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Strengthening of Masonry Columns with BFRCM or with Steel Wires: An Experimental Study

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Abstract: Nowadays, innovative materials are more frequently adopted for strengthening historical constructions and masonry structures. The target of these techniques is to improve the structural efficiency with retrofitting methods while having a reduced aesthetical impact. In particular, the use of basalt fiber together with a cementitious matrix emerges as a new technique. This kind of fiber is obtained by basalt rock without other components, and consequently it could be considered a natural material, compatible with masonry. Another innovative technique for strengthening masonry columns consists of applying steel wires in the correspondence of mortar joints. Both techniques have been recently proposed and some aspects of their structural performances are still open. This paper presents the results of an experimental study on the compressive behavior of clay brick masonry columns reinforced either with Basalt Fiber–Reinforced Cementitious Matrix (BFRCM) or with steel wire collaring. Uniaxial compressive tests were performed on eight retrofitted columns and four control specimens until failure. Two masonry grades were considered by varying the mix used for the mortar. Results are presented and discussed in terms of axial stress-strain curves, failure modes and crack patterns of tested specimens. Comparisons with unreinforced columns show the capability of these techniques in increasing ductility with limited strength enhancements.

Keywords: basalt fibers; steel wires; compression; confinement; experimental investigation

1. Introduction

The use of Fiber-Reinforced Polymer (FRP) composites as wraps for upgrading existing masonry columns has become increasingly popular in recent years. These wrapping techniques allow obtaining large increases of the strength and deformation capacity, and are effective for columns with poor structural features. FRP wrapping allows an outstanding combination of properties, such as ease of handling, speed of installation and the use of a material with a high strength-to-weight ratio. Despite these advantages, some critical issues are involved in this method, including ensuring a durable bond between FRP and masonry and the stress concentration near the column's edges.

For these reasons, several research works have been carried out in the recent past with the aim of investigating the compressive behavior of FRP-confined masonry columns. One of the first studies on the effect of external FRP wrapping on masonry columns was carried out by Corradi *et al.* [1]. Researchers performed compressive tests on FRP-confined clay brick columns and proposed an adaptation of the model of Campione and Miraglia [2] for masonry members. Similarly, Aiello *et al.* [3] performed compressive tests on masonry columns built with clay or calcareous blocks, and reinforced with external FRP wrapping or internal FRP bars. Based on obtained results, they proposed a calibration of some design expressions for obtaining the strength of confined masonry columns. Di Ludovico *et al.* [4] presented the results of an experimental investigation on the compressive behavior of tuff or clay brick masonry columns confined with carbon or glass FRP and proposed new expressions for evaluating the strength enhancement in these members. Faella *et al.* [5] tested 54 natural stone and artificial brick masonry columns under uniaxial compression and investigated the effects of three different kinds of composite systems applied for confinement. Researchers observed several failure modes in the various tests and values of the confined-to-unconfined strength ratio ranging between 1.22 and 3.94.

As general findings, most of the experimental studies pointed out that the strength increase is generally higher in the case of weak masonry columns and for stiffer wrapping layers, confirming the influence of the basic parameters on the behavior of confined members; the stress concentration at the corners induces brittle failure, and it does not allow the column to reach the maximum confining stress; and the bond between masonry and FRP depends on the kind of resin and tissue adopted.

From a theoretical point of view, recent studies investigated the strength increase due to FRP confinement of masonry columns. Koksal *et al.* [6] developed a Drucker-Prager–type constitutive model for the nonlinear finite element analysis of FRP-confined masonry columns, while Lignola *et al.* [7] summarized previous literature studies and proposed a theoretical approach based on the Mohr-Coulomb strength criterion for determining the strength increase due to FRP confinement. Despite the advantages of this method highlighted by this large amount of research works, some drawbacks were spotted when organic resins were used to bind the fibers, such as poor behavior at high temperatures, inapplicability on wet surfaces, high costs and problems of compatibility between materials for long-term effects.

