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A COMPREHENSIVE EXPERIMENTAL CAMPAIGN ON THE IN-PLANE CYCLIC RESPONSE OF STONE MASONRY PIERS JACKETED WITH COMPOSITE MATERIALS

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Abstract

This paper presents the experimental campaign carried out within the ERIES-RESTORING project to assess the behavior enhancement of undressed stone masonry, representative of historical buildings, strengthened with Composite Reinforced Mortars (CRM) and Fibre Reinforced Mortars (FRM). The main results of characterization tests on wallettes and quasi-static cyclic in-plane shear-compression tests on full-scale piers with different retrofit configurations are presented in terms of hysteretic and backbone curves.

Keywords: Composite Reinforced Mortars, Fiber-Reinforced Mortars, Quasi-Static Cyclic Shear-Compression Tests, Seismic Retrofit of Existing Buildings, Stone Masonry.

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1 INTRODUCTION

Historical unreinforced masonry (URM) buildings are highly susceptible to seismic damage because they were built without any consideration for earthquake effects. Therefore, strengthening solutions with materials compatible with the masonry substrate have been growing in recent years ([1], [2], [3]), such as Composite Reinforced Mortars (CRM) and Fibre Reinforced Mortars (FRM). Even so, information on URM enhancement with these solutions is still scarce in the literature: in fact, most of the experimental campaigns are limited to diagonal compression tests, and design standards or guidelines are very limited.

For this purpose, an experimental program consisting of quasi-static cyclic shear-compression tests on seven full-scale undressed stone masonry piers was devised. Three retrofit solutions were studied: CRM applied to one side of the masonry panel, CRM applied to two sides, and FRM applied to two sides. Bare masonry specimens were also tested as a reference to determine the behavior enhancement. Piers with two aspect ratios were tested to induce flexural and shear failures, respectively. Mechanical characterization tests were also conducted on mortar prisms and masonry wallettes, including vertical and diagonal compression tests. This campaign was carried out within the ERIES-RESTORING project at the EUCENTRE Foundation laboratories in Pavia, Italy, and at the "Giorgio Macchi" Laboratory of the Department of Civil Engineering and Architecture (DICAr) of the University of Pavia.

The experimental results, in terms of strength and ultimate displacement, are presented and compared between the different configurations. The aim is to contribute to the development of design guidelines on masonry retrofit with CRM and FRM materials.

2 MATERIAL CHARACTERIZATION

2.1 Constituent materials

The specimens were built with roughly cut Credaro-Berrettino calcareous sandstone rocks, from the province of Bergamo, Italy, sized about 100-300 mm. The stone units were characterized by a mean density of 2580 kg/m³, mean compressive strengths of 149 MPa perpendicular and 144 MPa parallel to the sedimentation layers and a mean tensile strength of 19 Mpa.

In order to represent the current state of historical masonry structures, where weak mortars are usually present, a low-strength natural hydraulic lime mortar was designed to be used in the construction of the masonry specimens. The mortar used on the CRM retrofit solution also presented a fraction of natural hydraulic lime to guarantee compatibility between substrate and strengthening, while the mortar used for the FRM solution was based on a pozzolan hydraulic binder with polyvinyl-alcohol fibers. The compressive and tensile strength were obtained from compression and flexural tests on 160 x 40 x 40 mm prisms after 28 days of curing, following the EN 1015-11 procedure [1]. Values of mean compressive strength equal to 0.17 MPa and mean tensile strength equal to 0.81 MPa for the masonry construction mortar were obtained, such as 5.84 MPa and 22.55 MPa for mortar used on the CRM retrofitting, and 6.91 MPa and 47.02 MPa on mortar used for FRM retrofitting, respectively.

The Glass-FRP (GFRP) mesh presented a 120 x 80 mm^2 grid, considering first the weft and then the warp direction, a total fiber density of 400 g/m^2, mean tensile strengths of 74 kN/m and 86 kN/m in the weft and warp directions, respectively, and an ultimate strain of 1.5% in both directions, according to the data provided by the supplier. Helicoidal stainless steel AISI 304 connectors, with a nominal diameter of 10 mm, were used to fix the GFRP mesh to the masonry surface.

