



Basalt ropes: a new product for the rehabilitation of historical masonry

A.h.R.T.E. - Architectural heritage Restoration through Tailored Engineering

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Rehabilitation of historical masonry is a demanding task, especially in seismic zones, where vulnerable buildings and structures can suffer severe damages and losses, as recent earthquakes testify. Lessons learned by previous experiences and the knowledge acquired through researches allowed us to say that one of the most important characteristic that historic masonry should have is that of a monolithic behavior. If this characteristic is absent, strengthening bearing masonry giving it a transversal monolithic behavior is one of the first consolidating actions to do to improve its seismic performance. Stitching masonry through basalt fiber ropes is an innovative technique, able to connect the several masonry elements and to convey it a monolithic behavior. The results of tests directed to evaluate performances against "in-plane" actions (vertical compression, shear and compression) indicate the effectiveness of this retrofitting system, increasing the monolithic behavior of masonry wall specimens.

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Introduction

As shown by several authors (Giuffrè, 1991; Doglioni, 1994), historical masonry buildings subjected to earthquake do not show a global structural behavior. If the building was made through good quality masonry, it has the tendency to split itself in several parts, called macro-elements which respond as single units to seismic action, and for which the main features of the collapse mechanisms are at least approximately known. So historical masonry buildings response to earthquake is the one offered by the number of macro-elements. Once macro-elements and their most probable collapse mechanisms are identified, possible damages can be predicted and countermeasures adopted. Masonry quality defines if this approach could be considered reasonable: in fact only good quality masonry is able to guarantee monolithic behavior. On the contrary, if it has been used poor quality masonry, a chaotic failure has to be expected and it is not right to reasoning about failure mechanism activation. Moreover, also a low earthquake could be enough to determine disastrous collapses, as has been seen in L'Aquila earthquake in the year 2009. Masonry structural effectiveness directly depends from its quality, and when it has been made following "rule of art" prescriptions a masonry can be considered of "good quality" (Fig. 1).



Figure 1. Masonry structural effectiveness directly depends from its quality: good quality masonry subjected to out of plane loads responds like a monolithic body (left), while poor quality masonry is characterized by a chaotic failure (right). For medium quality masonry (center), can be expected a middle behavior.

Essential features are presence of transversal connection elements, horizontality of the courses, the stagger of the vertical joints, shape and dimension of the single units, mortar quality and material strength of single units (Donà & De Maria, 2011). If the lacking of these features could be recognized, every structural assessment is quite reliable and the first thing to do is to improve masonry quality. A masonry typology often found in Italian historical building heritage is the "three-leaf wall", where an inner core of rubble material is included between two outer brick or stone shell. If three-leaf masonry presents poor or absent connection between the external leaves, due to the lack of elements so long to crossing wall section, it could result very weak under eccentric and horizontal loads.

In fact, it could meet problems of buckling of the external shell, due to its slenderness, and of weak resistance to action that could involve out-of-plane mechanisms, due to a global behavior nearest to two thin panels than a monolithic one (Fig. 2).

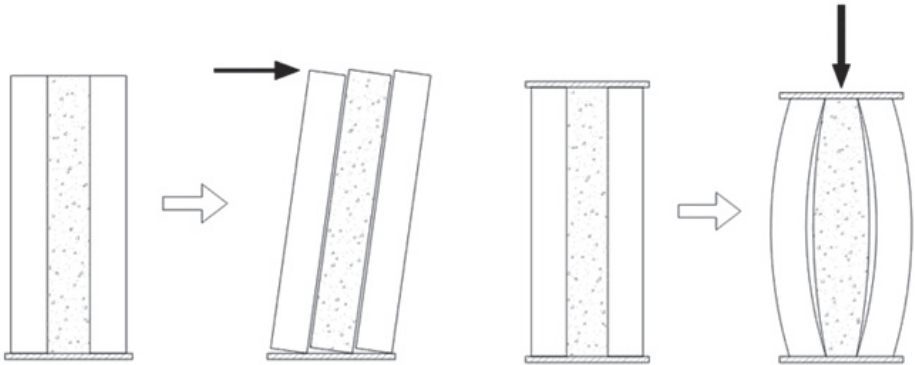


Figure 2. Vulnerability of "three-leaf wall" subjected to horizontal load.

