the tied walls, also here a continuous stiffness degradation zone was observed, with a considerable increase of the λ parameter near peak, see Figure 10. This means that close to the peak load the injection technique did not prevent the detachment of the external leaves in the same effective way as when the tied walls were tested.

The odd behaviour 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.

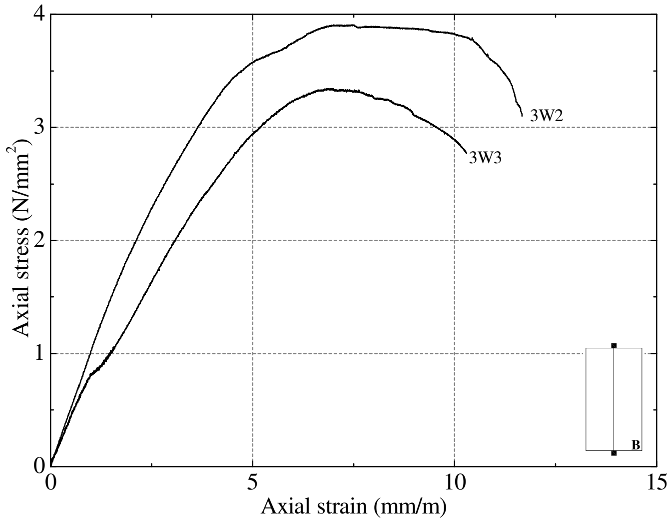


Figure 9. Axial stress - axial strain curves concerning injected walls.

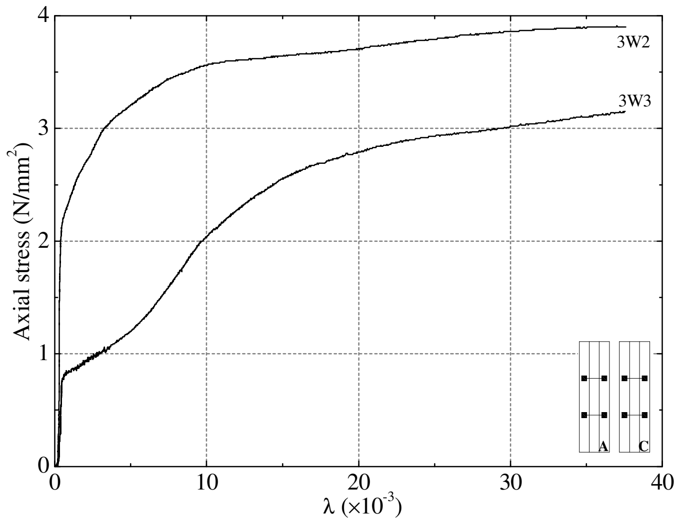


Figure 10. Injected walls: evolution of the λ parameter with regard to the axial stress.

The crack pattern for a near-collapse condition is showed in Figure 11 (wall 3W3), being composed mainly by vertical cracks, despite some horizontal cracks started to appear, indicating the incipient onset of an out-of-plane mechanism, which in these walls never reached the development achieved by the unstrengthened walls.

The 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.

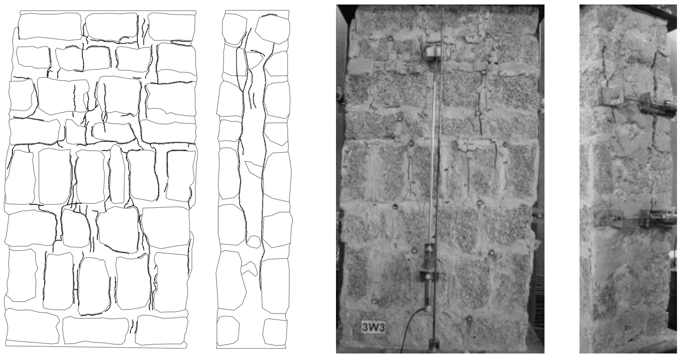


Figure 11. Crack pattern of injected wall 3W3.

Failure of the injected walls was due to localized stone cracking and instability, followed by the detachment of stones. The injection technique prevented the full external leaf detachment from happen, but it allowed partial detachments.

4.4 *Combined strengthening technique*

Aiming at assessing the combined use of the two previous techniques, one wall was simultaneously injected and strengthened with transversal GFRP ties. Table 5 summarizes the obtained results. It must be noted that the number of tested specimens is insufficient to validate the comments provided herein.

Table 5. Summary of the results of the wall subjected to injection and transversal tying.

Wall	f_c (N/mm^2)	ε_{ap} (mm/m)	E_0 (N/mm^2)	$E_{[30\text{-}60]}$ (N/mm^2)
3W4	3.8	4.86	3539	1849

On average terms, the compressive strength reached is close to the value obtained for the injected walls and slightly higher than the value obtained for the tied walls.

