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In-Plane Cyclic Shear-Compression Tests on Stone Masonry Piers Strengthened with Composite- and Fiber-Reinforced Mortars

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ABSTRACT

This paper discusses the effectiveness of Composite Reinforced Mortars (CRM) and Fiber-Reinforced Mortars (FRM) as seismic retrofit of existing stone masonry buildings, through experimental research carried out within the ERIES-RESTORING project at the EUCENTRE facilities in Pavia, Italy. The in-plane cyclic behavior of these innovative strengthening materials, compatible with historical masonry, was assessed on full-size piers, subjected to constant axial load and double-fixed boundary conditions. Four specimens were strengthened with CRM, consisting of a glass-FRP mesh embedded in natural hydraulic-lime mortar: CRM was applied to one or both sides of the specimen, while two different pier aspect ratios were investigated to study the flexural and shear behavior of strengthened walls. The FRM retrofit, consisting of a mortar with polymeric fibers, was applied directly to both sides of a single pier, with an aspect ratio inducing flexural behavior. Two bare masonry piers were also tested with identical aspect ratios and axial loads. A complementary mechanical characterization campaign on mortars, retrofit components, and bare or strengthened stone masonry wallettes provided information about material properties. The experimental results in terms of damage mechanisms, lateral strength, and deformation capacity, are presented herein. Ultimately, the project outcomes will form the basis for the development of design guidelines and code requirements for the retrofit of existing masonry structures with CRM and FRM.

KEYWORDS

composite reinforced mortars, fiber-reinforced mortars, quasi-static cyclic shear-compression tests, seismic retrofit of existing buildings, stone masonry.

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INTRODUCTION

In recent decades, the seismic vulnerability of unreinforced masonry buildings has become a significant concern, particularly in regions prone to earthquakes. Ancient structures, often built using rubble stone masonry, exhibit a high risk of failure during seismic events. Consequently, the development of effective, sustainable, and durable retrofitting techniques has garnered increasing attention. Among these, solutions such as Composite Reinforced Mortars (CRM), Fabric Reinforced Cementitious Matrices (FRCM), and Fiber Reinforced Mortars (FRM) have shown promise due to their compatibility with historic structures and the use of lime-based mortars [1], [2]. Despite their growing appeal, these retrofitting techniques remain largely unstandardized, necessitating further experimental investigation to establish robust design guidelines.

The work presented herein forms part of the ERIES project, which facilitates transnational access to state-of-the-art experimental facilities. This initiative is embodied in the ERIES-RESTORING (REtrofitting of STOne masonRy using INnovative Grid-based composites) experimental program, a collaborative effort led by the University of Lisbon (Portugal) alongside the University of Pavia (Italy), Universitat Politècnica de Catalunya (Spain), EUCENTRE Foundation, IUSS Pavia (Italy), and initial contributions from ETH Zurich (Switzerland). The primary objective of this program is to address the existing knowledge gap on the seismic effectiveness of CRM and FRM retrofitting techniques when applied to undressed rubble stone masonry walls, typical of historic buildings in European and Mediterranean regions.

The experimental campaign, conducted at the EUCENTRE Foundation laboratories in Pavia, Italy, with additional testing at the Material and Structural Testing Laboratory (DICAr) of the University of Pavia, encompasses a comprehensive series of tests. These include (i) characterization tests on mortar samples from the masonry and jacketing systems, (ii) nine vertical and nine diagonal compression tests on bare and CRM-retrofitted masonry wallettes, and (iii) cyclic shear-compression tests on full-scale masonry piers. The campaign investigates four configurations of masonry walls: unreinforced (bare) masonry, CRM strengthening on one side, CRM strengthening on both sides, and FRM strengthening on both sides. The quasi-static cyclic shear-compression tests focus on two height-to-length aspect ratios, 1.5 (slender piers) and 0.69 (squat piers), capturing the seismic behavior of walls with varying geometrical characteristics.

The experimental results, including damage mechanism, displacement, and lateral carrying capacity are presented and compared between the different solutions. The findings aim to contribute to the development of design guidelines for retrofitted masonry structures.

MATERIAL CHARACTERIZATION

Constituent materials

Natural stones used in the masonry walls were cut from Credaro-Berrettino calcareous sandstone rocks in the province of Bergamo, Italy, with a mean density of 2580 kg/m^3, mean compressive strengths of 149 MPa perpendicular and 144 MPa parallel to the sedimentation layers, and a mean tensile strength of 19 MPa. The mortar mix for constructing the walls was carefully designed to replicate the weak hydraulic-lime mortar typically found in historical masonry, ensuring compatibility with the overall masonry properties and the CRM retrofit solution, which also incorporated natural hydraulic lime-based mortar in its jacketing. For the FRM solution, a mortar mix based on a pozzolan hydraulic binder with polyvinyl-alcohol fibers was used. All mortars were tested for tensile and compressive strength following EN 1015-11 [3] using standardized prisms of 160 x 40 x 40 mm cured for 28 days under laboratory conditions. The CRM retrofit incorporated GFRP meshes, commercially known as G-MESH 400, with 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%, with mesh spacing of 120 mm in the weft and 80 mm in the warp, for a total fiber weight of 400 g/m². Additionally, stainless steel helicoidal connectors with a nominal diameter of 10 mm were used, based on specifications provided by the supplier. Table 1 summarizes the experimental results of the mortar sample tested.