To solve these problems, different techniques were developed to be used as alternative methods for enhancing the structural performances of poor masonry columns. Among these, the use of wraps with Basalt Fiber–Reinforced Cementitious Matrix (BFRCM) allows obtaining an external surface that is easy to finish, and with a material compatible with that of the column. In fact, basalt fibers are obtained from basalt rocks through a melting process and contain no other chemical components in the manufacturing process, and thus are low in cost. Basalt fibers show mechanical features comparable to that of glass fibers and exhibit good resistance to chemical and high temperature exposure [8]. The ultimate strain of basalt is higher compared to other common FRP materials and thus it is interesting to use this advantage in column strengthening to enhance the seismic performance. There is little research concerning the application of basalt fibers in civil engineering and their strengthening efficiency on masonry elements. Yilmaz *et al.* [9] investigated the efficacy of external confinement with open-grid basalt-reinforced mortar on the axial behavior of masonry columns by testing five specimens. Their results showed that the open-grid BFRCM provided a fairly small compressive strength gain but, on the other hand, basalt jacket–reinforced mortar improves energy dissipation of the masonry columns notably. Similarly, Carloni *et al.* [10] performed an experimental investigation on the compressive behavior of polyparaphenylene benzobisoxazole (PBO) FRCM–reinforced masonry columns, finding small increments of strength but a noticeable increase of ultimate strain.

Another alternative method is the application of steel wires in the correspondence of mortar joints, to provide overlapping hoops at every course over the entire height of the column. The main advantages of this technique are related to the low costs and the reduced aesthetical impact, which makes this method suitable for buildings of historical and/or architectural interest. The idea was initially proposed by Jurina [11,12], who performed an experimental investigation, showing the capabilities of the technique in enhancing the axial capacity of the column.

Borri *et al.* [13,14] developed the technique proposed in [11] by using prestressed high-strength steel cords, applied with mortar or with resin to masonry columns with various cross-section shapes. Strength gains of up to three times were recorded, with higher values for octagonal sections, while square and rectangular specimens proved to be more sensitive to stress concentrations at the corners.

This paper presents the results of an experimental comparative analysis on the compressive behavior of confined masonry columns reinforced with different techniques. In particular, four clay brick masonry columns wrapped with BFRCM (series BF) and four specimens strengthened by high-strength steel wires placed in the joints (series SW) were tested until failure.

All the columns were manufactured with binding mortars typical of existing masonry buildings, which require structural retrofitting. In particular, two masonry strengths were targeted by varying the mortar grade and composition: series M1 for low-strength mortar, and series M3 for medium-strength mortar. Adopted nomenclature follows the definition of mortar classes of Eurocode 6 [15]. In addition to the reinforced specimens, two unconfined clay brick columns were prepared as control specimens (denoted as U) for each series, M1 and M3, of specimens.

In this paper, after describing the geometry and construction of test specimens, the characterization of constituent materials is presented by discussing the results of bending tests on mortar samples and compressive tests on clay brick and mortar cubes. The preparation of test specimens is also described in detail, by examining the construction stages of the specimens. Results of the compressive tests are finally presented and discussed by analyzing the axial stress-strain curves, strength and ultimate strain gains and failure modes. Results of performed tests allow the examination of the efficiency of the investigated reinforcing techniques, BFRCM wrapping and steel wire collaring, in a comparative manner. Results obtained could be useful to clarify the structural performances of these strengthening techniques, which could be efficient and economical alternatives to traditional FRP wrapping.

2. Materials and Methods

2.1. Specimens

All specimens were about 960 mm in height and with square cross-section shape of 230 mm × 230 mm (Figure 1). The identification of unreinforced and reinforced specimens is reported in the first column of Tables 1 and 2 respectively. In particular, the first two letters identify the mortar grade, while the third and the four letters identify the strengthening technique (U for unreinforced specimens, BF for basalt fiber–reinforced specimens, SW for columns strengthened with steel wires). For example, the specimen M1_BF is a column made with binding mortar M1 and wrapped by BFRCM. A final code number (1 or 2) has been used for identical specimens to distinguish the columns.