2.2 Masonry

The masonry construction was performed to represent ancient historical masonry structures along the Mediterranean countries, being composed of two roughly dressed leaves of sedimentary natural stone arranged in irregular horizontal courses, separated by approximately 5 to 20 mm thick mortar layers and with the filling in between the two layers made of mortar and stone fragments (shown in Figure 1a-b). Through stones were only used at the edges of the walls and the masonry was characterized by a total thickness of 300 mm.

The layers of the CRM and FRM retrofit solutions were connected mechanically to the masonry through helicoidal connectors, embedded about 25 cm into the masonry when only one side was retrofitted, and passed through for two sides retrofitted. The total thickness of the retrofit was approximately 30 mm, depending on the irregularity of the masonry surface. Polymeric discs were also applied with the connectors to help distribute the concentrated stresses, as in Figure 1c. Approximately five connectors per square of façade were considered.

Figure 1: a-b) Details of the double-leaf stone masonry construction, c) detail of connectors and CRM-mesh lap splice, and finish look of URM d) squat and e) slender piers.

Nine vertical and diagonal compression tests were carried out to characterize the mechanical properties of the masonry in bare and retrofitted with CRM conditions. Three wallettes per retrofit type were tested, with dimensions of 120 x 80 x 30 cm for vertical compression tests and 100 x 100 x 30 cm for diagonal compression tests. In both cases, specimens were saw-cut from a larger wall, discarding sections near the edges to avoid confining effects from through-stones, and reinforced concrete spreader beams were used for vertical compression tests to ensure load distribution. After curing for 28 days, CRM was applied to the specimens, with the warp of the GFRP mesh oriented horizontally.

The specimen's dimensions and testing protocol followed EN 1052-1 [5], ASTM Standard [6], and RILEM guidelines [7], adapted for irregular stone sizes. Table 1 provides a summary of the average of the main parameters computed for each tested configuration, where f_c is the compressive strength, f_t is the tensile strength, E is the elastic modulus, and G is the shear modulus obtained from the diagonal compression test. The compressive strength increased by a factor of 1.3 with CRM on one side and of 1.5 with CRM on two sides, regarding the bare masonry, while the tensile strength increased by a factor of 2.6 and 4.1, respectively. The E presented the same value when retrofitted on only one side and an improvement factor of 1.4 when retrofitted on both sides. On the other hand, reliable conclusions cannot be made regarding G since potentiometers were not able to record significant deformations on three of the retrofitted specimens.

Retrofit configuration		f_c [MPa]	f_t [MPa]	E [GPa]	G [GPa]
Bare masonry	Average	1.98	0.092	3.47	1.10
	C.o.V	6.6%	2.2%	27.2%	53.8%
CRM on 1 side	Average	2.49	0.23	3.46	1.12
	C.o.V	1.8%	3.4%	24.5%	52.9%
CRM on 2 sides	Average	2.85	0.37	4.76	1.58
	C.o.V	6.9%	8.9%	21.2%	- %

Table 1: Vertical and diagonal compression test results.

3 QUASI-STATIC CYCLIC SHEAR-COMPRESSION TESTS ON PIERS

3.1 Test specimens

Seven full-scale specimens were built with two geometries: slender piers with aspect ratio h/l=1.5 to induce a flexure type failure, simulating walls with window openings, and squat piers with aspect ratio h/l=0.69 to induce a shear type failure occurring typically in solid long walls or with largely spaced openings (Figure 1d-e). The slender piers presented dimensions of 1.5 x 1.0 m^2 and the squat of 2.0 x 3.0 m^2. The retrofit configurations tested were: bare masonry (URM), CRM applied on one side (CRM1), CRM applied on two sides (CRM2), and FRM applied on two sides (FRM2). The CRM mesh was mounted with the warp horizontally for the slender piers and vertically for the squat piers to induce the flexural and shear-type failures, respectively. The studied retrofit configurations and aspect ratio are summarized in Table 2, together with the corresponding specimen's designation.

