Behaviour of multi-leaf stone masonry walls strengthened by different intervention techniques

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ABSTRACT: In the paper, the performances of three-leaf stone masonry walls repaired by three different techniques (injections, repointing and transversal tying), applied both singularly and in combination, are compared. The mechanical behavior has been pointed out by a series of laboratory tests on real size section walls before and after interventions. Feasibility problems, execution aspects and effectiveness evaluations of the techniques are also discussed.

1 INTRODUCTION

Multi-leaf stone masonry walls are very common in many European historical centers (Italy, Greece, Slovenia, etc..), many of which characterized by medium-high seismic hazard. Such walls are characterized by the use of poor materials, an irregular morphology and by the presence of voids, often concentrated in a loose internal core. The causes of the main structural problems of those walls are: (i) the weakness of the internal layer, (ii) the deterioration of the mortar in the external joints and (iii) the lacking of the connection among the whytes. As a consequence, they are very sensitive to brittle collapse mechanisms, which usually happen, both under vertical and horizontal loads, by the detachment of the layers and out-of-plane expulsions.

In such connection, an experimental study on the mechanical behavior of three-leaf stone masonry walls has been recently performed at the University of Padua. Seventeen rubble stone walls, 140 cm high, 80 cm wide and 50 cm thick, have been subjected to compressive loads tests before and after repair.

The experimental campaign was defined on the basis of the assumption that the choice of a proper intervention cannot disregard the knowledge of the type of masonry (typology, materials, etc..) and the structural behavior connected to the specific deficiency to eliminate. Therefore, a particular attention was taken in choosing the geometrical and the morphological characteristics and the constituent materials of the walls to test, to make them as much as possible representative of the real typologies available in situ. Moreover, with conservation purposes, an important effort was done to define and detect materials and techniques as much as possible compatible (from a mechanical, physical and chemical point of view) with the original materials.

As for the intervention choice, three repair techniques have been involved in the study: (i) injections, (ii) repointing of the mortar joints, and (iii) the transversal tying through the thickness of the wall. Such techniques are considered to apply both singularly and in the possible combinations, depending on the real conditions detected on site. In particular, the application of all the three techniques can lead to a possible "integrated intervention", characterized by the consolidation of the inner core (by the injection) extended, in case, to the outside (by the repointing), and by the improvement of the connection between the layers (by the tying and the injection itself).

In all cases lime-based mortars and admixtures have been considered, for a better compatibility with the existing materials and a consequent durability of the intervention. In particular, two types of grouts, having the same fluidity but different strength have been used for the injection of the walls. Rheological and stability measures (fluidity, bleeding and segregation), and injectability tests on cylinders were preliminary performed in order to detect the proper characteristics of the admixtures to inject in the real walls. In such connection the use of different additives were investigated (a superplasticizer and a water retaining, also used in combination) (Valluzzi 2000). As for the repointing technique, two different execution ways of filling the joints have been compared, as well as the use of two different anchorage systems for the transversal ties intervention.

The mechanical behavior of the walls before and after intervention is discussed in terms of strength, stiffness and deformability parameters evaluated in all the three dimensions. Moreover, the on site control during the execution of the intervention pointed out some useful indications to improve the effectiveness of the single and the combined techniques.

2 DESIGN AND CONSTRUCTION OF THE TEST SPECIMENS

The design of the test specimens was mainly based on the analysis of a large on site research performed by the Polytechnic of Milan in recent years (Binda 1998, Binda et al. 1999), describing about 250 wall sections, and on laboratory tests and on site surveys of more than 70 existing walls available in literature (da Porto 2000).

The specimens are 0.80 m wide, 1.40 m high and 0.50 m thick. In particular, the thickness was given by the average value detected for existing walls (da Porto 2000), whereas width and height were chosen with regard to their influence in compressive tests procedures (Bettio et al. 1993).

The two external leaves, approximately 18 cm thick each, consists of rough-shaped limestone blocks having the highest dimension of about 25 cm, arranged in sub-horizontal courses, with mortar joints having thickness varying from 1 to 4 cm. The internal core, about 14 cm thick, has been built with mortar and limestone scabblings (derived from the rough-shaping of the stones), poured into not compacted layers between the two external leaves, so that a certain amount of voids was created. The thickness ratio between external and internal leaves (1:0.78), besides reproducing a typical ratio collected in the north-eastern part of Italy, is the average between the values detected for existing walls (1:0.55) and laboratory specimens (1:1).