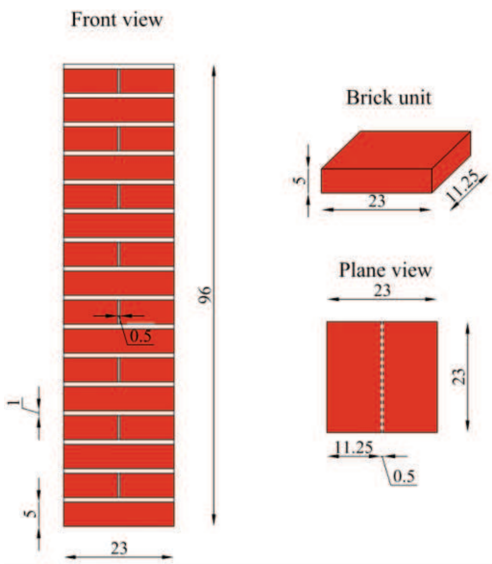

Figure 1. Geometry of test specimens (units in cm).

Table 1. Details of unconfined brick masonry columns (control specimens) and key results.

Specimen	Mortar	Reinforcement	Maximum Stress	Ultimate Stress	Axial Strain at Maximum Stress	Ultimate Axial Strain	Absorbed Energy
			f_{co} (N/mm^2)	f_{uo} (N/mm^2)	ε_{co}	ε_{uo}	E_o (MJ/m^3)
M1_U_1	M1	NONE	4.31	3.74	0.0145	0.0169	0.0415
M1_U_2	M1	NONE	5.05	4.20	0.0139	0.0167	0.0491
	Average value		**4.68**	**3.97**	**0.0142**	**0.0168**	**0.0453**
M3_U_1	M3	NONE	9.14	7.53	0.0120	0.0132	0.0685
M3_U_2	M3	NONE	9.70	8.23	0.0128	0.0147	0.0739
	Average value		**9.42**	**7.88**	**0.0124**	**0.0139**	**0.0712**

Table 2. Details of confined brick masonry columns and key results.

Specimen	Mortar	Reinforcement	Normalized Maximum Stress	Normalized Ultimate Stress	Normalized Axial Strain at Maximum Stress	Normalized Ultimate axial Strain	Normalized Absorbed Energy
			f_{cc}/f_{co}	f_{cu}/f_{uo}	$\varepsilon_{cc}/\varepsilon_{co}$	$\varepsilon_{cu}/\varepsilon_{uo}$	E/E_o
M1_BF_1	M1	basalt fiber mesh	1.81	1.72	1.5842	1.6053	2.8046
M1_BF_2	M1	basalt fiber mesh	1.67	1.66	1.4093	1.4709	2.5259
M1_SW_1	M1	steel wires	1.30	1.30	2.4869	2.3753	3.9057
M1_SW_2	M1	steel wires	1.35	1.32	2.4176	2.7062	4.3391
M3_BF_1	M3	basalt fiber mesh	1.19	1.19	1.0575	1.0373	1.3959
M3_BF_2	M3	basalt fiber mesh	1.09	1.09	1.2579	1.2669	1.5027
M3_SW_1	M3	steel wires	1.02	1.03	1.3004	1.3217	1.5743
M3_SW_2	M3	steel wires	1.33	1.32	1.6178	1.6373	2.3014

2.2. Materials

In order to characterize the mechanical behavior of the clay brick units, 10 cubes with size equal to 50 mm were cut from the bricks and tested under uniaxial compression (Figure 2a). An average value of the cube compressive strength of about 42.3 MPa was recorded.

(**a**) (**b**)

Figure 2. Mechanical characterization of constituent materials: (**a**) compressive test on a clay brick cube; (**b**) three-point bending test on a mortar prism.

Mortar of M1 series was manufactured by assembling hydraulic lime and sand with a volume ratio of 1:3. The mortar used for the M3 mortar was composed of Portland Cement (14% in volume), hydraulic lime (14% in volume) and sand (72% in volume). Water was added until workability was achieved. The mechanical properties of the two mortar mixes were obtained by means of three-point bending tests on six standard 40 mm × 40 mm × 160 mm prisms (Figure 2b) and uniaxial compressive tests on six standard 40 mm × 40 mm × 40 mm cubes for each mortar grade series. The average 28-day tensile-flexural strength was 0.44 MPa for the M1 series and 3.13 MPa for the M3 series. The average 28-day compressive strength was equal to 0.55 MPa for M1 series and 4.54 MPa for M3 series.