Nowadays there are many different techniques for strengthening masonry panels. Some are traditional (and usually most invading) like grout injection, jacketing with reinforced plaster or the introduction of artificial connectors (metallic rods) and some other could be considered innovative, like the use of composite strips (Corradi et al., 2002). However, when it is wanted to maintain the original aspect of the masonry brickwork, these techniques cannot be applied. A possibility could be represented by repointing of the masonry joints, which consists in replacing the damaged mortar on the wall surfaces inserting also in mortar bed joints steel rods as reinforcement that could convey an important strength increase (Modena et al., 2002; Tinazzi et al., 2000; Valluzzi, 2005). Recently, innovative reinforcing fibers and products, like basalt ones, are emerging in constructions field. From the awareness that one of the worst structural defects of an historic masonry wall is the lack of monolithic behavior, arises the idea of a strengthening technique able to connect the several masonry elements, stitching them. The proposed technique is based on the reinforcement and connection of external masonry shell of "three-leaf wall" (this work focuses on this masonry typology) using basalt fiber ropes. The technique has been already tested using synthetic adhesives (resins) and showed good results in improving the behavior against compression load (Quagliarini et al., 2012a; Quagliarini et al., 2012b). In this paper, the results of an experimental campaign aimed to test the technique effectiveness also excluding synthetic adhesives (with an enhancement about reversibility and sustainability) are presented.

Materials and methods

Basalt fibre ropes

Basalt is a natural material that is found in volcanic rocks originated from frozen lava. Continuous basalt fibers are obtained by melting basalt and are characterized by high modulus, heat resistance, good resistance to chemical attack and seem to be a good alternative to glass fibres (Van de Velde et al., 2003; Wei et al., 2010; Sim et al., 2005). In construction field, basalt is proposed in form of short fibres for insulating material (basalt wool), for reinforced concrete (chopped fibres) or like reinforcing material in restoration and rehabilitation of concrete (Sim et al., 2005) and masonry structures (Papanicolaou et al., 2011), or like reinforcing material for fibre reinforced polymer (FRP) bars used in concrete technology (Brik, 2003). It is also important the application in passive fire protection field (Landucci et al., 2009). Continuous basalt fibres can be processed with classic textile transformation to obtain also ropes, unlike other kinds of reinforcing fibres. Basalt fibres ropes of 4mm of nominal diameter (declared by manufacturer), have been used in this experimental program (Fig. 2). A mechanical characterization of this product has been developed by (Quagliarini et al., 2012c) and reported in Table 1.



Figure 3. The basalt fibre rope.

Table 1. BF ropes mechanical features (values from Quagliarini et al., 2012c).

Basalt fibre rope mechanical features	
Nominal diameter [mm]	4
Failure load F_{max} [N]	3157.27
Failure strain ϵ_{max}	0.05

Technique description

The proposed technique aims to connect outer brick masonry shell to exclude buckling failure and to impart monolithic behavior, without modify masonry original aspect. It consists in insertion of basalt fibre ropes in the mortar bed joints previously partially cleared out and refilled with simple mortar only to cover the ropes and restore original appearance and homogeneity. The holes disposition has been chosen following an appropriate and tailored designed path. The main operative phases for a correct execution of the intervention are: (i) execution of crossing hole by means of drill equipped with a bit long as the wall depth; (ii) cutting of the bed mortar joints creating a groove at least 10mm high and about 30-40mm deep

on the two wall faces; (iii) removal of powder or rubble; (iv) placing of a first layer of mortar; (v) placing of the basalt fiber rope; (vi) placing a second layer of mortar over the rope to cover it sufficiently. Respect insertion of steel or FRP bars, as in repointing application, come out the opportunity of working with a lighter and versatile material and able to connect the masonry elements also in the panel depth direction.