The walls were characterized by a proportion of 68% of stones, 22-17% of mortar and 10-15% of voids. Such percentage of voids is in agreement with real values detected in a group of walls defined as with high probability injectable (Binda et al. 1999). Therefore, the panels were dimensioned with a percentage of voids and a thickness ratio such that the effects of the injections will make clear, but being however sufficiently representative of real walls, as obtained by the deep analysis of the literature cases.

To reproduce the worst wall conditions, no constructive transversal connection has been provided through the leaves. For the handling and the load distribution, two concrete beams, 20 cm high each, were built on the bottom and on the top of the specimens. The walls were built as a one whole wall, and then cut into 17 parts with a wire saw, after 3 weeks curing (Fig. 1).

The materials used for the construction have combined the exigencies of reproducing historical walls conditions (e.g. chemical and mechanical characteristics of mortar, composition of the internal core, etc.) and of using local and easy-to-find materials.

Therefore, the limestone used has been taken from the Cugnano quarry, located in the north-eastern part of Italy. Its compressive strength, measured on cubes (71x71x71 mm), was about 164 MPa. The lime mortar is composed by a binder of natural hydraulic lime and lime putty (in ratio 1:3), and has a ratio lime/sand equal to 1:3 and a ratio water/binder equal to 0.5. The compressive strength of such mortar, measured on 40x40x160 mm prisms after 28 days of curing, was found equal to 1.57 MPa.

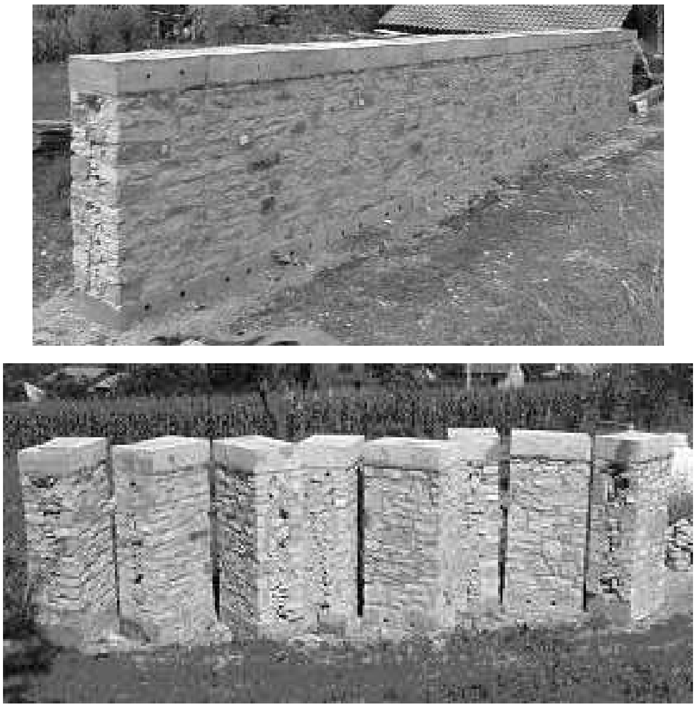

Figure 1 : View of the entire wall built and of some of the 17 specimens obtained after the wire sawing.

3 EXPERIMENTAL PROGRAM

The experimental test program is resumed in Table 1. The specimens were labelled with progressive numbers and alphabetic indexes referred to the applied strengthening techniques: injection of two different grout admixtures (I1, I2), repointing (R), transversal tying (T), and their possible combinations. Walls 1 up to 9 were tested before (after 28 days of curing) and after intervention (about 60 days after construction), whereas walls 10 to 17 were tested under cyclic loads only after strengthening. In the repaired/strengthened condition the first loading cycle was led to the same stress level reached at the maximum load during the test on original walls, so a direct comparison between deformations and cracks patterns was allowed.

The compressive tests were performed under load control, with vertical increments of a rate about of 0,25 kN/s. Six displacement transducers were used to measure the deformations under loading: two vertical W20 (20 mm of maximum deformation) and two horizontal W10 (10 mm of maximum deformation) on each main façade of the walls, and two horizontal W10 on each transversal section (see Figs. 2 and 3).

To compare the destructive tests with on site NDT and MDT evaluations, some of the walls were subjected also to sonic and double flat jacks tests.