The tissue adopted for reinforcing the specimens consists of an open mesh basalt fabric, with mesh openings having sizes equal to 6 mm × 6 mm. Its mechanical properties were deduced from the technical data provided by the producer, due to the difficulties in arranging a test set-up with the available machine. The tensile strength of the basalt fiber net was equal to 60 kN/m, ultimate strain was 1.8% and elastic modulus equal to 89 GPa.

Steel wires had a diameter equal to 1.8 mm. Also in this case, mechanical properties were provided by the producer. In particular, tensile strength was equal to 2845 MPa, Young modulus equal to 190 GPa and ultimate strain equal to 2.6%.

2.3. Preparation of Test Specimens

Columns were made up by assembling two brick units for the course, arranged orthogonally to the units in the upper and lower courses, and connected with mortar joints with a thickness of 10 mm. Specimens were reinforced after manufacturing and after a curing time of about two weeks.

The vertical edges of BF specimens were preliminary rounded with a corner radius of 20 mm for limiting stress concentration at the corners of the external wrap during the test. The basalt fabric was applied after initially treating the external surface with a high-strength cement-based mortar, reinforced with glass fibers (Figure 3a). A single layer of fabric was installed, with an overlapping length equal to the half perimeter of the section. This overlapping zone between the beginning and the end of the tissue plays a fundamental role on the efficacy of the method, since it allows the transfer of circumferential stresses along the external jacket. Finally, an additional cover of mortar was laid on the external surface after specimens were wrapped with the basalt fiber mesh, ensuring complete filling of voids and adhesion of the fabric. The overall thickness of the external reinforcing layer was equal to about 10 mm.

(**a**) (**b**)

Figure 3. Preparation of specimens: (**a**) basalt-reinforced specimen; (**b**) specimen reinforced with steel wires.

It should be noted that in this case continuous wrapping was allowed along the member's height due to the small scale of the specimens. When full-scale columns are reinforced in realistic conditions, a certain angle of the fibers with the horizontal axis (more or less like a helix) is necessary. It is clear that this angle influences the maximum available confinement pressure and the adoption of an in-elevation efficiency coefficient of confinement should be considered in calculations. This fact highlights the need for future studies on full-scale columns.

An easy procedure was followed to reinforce specimens with steel wires. Horizontal mortar joints of specimens were flattened mechanically and four high-strength steel wires with a diameter equal to 1.8 mm were introduced by collaring the joint (Figure 3b). Tightening of the wires was made by hand-pinch closing. Afterwards, mortar joints were filled with the above-mentioned fiber-reinforced mortar. Finally, every specimen was capped with a self-leveling mortar on the top surface, in order to warrant its plane regularity in contact to the plate of the testing machine.

2.4. Test Set-Up and Instrumentation

Compression tests on all columns were carried out with a hydraulic actuator with maximum load capacity of 2000 kN, which enables tests in displacement-controlled mode. An electronic control unit, together with a user interface via personal computer, regulated the test type and the equipment.

To measure the applied displacements of the samples, a linear voltage displacement transducer (LVDT) was placed between the press plates. Moreover, two transducers were installed in the axial and orthogonal direction at the middle height of each specimen. Figure 4 shows a typical test set-up. All specimens were loaded up to failure with small increments of displacement (0.5 mm/s).