Retrofit configuration	*Aspect ratio (h/l)*	*Specimen designation*
Bare masonry	0.69	SQ_URM
	1.5	SL_URM
CRM on 1 side	0.69	SQ_CRM1
	1.5	SL_CRM1
CRM on 2 sides	0.69	SQ_CRM2
	1.5	SL_CRM2
FRM on 2 sides	1.5	SL_FRM2

Table 2: Specimens' designation.

3.2 Test set-up, loading protocol, and instrumentation

A system of 3D strong-wall/strong-floor configuration with three servo-hydraulic actuators was adopted to perform quasi-static cyclic shear compression tests. Two of the actuators applied a constant combined vertical load and ensured a double-bending boundary condition, while the third actuator applied a horizontal cyclic load. The actuators were all connected to a steel beam, which in turn was connected to a spreader RC beam. A system to prevent out-of-plane movements at the top of the walls was also mounted. Figure 2a shows the test setup described. The vertical and horizontal displacements were measured through a large set of 40 transducers (Figure 2b), located mostly in the back façade and sides of the wall since the Digital Image Correlation (DIC) method was applied on the front façade.

An axial level of stress corresponding to 20% of the masonry's compressive strength was imposed at the pier's base, corresponding to a vertical force of 119 and 344 kN for the slender and squat specimens, respectively. The horizontal force was applied in groups of three push-and-pull cycles of increasing amplitude. The first cycles were set in force control until reaching up to less than half of the predicted lateral strength. Then, the horizontal actuator was set in displacement control until reaching the near-collapse conditions, which were defined when the pier was severely damaged, losing more than 20% of the lateral strength or becoming unstable under the vertical load.

a) b)

Figure 2: a) Test setup, and b) instrumentation on a slender pier.

4 EXPERIMENTAL RESULTS

The quasi-static cyclic tests performed on squat and slender masonry walls demonstrated how different geometries and retrofit configurations lead to distinct structural enhancements.

Observing the hysteretic curves presented in Figure 3 and Figure 4, squat masonry piers exhibited a shear failure mode, characterized by larger energy dissipation and residual displacements also under small amplitude cycles. On the other hand, slender piers presented a flexural behavior, with higher deformation capacity than the squat piers. In addition, this pier geometry was also tested with FRM applied to both sides (Figure 4d), showing an almost rigid rocking behavior after the fracture of the mortar fibers all the way to a 4% drift ratio.