Experimental program

To assess the effectiveness of proposed technique, laboratory tests have been performed. The masonry reproduced was the "three-leaf wall", where an inner core of rubble material is included between two outer brick shell. 12 "three-leaf" masonry samples have been made, and tested under vertical compression (6) and shear-compression (the others 6) load. The masonry wallets have been made on steel plates (to have the possibility of easily move them) and cured in the same condition for the same time (about 60 days). Specimen dimensions (better presented in Fig. 4) have been chosen similar to the one suggested by the Italian standards on masonry compression test (UNI EN 1052-1) and comparable to the ones used in other analogous experimental experience available in literature (Binda et al., 2006; Vintzileou et al., 2008). Before testing, 8 masonry samples have been reinforced through proposed technique, in particular in 4 of these, BF ropes have been arranged only in horizontal bed mortar joints (reinforcement called "RO", Fig. 5), while in the other 4, BF ropes have been inserted also in vertical bed mortar joints (reinforcement called "RR"). Only 4 masonry samples have been tested in unreinforced condition ("NC"). The experimental program is better explained in Table 2. Figure 6 reports the final aspect of masonry wallets at the end of reinforcing process. Vertical compression and shear-compression tests (performed under load control) have been carried out placing sample into a steel frame (Fig. 7). Forces has been applied through pressure jacks and measured by means of pressure transducers; vertical and horizontal displacements have been monitored by means of transducers placed on the top and on the sides of the wall, in order to measure transverse deformations of wall and separation between exterior leaves and filling material.

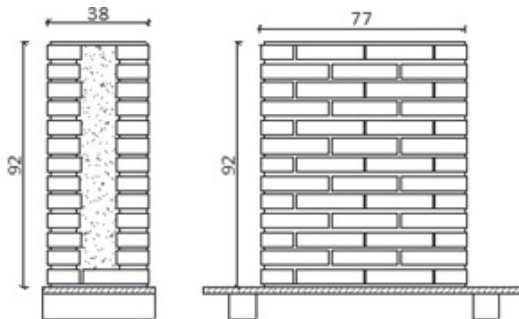


Figure 4. Masonry sample metric survey (values in centimeters).

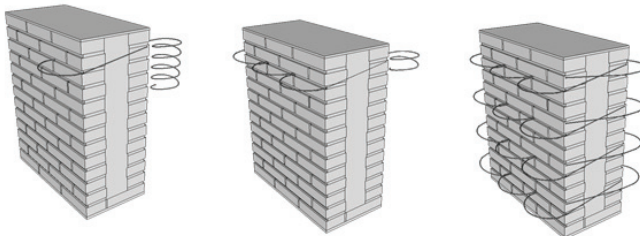


Figure 5. Operative phases for the application of "RO" reinforcement.

Table 2. Experimental program.

Masonry sample built: n.12					
Samples subjected to vertical compression tests: n.6			Samples subjected to shear/compression tests: n.6		
N.C. n.2	R.O. n.2	R.R. n.2	N.C. n.2	R.O.n.2	R.R. n.2



Figure 6. The final aspect of masonry wallets at the end of consolidating process. Sample after "RO" strengthening on the left and after the "RR" one on the right.



Figure 7. The test device used for vertical compression test (left) and the test device used for shear-compression test (right).

Masonry components: mortar, brick and inner core mixture

The tested technique is turned to Italian historical building heritage, so the material used in external shell of specimen is brick masonry. A non-hydraulic lime mortar was adopted to build the samples, mixing 1 volume lime putty (with a volume ratio between water and lime powder of 0.7) to 3 parts washed, well graded, sharp sand, according to literature experiences (Lanas, 2003; Faria, 2008; Moropoulou, 2005). For materials characterization flexural and compressive tests on mortar samples and compressive tests on bricks have been carried out according to Italian standards UNI EN 1015-11 and UNI EN 772-1. Average results obtained are reported in Table 3. As regard inner core, a mixture of flake, rubble bricks and mortar, was used, according with historic handbook (Rondelet, 1817; Sacchi, 1879). To obtain mechanical features of this mixture, compressive tests were carried out on three $150 \times 150 \times 150 \text{ mm}^3$ cubes, cured and tested following UNI EN 12390-1-2-3 recommendations. Average results obtained are also reported in Table 3.