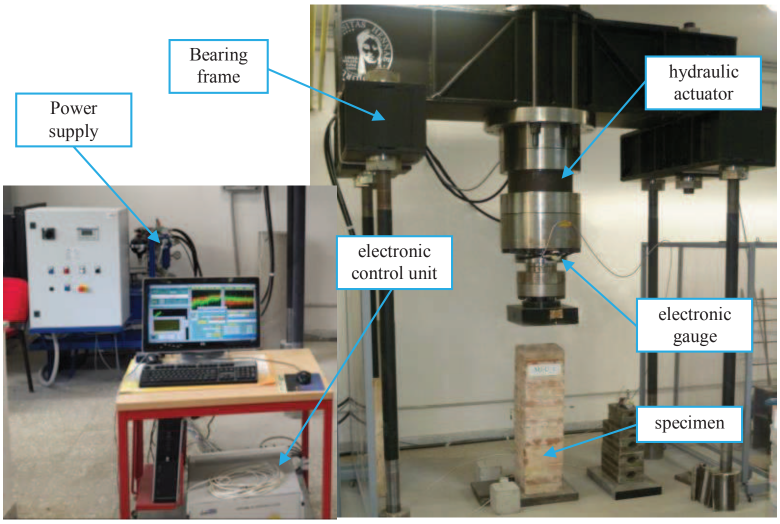

Figure 4. Test equipment and set-up.

3. Results and Discussion

3.1. Unreinforced Columns

The monotonic stress-strain curves of the control specimens are shown in Figure 5. Axial stress has been calculated by dividing the axial load by the cross-section area. The axial strain is obtained from the displacement transducer placed between the press plates.

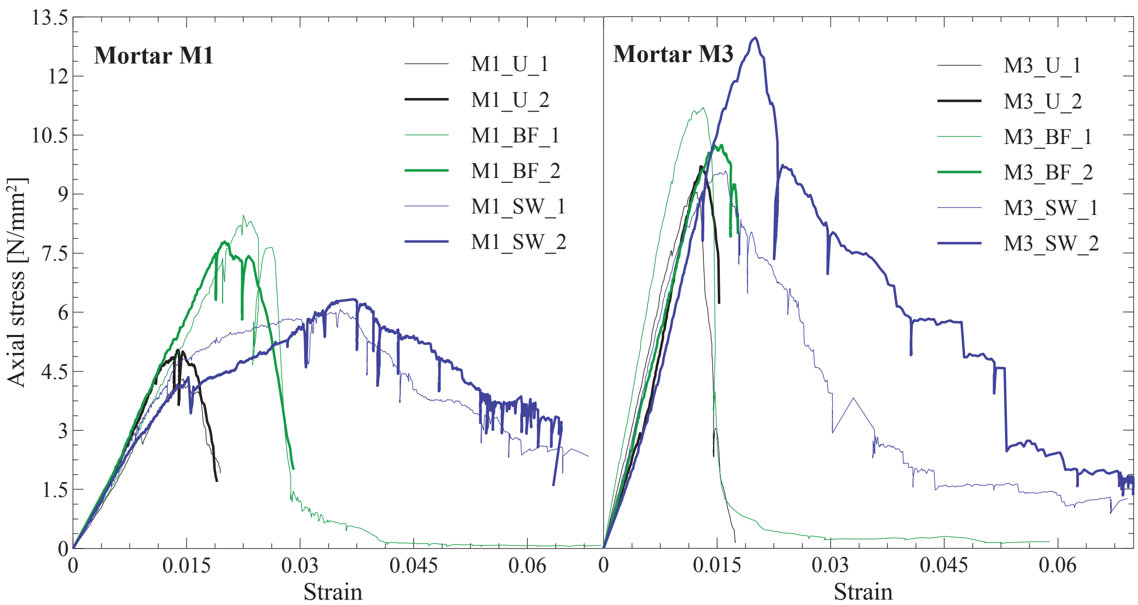

Figure 5. Axial stress-strain curves of unconfined and confined clay brick masonry columns.

Figure 5 plots the stress-strain curves for unreinforced clay brick masonry columns under axial compression characterized by an ascending branch up to the peak and by a rapidly descending post-peak branch until collapse (brittle failure). The peak stress f_{co} and the corresponding strain value ε_{co} are reported in Table 1 for each control specimen. Similarly, the ultimate or failure values are defined as (f_{uo}, ε_{uo}). The conventional ultimate strains were fixed as the strain values at 85% of the maximum stress. Also, the energy absorption capacity (E_o) measured for all specimens as $\Sigma(d\sigma \cdot d\varepsilon)$ is reported in Table 1.