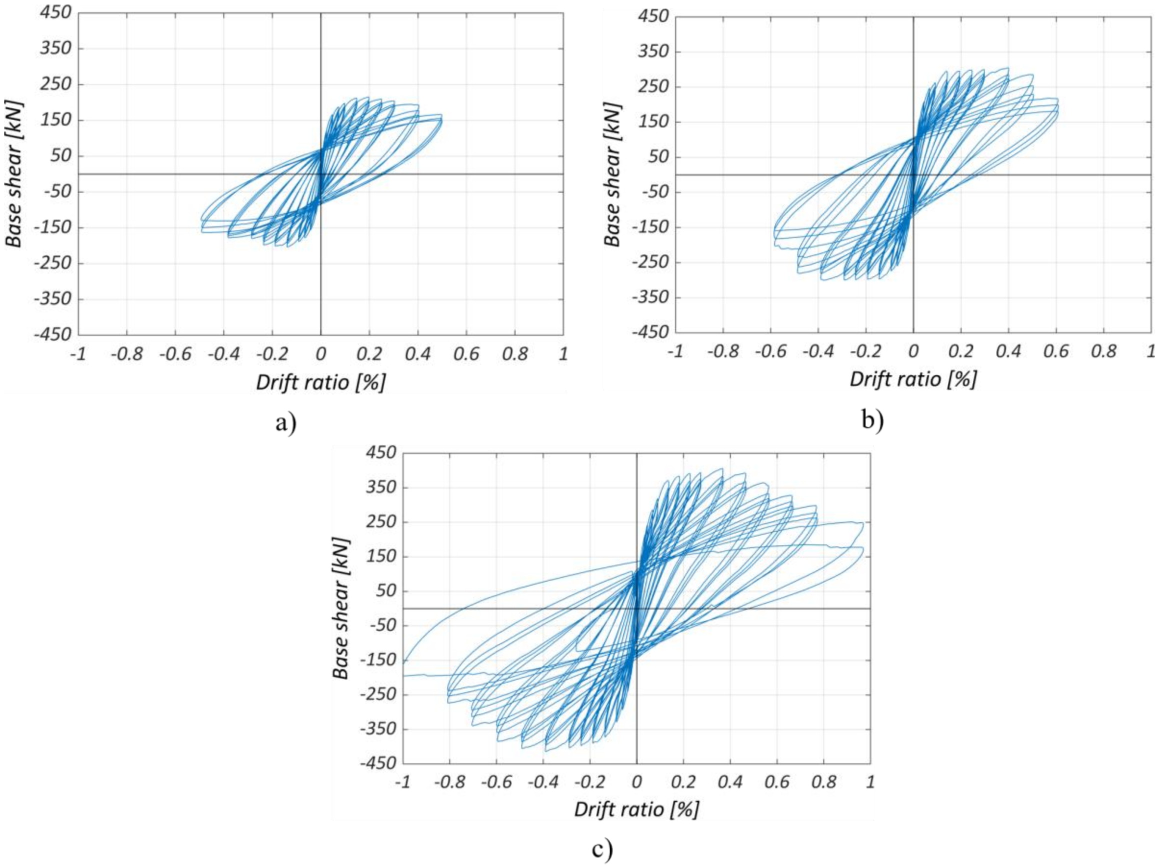

Figure 3: Hysteretic curves for squat piers: a) SQ_URM, b) SQ_CRM1, and c) SQ_CRM2.