Table 3. Average results of test carried out to obtain mechanical characterization of masonry component (brick and mortar) and inner core. f_f represents mortar flexural strength, f_c mortar and brick compressive strength, E30-60 elastic modulus secant modulo values corresponding, respectively, to 30% and 60% of maximum compressive strength. All these values are reported in MPa. S.D. is the standard deviation of values recorded.

Material	f_f [MPa]	S.D.	f_c [MPa]	S.D.	E30-60 [MPa]	S.D.
Mortar	0,39	0,057	0,468	0,109	26,2	19,68
Brick	---	---	16,9	0,6	358,16	74
Inner core	---	---	0,159	0,045	6,95	2,5

Results

In this section, the main results concerning the testing of the three-leaf masonry samples are discussed. As predictable, under vertical compression load, unreinforced samples exhibit the same failure mode, characteristic for three-leaf masonry: separation between the interior filling material and the external leaves and buckling collapse of one of them (Fig. 8, on the left). This fact is probably due to the inevitable eccentricity of the applied load. Reinforced samples, instead, exhibit a different failure mode: the external leaves work together to carry the applied load and the failure occurs due to overcoming of material ultimate strength (Fig. 8, in the center and on the right). This fact is well underlined by the cracks appeared on bricks of reinforced samples: only in that cases the materials have been entirely subjected to the stress generated by applied load (Fig. 9).



Figure 8. Three-leaf masonry samples after vertical compression tests: on the left the unreinforced ones ("NC"), in the center the ones strengthened through BF arranged only in horizontal bed mortar joints ("RO") and on the right, the ones strengthened through BF arranged both horizontal and vertical bed mortar joints ("RR"). The sample aspect after test shows the effectiveness of the proposed technique.



Figure 9. Cracks appeared on bricks of reinforced samples subjected to vertical compression test.

Comparing the graph that binds vertical stress and transverse strain (Fig. 10), come out as the intervention, discarding buckling collapse and better exploiting material properties, contributes to impart a monolithic behavior to the masonry panel. In fact, the stitches application is able to reduce transverse strain of 70% ("RO") and 80% ("RR").

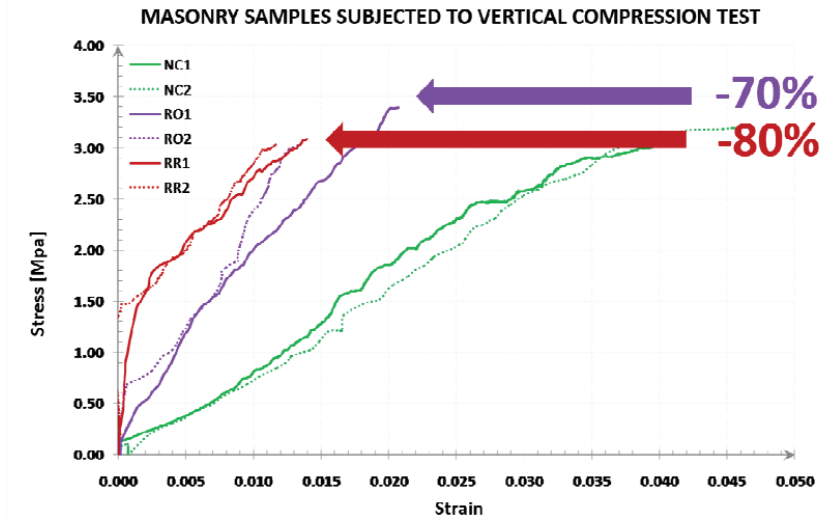


Figure 10. Comparison between stress-transverse strain graphs recorded for three leaf masonry samples subjected to vertical compression test.