Table 1: Mechanical properties of the masonry and retrofit mortars

	Masonry walls		CRM retrofit		FRM retrofit	
	f_{mc} [MPa]	f_{mt} [MPa]	f_{mc} [MPa]	f_{mt} [MPa]	f_{mc} [MPa]	f_{mt} [MPa]
Average	0.81	1.17	22.55	5.84	47.02	6.91
C.o.V	33%	72%	12%	9%	19%	7%

Masonry

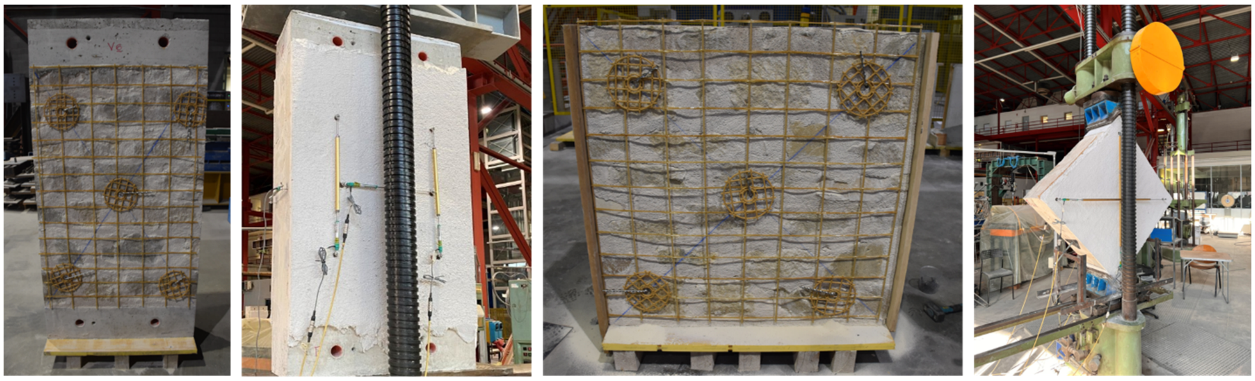
The stone masonry walls tested in the experimental campaign were constructed to replicate the typical features of ancient European and Mediterranean buildings, composed of double-leaf natural stone masonry with roughly dressed sedimentary rock blocks measuring 100–300 mm. The two masonry layers were arranged in irregular horizontal courses, separated by 5–20 mm thick mortar layers, with the interspace filled with mortar and stone fragments, resulting in a nominal wall thickness of 300 mm, as shown in Figure 1. No through stones were used except at wall edges.

a) b) c)

d) e)

Figure 1:a-c) Details of the construction of the double-leaf stone masonry walls, d) finished look of the masonry long wall for vertical compression testing, e) construction process of the slender specimens

The CRM retrofit consisted of a GFRP mesh embedded in a 30 mm thick hydraulic lime mortar jacket. Due to the irregular masonry surface, the mortar thickness varied, and helicoidal steel connectors provided transverse passive confinement. These connectors, spaced at approximately five per square meter, either passed through both masonry leaves when applied on both sides or penetrated three-quarters of the wall thickness for single-sided applications, with polymeric discs added to reduce stress concentrations, see Figure 2.



a) b) c) d)

Figure 2: a) Retrofitted specimen for vertical compression tests, b) vertical compression test setup, c) retrofitted specimen for diagonal compression tests, d) diagonal compression test setup

Nine wallettes (120 x 80 x 30 cm) were tested under vertical compression in three configurations: bare masonry (URM), CRM on one side (CRM1), and CRM on two sides (CRM2). Similarly, nine wallettes (100 x 100 x 30 cm) were tested under diagonal compression. In both cases, specimens were saw-cut from a larger wall (see Figure 1d), discarding sections near the edges to avoid confining effects, and reinforced concrete spreader beams were used for vertical compression tests to ensure load distribution. After curing for 28 days, CRM retrofits were applied to the designated specimens, with GFRP meshes oriented horizontally. The specimen's dimensions and testing protocol adhered to EN 1052-1 [4], ASTM Standard [5], and RILEM guideline [6], adapted for irregular stone sizes. Table 2 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. For further information on the computation of each parameter, the reader is referred to [7].