Table 1 : Experimental program.

Wall label	Strengthening technique	Compression test before/after intervention	Compression test only after strengthening	Flat jacks before/after intervention	Sonic tests before/after intervention
4X	None	4X$^{(*)}$	-	-	-
5I1, 6I1, 13I1	Injection 1	5I1, 6I1	13I1	5I1	5I1, 6I1, 13I1
1I2, 8I2,16I2	Injection 2	1I2, 8I2	16I2	-	1I2, 8I2,16I2
3R, 7R, 15R	Repointing	3R, 7R	15R	3R	3R, 15R
2T, 9T, 11T	Steel Ties	2T, 9T	11T	-	-
14I1R	I1 + R	-	14I1R	-	14I1R
12I1T	I1 + T	-	12I1T	-	-
10RT	R + T	-	10RT	-	-
17I1RT	I1 + R + T	-	17I1RT	-	-

$^{(*)}$ non-repaired wall, tested at the same times of the repaired ones (28 and 60 days after construction).

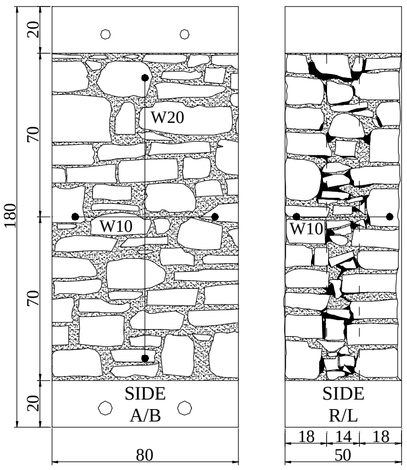

Figure 2 : Geometrical characteristics of the walls and measurement points.

Figure 3 : Experimental set-up.

4 STRENGTHENING TECHNIQUES

4.1 Injection of grouts

The injection of grouts was performed on nine walls (s. Table 1), in order to fill the voids, consolidate the weak internal core and improve its adherence with the external layers.

The two injection admixtures used, all made of natural hydraulic lime binder, were selected through physical, chemical, rheological, mechanical and injectability tests (Valluzzi, 2000). The grout I1 is a basic mixture with a superplasticizer additive (0.25% on the lime weight), whereas the I2 one is a commercial mixture ready for use.

The selected grouts have been subjected to mechanical tests, after 28 days curing, on 40x40x160 mm prisms. Mechanical tests (28 days after injection) have been carried out also on cylinders filled as the core of the real walls and grouted for injectability tests. Some results are shown in Table 2.

Table 2 : Characteristics of injection grouts and cylinders.

Injection grouts	Water/lime Ratio	Density	Compressive strength of grouts (28 days)	Compressive strength of injected cylinders
	-	kg/m^3	MPa	MPa
I1	0.5	1.8	5.10	2.07
I2	0.5	2.0	3.20	0.81

Before grouting, a series of injection holes have been drilled on one side of the walls, spaced of about 25-30 cm one to the other, following approximately a scheme of equilateral triangles. A number of 11-12 holes per m^2 were used. Such holes distribution was arranged to assure the complete injection of the voids and to check the diffusion of the grout during the intervention. Actually, about the 70% in average of the holes were really injected. To the same purpose, some checking holes were drilled also on the other surfaces, that is on the two lateral sections and on the not injected façade. Subsequently, plastic tubes (9 mm internal diameter, 12 mm external) have been introduced and sealed into each hole. The lateral sections have been roughly sealed with plaster to avoid excessive leakages of grout, but allowing some small outflows. In Fig. 4 a wall ready to be injected can be seen.

The grouts have been injected under low pressure (around 0.5 atm) into the hoses starting from the bottom of the walls, even if keeping the pressure constant was a noticeable difficulty encountered. To reproduce the real absorption of old mortars in dehydrated walls, no preventive injection of water was done. As a consequence, during injections, the leakages from the cracks (Fig. 5) and the hoses (Fig. 6) revealed a lower fluidity of the overflowing grout, despite their good original fluidity.

The diffusion and the propagation of the grouts inside the wall were controlled during the whole injection phase; the recording of the amount and the time of grouting allowed to detect information about the percentage of the filled voids and the duration of the intervention (see Table 3).

Table 3: Quantity of injected grouts.