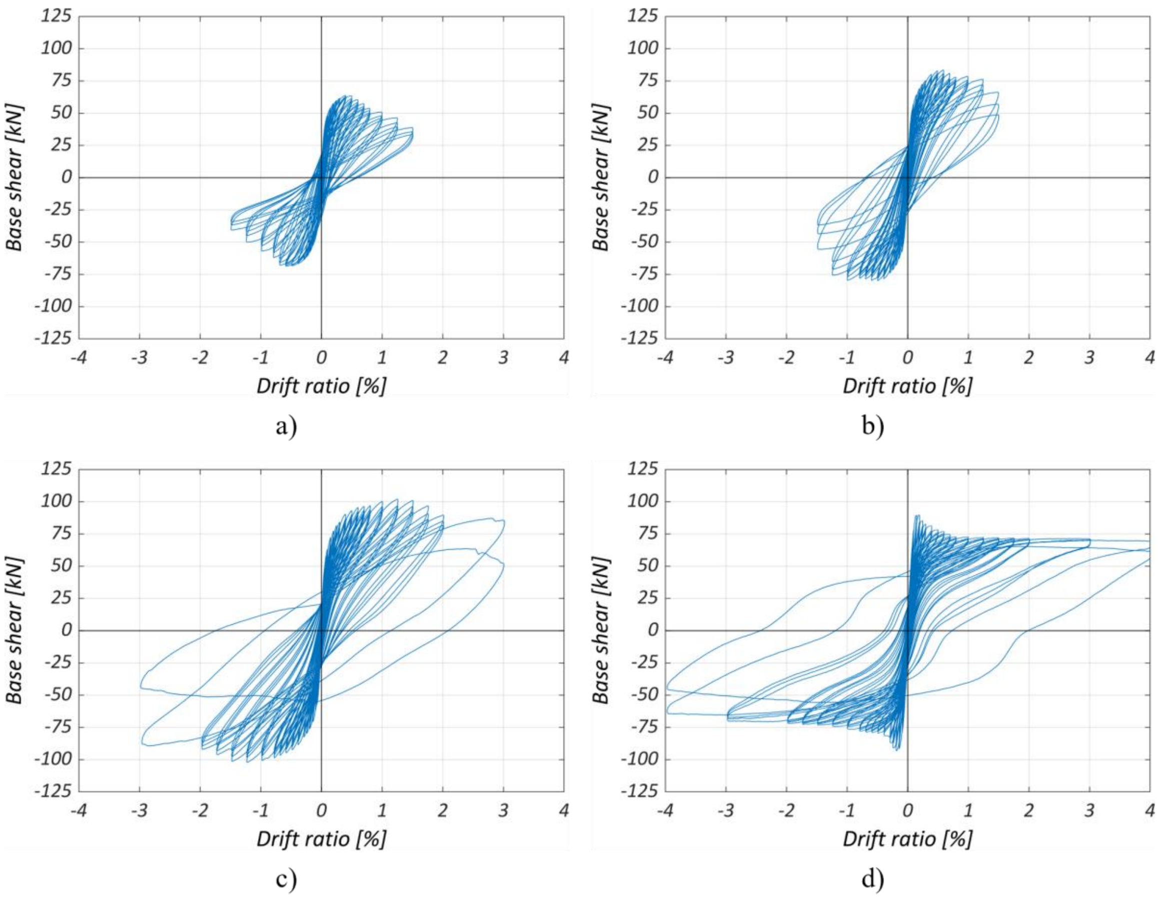

Figure 4: Hysteretic curves for slender piers: a) SL_URM, b) SL_CRM1, c) SL_CRM2, and d) SL_FRM2.

The increase in strength and deformation capacity is easily analyzed through the backbone curves displayed in Figure 5, where the peak force and ultimate displacement, set at 20% strength loss, are identified by circles and triangles. Applying the CRM on one or two sides of squat piers increased the shear strength of the bare masonry by a factor of 1.4 (from 210 kN to 303 kN) and 2.0 (from 210 kN to 411 kN), respectively, and the ultimate drift by a factor of 1.2 (from 0.5% to 0.6%) and 1.6 (from 0.5% to 0.7%), respectively. For the slender piers, applying the CRM on one or two sides led to slightly lower increases in flexural strength, by factors of 1.2 (from 66 kN to 82 kN) and 1.5 (from 66 kN to 102 kN), respectively; instead, the ultimate drift capacity due to the CRM retrofit on two sides improved by a factor of 3.0 (from 1.0% to 3.0%), while with CRM on one side the enhancement was not so pronounced, corresponding to a factor of 1.4 (from 1.0% to 1.4%).

The FRM retrofit applied to both sides of a slender pier provided a behavior enhancement similar to the one achieved with CRM. The lateral strength improved by a factor of 1.4 (from 66 kN to 92 kN) and the ultimate drift by 3.0 (from 1.0% to 3.0%). However, it is worth noting that the high-performance FRM increased also the elastic stiffness of the pier and caused the peak load to be reached at a much lower displacement.