It is worth noting that the use of high-grade binding mortars significantly influences the mean value of the maximum stress, ultimate stress and absorbed energy. For these parameters, increases of 101%, 98% and 57% were recorded by adopting the mortar grade M3 instead of M1.

3.2. Reinforced Columns

Table 2 shows the peak and ultimate stress, peak and ultimate strain, and absorbed energy values normalized to those relative to unreinforced specimens. They prove that strengthening by BFRCM wraps or by steel wires can enhance the performance of brick masonry columns with a substantial gain in strength, ductility and energy absorption capacity.

In particular, comparing the key results between reinforced and unreinforced columns (control specimens), the mean strength, ultimate strain and absorbed energy for series M1 increased respectively by 53%, 104% and 239%. In contrast, for series M3, the mean strength, ultimate strain and absorbed energy increased respectively by 16%, 32% and 69%.

In more detail, regarding series M1, the mean values of maximum stress, ultimate strain and absorbed energy increased respectively by 74%, 54% and 167% for BF specimens and by 33%, 154% and 312% for SW specimens. Similarly, for series M3 columns, they increased respectively by 14%, 15% and 45% for BF specimens and by 18%, 48% and 94% for SW specimens.

Concerning the overall effect of the two investigated techniques, an average increase of maximum stress of 44% was achieved for BF specimens, while it was equal to 25% for SW specimens. With reference to the ultimate strain and absorbed energy, observed increases were equal to 35% and 106% for BF specimens and 101% and 203% for SW specimens.

3.3. Failure Modes and Crack Patterns at Failure

In order to describe and compare the main damage patterns and the failure mechanisms for unconfined and confined columns, Figure 6 shows the failure mode observed for some specimens.

(**a**) (**b**) (**c**) (**d**)

Figure 6. Failure mode for clay brick masonry columns: (**a**) unconfined; (**b**) confined with BFRCM wraps; (**c**) reinforced by steel wire collaring. (**d**) Tensile fracture of the basalt fiber mesh.

Unconfined specimens were characterized by brittle failure. In fact, the stress-strain curves of Figure 5 were characterized by an almost linear ascending branch up to the peak, followed by a rapidly descending post-peak branch until collapse.

Generally, BF specimens behaved monolithically in the first stage, up to a strain value equal to about one-third of the peak strain. During this phase, no crack was observed in the external mortar layer and this load stage corresponded to an initial linear ascending branch of the stress-strain curves of Figure 5. Afterwards, first cracking of the external layer occurred at the corners and the trend of the stress-strain curves assumed a non-linear shape up to the peak load. Failure of BFRCM-confined specimens occurred with the propagation of a unique fracture plane inclined at about 45 degrees across the mortar joints. Moreover, failure mechanisms occurred suddenly, when the jacket could not restrain the unstable expansion of the clay brick masonry core. In all cases the failure mechanisms were due to the jacket collapse at the corner.

Alternately, the behavior of the SW specimens was characterized by a slow damage process. First cracking occurred for a strain value similar to that recorded for unreinforced specimens. In particular, multiple sub-vertical cracks were observed in the brick units, while mortar joints were restrained by the wires. Progressive rupture of steel wires was also observed in the correspondence of knots and the failure of specimens occurred when all wires failed in one or two mortar joints.

4. Conclusions

This paper presented the results of an experimental investigation on the compressive behavior of clay brick masonry columns reinforced with BFRCM wraps or with steel collars in the mortar joints, varying the mortar grade. From obtained results and for the limits of investigated variables, the following main conclusions can be drawn:

- BFRCM jacketing proved to be more effective in terms of strength enhancement, while significant increases of the ultimate strain and absorbed energy were observed mainly in specimens reinforced with steel wires;
- the efficiency of both strengthening techniques depended on the mortar grade of the masonry, both being more effective for low-grade mortar masonry;
- failure of the BFRCM layer was observed at the corners, highlighting the importance of ensuring an adequate corner radius to avoid stress concentration;
- failure of the specimens reinforced with steel wires occurred due to the opening of the wires' knots, stressing the need for future studies on possible new joints to close the steel wires.

Further investigations should be addressed in the future in order to highlight the role of scale effect on full-size members and to draw more general conclusions.

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