Wall	Injected grout l	Injected grout/ internal leaf volume l/m^3	Injected grout/ entire wall volume l/m^3	Derived percent. of voids %	Time of grouting -
5 I1	85	542	152	15.2	42’20”
6 I1	85	542	152	15.2	45’10”
13 I1	65	415	116	11.6	45’45”
1 I2	85	542	152	15.2	45’30”
8 I2	75	478	134	13.4	60’30”
16 I2	75	478	134	13.4	29’10”
12 I1T	85	542	152	15.2	42’
14 I1R	95	606	170	17.0	31’55”
17 I1RT	75	478	134	13.4	30’45”
Average	81	517	144	14.4	~36’30”

The injection procedure has been quite fast and easy to perform. The entire intervention, including also the preliminar preparing of the wall and the subsequent removal of the hoses and the sealing of holes, has lasted about $1^h30'$. The average quantity of injected grout is about 80 l per wall, which corresponds, assuming the whole filling of the walls, to a mean percentage of voids of 14.4%, which confirmed the initial assumptions. After rupture, the visual inspection of the wall confirmed the filling of all the voids and cavities and revealed a good bonding between the injection material and the existing mortar.

Figure 4: View of a wall before injection

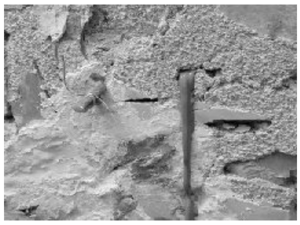

Figure 5: Leakage from a joint

Figure 6: Leakage from an injection hose

4.2 *Mortar joints repointing and transversal tying*

The repointing of the mortar joints and the transversal tying through the thickness of the walls were applied on six walls each (s. Table 1).

The repointing technique consists in the removal of the external layers of the joints and the filling by mortar having better characteristics of the existent one; the aim is to restore possible deteriorated mortar joints, to re-establish the bond among the stones and, consequently, to improve the strength of the walls.

The technique was applied on both sides of the walls, and a natural hydraulic lime mortar, premixed with sand, was used to fill the excavated joints. Its compressive strength, measured on 40x40x160 prisms after 28 days, was equal to 1.72 MPa.

The existing mortar was removed to a changeable depth (5 up to 8-10 cm), controlled during the execution to ensure at least a minimum filling of the joints with the new mortar. The excavation of the joints was obtained first by an electric hack hammer (see Fig. 7) and then by hand with hammer and chisel. Some problems related to the stability of stones occurred during the mechanical removal of the original mortar, and led to a less depth of the involved joints.

In some cases, the joints were filled with a first layer of mortar that, after a short curing (about 30', to allow the mortar to achieve the sufficient plasticity), was pressed and covered with a finishing sealing. On the contrary, in connection to the abovementioned problems, some of the walls were repointed with a single layer of mortar (Fig. 8). Before the filling phases, the joints were previously washed with water, to remove small rubbles and dust and to limit the water absorption of the wall from the repointing material, in order to improve the bond between the new and the original mortar. After the intervention, a finishing brushing of the joints was performed.

Due to the accuracy of the two main phases of the execution (excavation and filling of the joints), the intervention has been particularly lengthy, lasting from $2^h15'$ up to $3^h30'$. For each wall a quantity of about 40-60 kg of repointing mortar was used, which corresponds to a consumption of 18-27 kg/m^2 of mortar on the wall surface.


Figure 7: Mechanical excavation of the joints


Figure 8: Filling of the joints with new mortar


Figure 9: Bending of reinforced steel bars


Figure 10: Tying with threaded bars

Finally, the application of transversal ties was considered; the main scope of the technique is the improvement of the connection between the leaves and the consequent reduction of the transversal deformations. Four bars were used for each wall (around 3.5 bars per m^2), inserted into holes drilled at 1/3 of the height from the bottom and the top, and at 1/4 of the width from the left and the right sides of the wall. The holes were executed through corresponding mortar joints, where possible; otherwise the stone blocks, that were quite workable, were directly bored.

Two different kinds of steel ties have been used: reinforced bars (6 mm in diameter) and threaded bar (8 mm in diameter), both having a tensile strength of about 600 MPa. Therefore, two anchorage systems were adopted: the reinforced steel bars were simply introduced into the holes, bended for a length of approximately 15 cm into previously excavated joints and then covered with new mortar (see Fig. 9). On the contrary, the threaded bars were used in the case of stone-through holes; they were fixed by washer and bolt against the stone, and eventually hidden into artificial joints obtained by the rough-shaping of the stones themselves (such technique was applied on the wall 2T, see Fig. 10).