Figure 11 shows the axial stress - axial strain curve of the 3W4 wall. This figure allows to identify smooth and continuous stiffness degradation. This feature is further confirmed by Figure 12, 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 behaviour was reached, namely in terms of stiffness degradation and control of the out-of-plane movement of the external leaves.

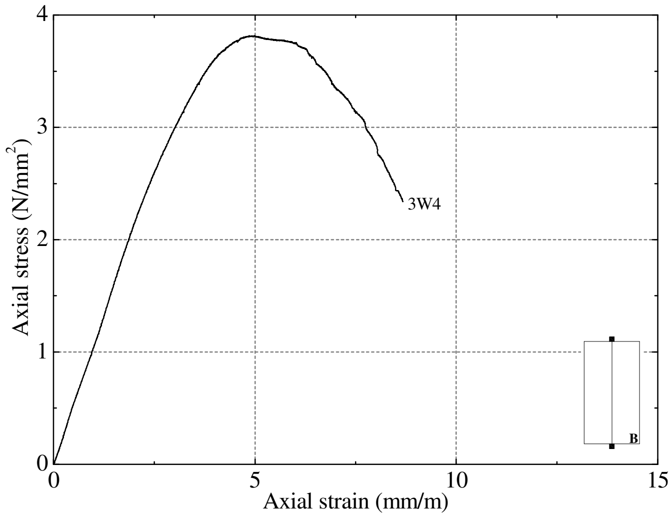


Figure 11. Axial stress - axial strain curve relative to wall 3W4 (combined strengthened wall).

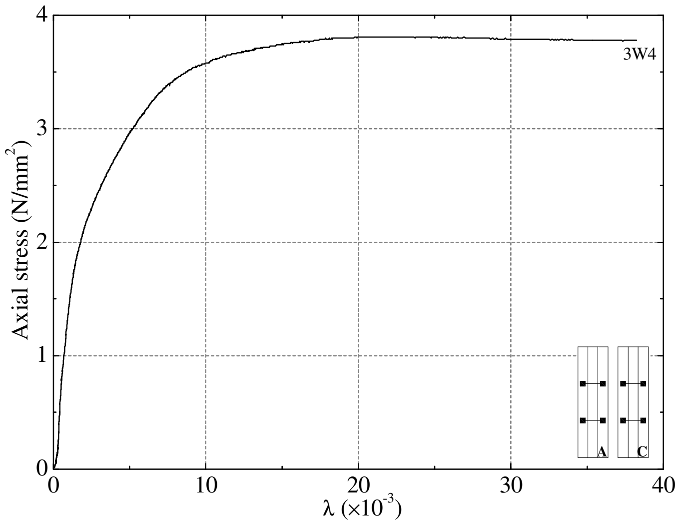


Figure 12. Combined strengthened wall: evolution of the λ parameter with regard to the axial stress.

Figure 13 illustrates the crack pattern of wall 3W4 observed near collapse. Visible cracks are mainly vertical, which may go trough some stones, with a diffuse crack pattern distribution. 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 bars. During the wall dismounting huge vertical cracks crossing the entire inner leaf were observed.

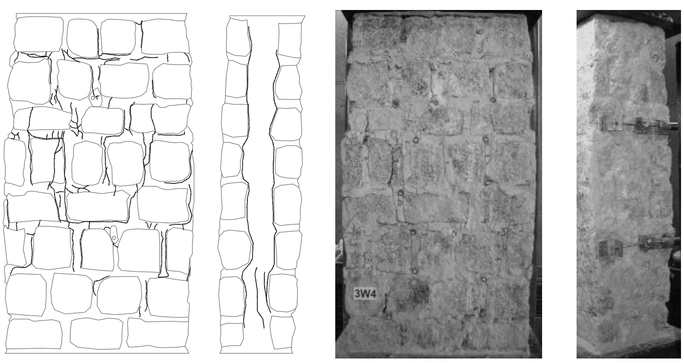


Figure 14. Crack pattern of wall 3W4 (combined strengthened wall).

5 CONCLUDING REMARKS

The test results on three-leaf walls showed that both strengthening techniques, applied either individually or in a combined fashion, have led to compressive strength enhancements. The technique that allowed the biggest 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.

Due to scattering and differences among series, it was observed that the Young's modulus decreased when shifting from plain to tied walls, which might be considered an anomalous behaviour. However, when comparing walls built in a same series, it is possible to observe that, on average terms, strengthening usually causes an increase of the initial stiffness, around 13% for tied walls, 19% for injected walls and 127% for the combined strengthened wall. It is worth to mention that, due to scattering, these figures need further support based on more experimental results.

The transversal tying technique promoted the leaves detachment control, which caused changes in the stiffness degradation evolution as well as in the crack pattern, with 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.

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

Finally, it is important to refer that scattering is a key issue when dealing with historical constructions as well as with natural and handmade materials.

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