Also from shear-compression tests come to light that under this kind of load three-leaf masonry has a behavior nearest to several thin panels than a monolithic one. In fact in "NC" samples, it could be seen a crack pattern typical of shear stress (Fig. 11, on the left) and a separation between interior core and outer brick leaf. In this case the "RO" strengthening is not able to produce clear improvements, on the contrary of the "RR" one that seems to be able to modify panel failure mode (Fig. 11, on the right) in the way to sustain a more serious crack pattern, and to improve substantially the system pseudo-ductility (Marcari G. et al., 2007) as can be seen in Figure 12.



Figure 11. Three-leaf masonry samples after shear-compression test: on the left the unreinforced ones ("NC") and, on the right, the ones strengthened through BF arranged both horizontal and vertical bed mortar joints ("RR").

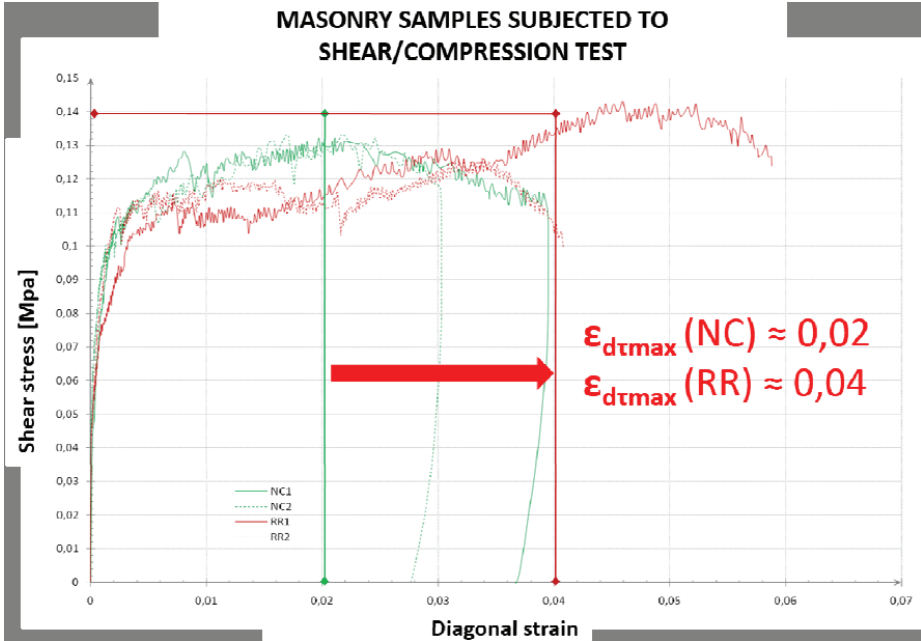


Figure 12. Comparison between shear stress/diagonal strain graphs recorded for three leaf masonry samples "NC" and "RR" subjected to shear compression test.

Conclusion

This paper presents the results of an experimental program with the aim of investigate the strengthening of "three-leaf" masonry walls through the employment of basalt fiber ropes, used for stitching masonry panel. The proposed technique is able to change the failure mode of "three leaf" masonry wall, exploiting material properties, and to determine a transverse strain reduction under compression load: in brief it is able to impart to masonry monolithic behavior. It also means that it is able to improve the ultimate strength of bearing panel that, in a real wall, more slender than the tested ones, could be strongly limited by buckling failure. Moreover other advantages are represented by the fact that: (i) the application is very fast and so cheap, (ii) the material used (basalt) presents an high compatibility with masonry: stone stitches stone; (iii) the reinforce is almost totally reversible; (iv) it is invisible, respectful of masonry original aspect; (v) it improves but not replaces original materials, (vi) it is fire and chemical resistant and, finally, (vii) it does not use synthetic adhesives. On the other hand, it has to be said that tests have been conducted on a masonry typology characterized by no features that could suggest a monolithic behavior, with a global behavior nearest to two thin panels than a monolithic one. So further developments of this work should be directed to investigate the technique pertinence also on others masonry typology. Furthermore, also the evaluation of the technique effectiveness against other kinds of load (i.e. "out-of-plane" loads) should be studied in depth.

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