Due to the narrow working area (the excavated joints) the bending of the second tip of the reinforced steel bars has been particularly problematic. Nevertheless, since to simplify the execution phase no injection of the holes was planned to be performed after the placement of the tie, the correct completing of the bending has great importance, in order to ensure an adequate anchorage to the bars. On the contrary, the use of threaded bars has been very easy, but it can require particular aesthetical solutions.

However, transversal tying revealed to be feasible, especially with regard to the short duration of the intervention (less then 1^h per wall).

5 COMPRESSIVE TESTS RESULTS

5.1 Original walls

Before the interventions, the maximum strength of the tested walls ($f_{wc,0}$) varies between 0.99 and 1.97 MPa; however, evident cracks patterns already started at a stress level varying from 0.55 to 1.09 MPa. The average value of the secant modulus of elasticity (calculated between the 30% and the 60% of the maximum strength) is of about 1700 MPa.

No retrieval of strain during the unloading phase was detected, probably because of compaction of the voids and of the mortar (cured for 28 days before the testing). Similar values were detected for the ultimate strains both in the vertical and horizontal transducers (0.2 to 6.5‰, as absolute value), whereas much higher deformation were recorded in the transversal section, varying from 1.3 up to 19.6‰. The cracks had a vertical or sub-vertical trend, as expected for a compressive failure. Most of them were located in the transversal sections, between the different leaves, so the collapse occurred by the detachment of the layers and out-of-plane expulsions.

5.2 Injected walls

Twenty-eight days after grouting, the average value of the maximum strength ($f_{wc,s}$) is about 2.5 MPa. The maximum strength is thus increased in average of about 40%, compared to the maximum strength of the non-consolidated walls, but it reaches increments up to the 70% (wall 5I1).

The final strength of grouted walls does not apparently depend on the compressive strength of the injected grout. In fact, the same average value of compressive strength was detected for walls injected both with the grouts I1 and I2, whereas the compressive strength of grout I2 was about the 60% of the compressive strength of I1, as shown in Table 2. In such connection, the results of an analysis recently performed by the authors showed that the use of high strength grouts (compared to the original strength of the walls) can be unnecessary, because they are not able to increase with the same contribution the final strength of the wall (Valluzzi et al 2001).

The modulus of elasticity (calculated between the 30% and 60% of the strength reached during the first loading cycle) varies between 1223 MPa and 3992 MPa, showing an average increase of about the 35%. The final values of stiffness are anyway still compatible with the elastic characteristics of existing stone masonry walls. In Fig. 11 an example of a typical stress-strain diagram (wall 6I1) is given. At the end of the first loading cycle, at the same stress level of the maximum load detected in the non-consolidated walls, a strong reduction of the crack pattern (see Fig. 12) and of vertical, horizontal and trasversal strains were detected (see Table 4, where negative values of the strains indicate dilation). When maximum strength is reached on grouted walls, the deformations show different trends: both vertical and horizontal strains are higher then of the non-consolidated walls, varying both from 4.2 and 10.7‰ (absolute values). Therefore, considering the higher compressive strengths reached after grouting, it is possible to state that, in the plastic phase, the walls have a better behavior after grouting. Vice versa, the transversal strain is in general lower after grouting than before, so the grout injections are efficient in homogenizing the wall and preventing the detachment of the leaves. In any case, strains start at a stress level even ten times higher than on the non-consolidated walls (Fig. 11).

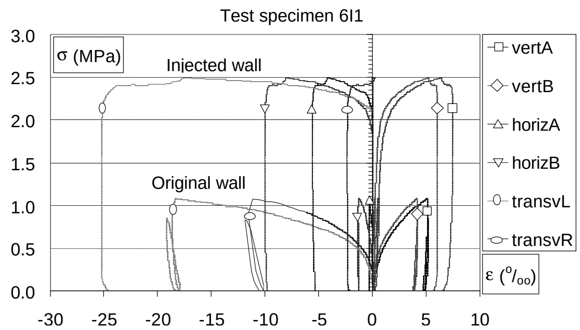

Figure 11: Stress-strain diagram after (at final strength) and before (at first loading cycle) injections.