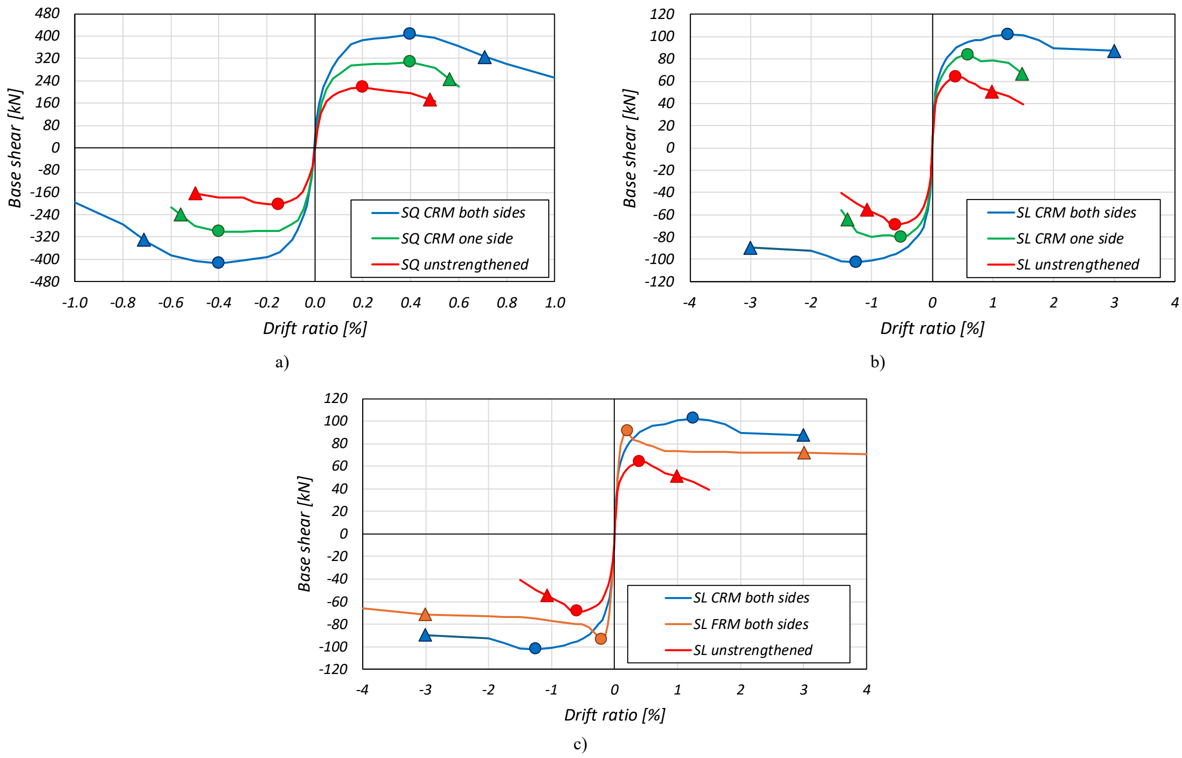

Figure 5: Backbone curves: a) Squat piers with CRM on one or both sides, b) Slender piers with CRM on one or both sides, c) Slender piers with CRM or FRM on both sides.

5 CONCLUSIONS

This paper presents an overview of the ERIES-RESTORING project, demonstrating the effectiveness of CRM and FRM retrofitting techniques in enhancing the structural performance of stone masonry. The main results of characterization tests on wallettes and quasi-static cyclic in-plane shear-compression tests on full-scale piers with different retrofit configurations are presented.

Characterization tests showed that the compressive strength of unreinforced masonry increases by a factor of 1.3 with CRM on one side and 1.5 with CRM on two sides, mainly due to the confining effect of the steel connectors. The tensile strength exhibits a more substantial improvement, increasing by factors of 2.5 and 4.0 for CRM on one and two sides, respectively.

The lateral strength of squat piers failing in shear was improved by factors of 1.4 and 2.0 when the CRM was applied on one or two sides, respectively, while the displacement capacity by factors of 1.2 and 1.6. For slender piers failing in flexure, applying CRM to one or two sides improved the lateral strength by factors of 1.2 and 1.5, respectively, and the displacement capacity by factors of 1.4 and 3.0. Applying the FRM to two sides of a slender pier led to similar improvement factors of 1.4 and 3.0 for lateral strength and displacement capacity.

The project outcomes will be used to derive and calibrate analytical and numerical formulations, and will ultimately contribute to the development of design guidelines or code requirements for CRM and FRM retrofit of existing masonry structures.

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