Table 4: Mechanical characteristics and strain of injected walls, before and after repair

Wall	Compressive strength; MPa		Elastic modulus (30÷60%); MPa		Vertical strain ‰			Transversal strain ‰		
	Before ($f_{wc,0}$)	After ($f_{wc,s}$)	Before ($E_{wc,0}$)	After ($E_{wc,s}$)	Before at $f_{wc,0}$	After at $f_{wc,0}$	After at $f_{wc,s}$	Before at $f_{wc,0}$	After at $f_{wc,0}$	After at $f_{wc,s}$
5I1	1.45	2.49	2390	2273	3.63	0.49	7.26	-4.49	-0.004	-9.17
6I1	1.95	2.49	2029	3093	4.57	0.36	5.71	-18.4	-0.003	-17.1
13I1	--	2.54	--	3992	--	0.55	9.91	--	-0.12	-27.7
1I2	1.97	2.57	1450	3449	6.21	0.58	6.25	-7.93	-0.32	-7.34
8I2	1.91	1.82	1559	2367	6.22	0.73	7.20	-11.8	-0.08	-9.90
16I2	--	2.48	--	1223	--	1.07	10.7	--	-0.22	-18.9
12I1T	--	2.59	--	1336	--	0.78	8.18	--	-0.04	-15.9
14I1R	--	2.14	--	1617	--	0.71	8.21	--	-0.01	-19.6
17I1RT	--	3.06	--	1772	--	0.63	8.24	--	-0.001	-21.9
Average	1.82	2.46	1857	2347	--	--	--	--	--	--

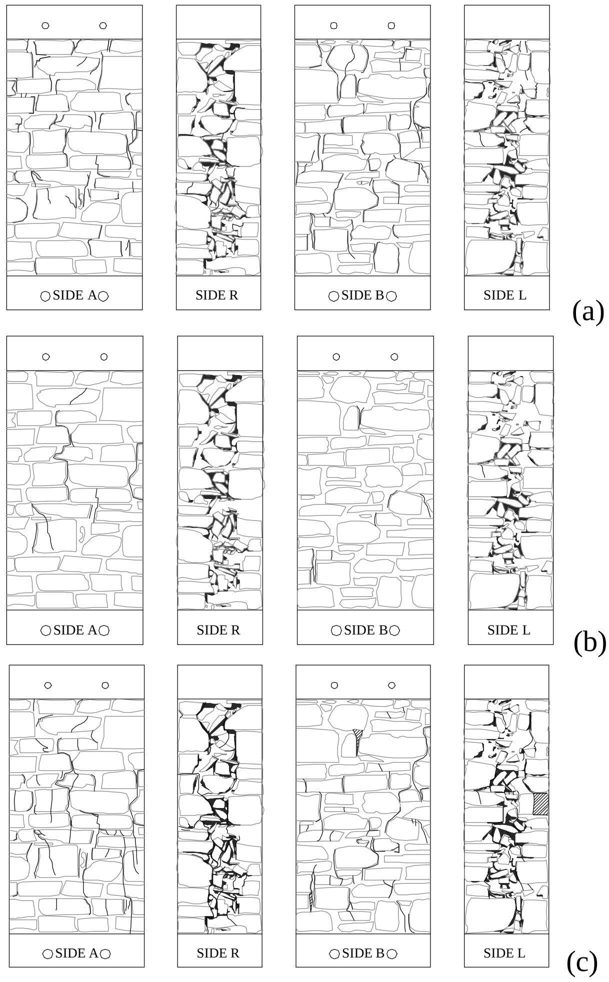

Figure 12: Cracks patterns at the same stress level before (a) and after (b) injection and after injection at the peak strenght (c)

5.3 Repointed and tied walls

The walls consolidated by the repointing of the mortar joints and with the transversal tying have shown compressive strengths and elastic moduli similar to those of the original ones. On the other hand, the features of the walls (in particular, the weakness of the internal core) led to consider the injection technique as the most effective intervention.

Nevertheless, a general decrease of the deformations after consolidation at the same stress level of the peak before consolidation was detected.

As for the repointed walls, the combination between the difficult execution of the technique and the low strength of the new mortar (just a little bit higher than the original mortar after 28 days curing), played probably a negative role on its effectiveness. Nevertheless, horizontal and transversal strains start at a stress level higher than for the non consolidated walls.

The transversal tying of walls, on the other hand, strongly reduced vertical and transversal strains at the peak stress. In particular, the transversal strain, thanks to the restraint effect of the ties, showed an average reduction, compared to the case of the unstrengthened walls, of about the 50% at the peak stress, and of about the 90% at the same stress level (see Table 5 and Fig. 13, where the improvement in comparison with the injection cases is also shown).

Table 5: Measured strain for tied and repointed walls, before and after intervention.

Wall	Vertical strain ‰			Horizontal strain ‰			Transversal strain ‰		
	Before at $f_{wc,0}$	After at $f_{wc,0}$	After at $f_{wc,s}$	Before at $f_{wc,0}$	After at $f_{wc,0}$	After at $f_{wc,s}$	Before at $f_{wc,0}$	After at $f_{wc,0}$	After at $f_{wc,s}$
2T	6.55	0.71	4.05	-0.70	-0.23	-7.09	-19.57	-2.02	-8.29
9T	4.12	0.80	3.04	-2.45	-0.11	-5.49	-10.61	-1.10	-6.34
11T	--	3.04	7.59	--	-1.43	-9.95	--	-2.57	-8.45
3R	3.19	2.78	10.45	-2.17	-2.06	-10.1	-9.84	-0.24	-13.45
7R	4.39	2.23	5.10	-5.06	-2.00	-9.27	-5.81	-2.32	-10.35
15R	--	2.36	7.90	--	-0.76	-5.57	--	-0.50	-14.01

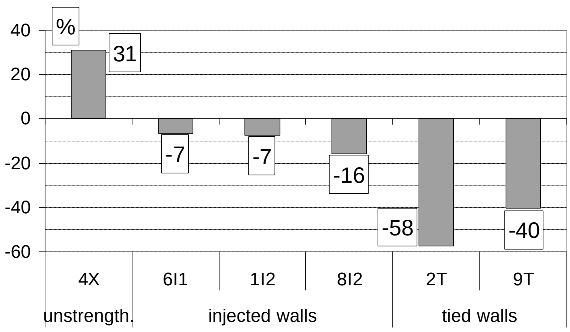

Figure 13: Transversal strain variation at the peak strength after injection and tying

5.4 Combined techniques

As expectable, the walls consolidated by injection combined to other techniques have reached good values both for compressive strength and modulus of elasticity (see Tab. 4). Therefore, simple or combined injections can be considered as the most effective strengthening technique for such typology of walls.

Nevertheless, it is worth to mention that the combined techniques play an important role in improving the global behavior of the walls, raising one another their own effects and allowing an enhancement of the feasibility in the execution phase (in fact, the highest performances have been obtained for the wall strengthened by the “integrated intervention”, that is by all the three techniques). Thus, the excavation phase during the repointing execution is effective in bettering the injection procedure, because it makes easier the hole drilling and the placement of the hoses; on the other hand, the filling of the joints can prevent the leakage of the grout. Furthermore, the repointing is effective in strengthening the outer stratum of the external leaves where, to a large extent, the influence of injections can be regarded as less strong. In the case of tying, the injection of grouts is able to connect the ties to the inner part of the wall, so that the adherence that develops can increase the confinement effects of the ties themselves.

6 CONCLUSIONS

The presented study has shown how the mechanical behavior of three-leaf stone masonry walls can be improved by the use of different strengthening techniques, properly designed to solve the specific structural problems of such particular but diffused typology of masonry.

The injection of grouts has revealed to be the most effective in raising the ultimate load capacity of the walls (even more than the 50% of the original panels) and in improving the brittle mechanism of failure of the non consolidated walls. Moreover, increments of the modulus of elasticity still compatible with the existing structures have been detected, but with significant reductions of the transversal dilation. No significant differences in the ultimate strength have been detected for the different types of the used grouts.

Repointing and transversal tying have revealed their efficiency mostly in terms of reduction of deformations. Nevertheless, the best performances can be ascribed to the walls strengthened with combined techniques, especially when injections are involved in.

As for the evaluation of the effectiveness of the intervention, the use of sonic tests and tomography elaborations, together with local inspections, have demonstrated their reliability.

Finally, particular attention has to be paid to significant parameters and critical aspects of the single phases of the intervention techniques, in order to identify correct design and execution procedures.

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