Table 2: Mechanical properties of the masonry and retrofit mortars

Specimen		f_c [MPa]	f_t [MPa]	E [MPa]	G [MPa]
URM	Average	1.98	0.092	3077	1096
	C.o.V	6.6%	2.2%	13.5%	53.8%
CRM1	Average	2.49	0.23	3464	1122
	C.o.V	1.8%	3.4%	24.5%	52.9%
CRM2	Average	2.85	0.37	6008	1580
	C.o.V	6.9%	8.9%	29.6%	-

QUASI-STATIC CYCLIC SHEAR-COMPRESSION TESTS ON PIERS

Test specimens

The piers were constructed using double-leaf natural stone masonry with irregular sedimentary rock blocks, roughly shaped with a hammer, and mortar joints between 5–20 mm thick. The voids between the two masonry leaves were filled with mortar and stone fragments. Two geometries were studied: slender piers (h/l=1.5) representing walls with window openings, and squat piers (h/l=0.69) simulating solid walls or those with widely spaced openings, see Figure 3. These geometries aimed to ensure that slender piers would fail in flexure and squat piers in shear, aligning with their intended structural behavior. The experimental campaign comprised two retrofitting systems: CRM and FRM. Table 3 summarizes the combing retrofitting configuration and their corresponding specimen designation.

Table 3: Test specimen combination and designation

Configuration	Aspect ratio (h/l)	Specimen designation
Unreinforced	0.69	SQ_URM
	1.5	SL_URM
Masonry with CRM on one side	0.69	SQ_CRM1
	1.5	SL_CRM1
Masonry with CRM on both sides	0.69	SQ_CRM2
	1.5	SL_CRM2
Masonry with FRM on both sides	1.5	SL_FRM2

Test Set-up

The experimental setup for the in-plane cyclic tests leveraged the strong-wall/strong-floor system at the EUCENTRE laboratory [8]. Three servo-hydraulic actuators, connected to a steel beam securely attached to the RC spreader beam, were used: two vertical actuators applied constant axial loads, while one horizontal actuator induced lateral displacements, as shown in Figure 3. The two vertical actuators were positioned on top of the specimens, symmetrically to the centerline of the masonry pier, and applied a constant axial load and boundary conditions by controlling the top rotation. The horizontal actuator induced the lateral displacements on the top RC spreader beam placed above each specimen to ensure the uniform distribution of the loads. The specimens were built on top of an RC foundation beam, which was fastened to the strong floor of the laboratory using post-tensioned steel threaded bars. Two sets of actuators were employed to accommodate the large range of strength of the tested specimens. For the specimens with low expected resistance (SQ_URM, SL_URM, SL_CRM1, SL_CRM2), the vertical actuators had a maximum force capacity of 250 kN in tension and 500 kN in compression, while the horizontal one had a force capacity of 500 kN in tension/compression. For the other specimens, it was used a horizontal actuator with a maximum force capacity of 1000 kN in tension/compression and vertical actuators with a maximum force capacity of 500 kN in tension/compression.

Testing protocol and instrumentation

To simulate realistic loading conditions, axial forces equivalent to 20% of the masonry's compressive strength were applied to the slender and squat piers. From the results of the vertical compression tests, such axial force was computed equal to 119 kN and 344 kN, for the slender and the squat piers, respectively. Subtracting the weights of the masonry pier (8.2 kN for the slender and 32 kN for the squat piers), top masonry or RC spandrel (11 kN), RC spreader beam (16 kN), steel loading beam (7.2 kN), and half horizontal actuator (3.6 kN for the 500-kN capacity actuator or 11 kN for the one with 1000-kN capacity), the constant sum of the forces applied by the pair of vertical actuators, was 66 kN for SL_FRM2, 73 kN for

SL_URM, SL_CRM1, and SL_CRM2, 267 kN for SQ_CRM1 and SQ_CRM2, and 275 kN for SQ_URM. To ensure a double-bending configuration, the vertical rotation of the pier top was restrained through a hybrid control of the vertical actuators to ensure constant axial load while preventing out-of-plane displacements [9]. This control imposed the sum of the two forces to remain constant, while the two actuators elongate or shorten by the same amount.

a) b)

Figure 3: Jacketing system mesh and connector placement *(up)*, quasi-static cyclic shear-compression test set-up *(down)*: a) slender, b) squat

The horizontal loading protocol began with force-controlled cycles of increasing amplitude, followed by displacement-controlled cycles to near-collapse conditions. The horizontal actuator was set in force-controlled cycles, where the horizontal actuator applied three push-and-pull cycles at 1/4 of the predicted shear strength, followed by another set at 1.5 times the previous force. Next, displacement-controlled cycles were introduced with amplitudes 2 to 3 times the first displacement, depending on prior force-controlled results. Subsequently, displacement-controlled cycles increased in amplitude until the specimen reached near-collapse due to severe damage, strength degradation, or unstable behavior under constant vertical load.

The displacement-controlled cycles targeted drifts ranging from 0.05% up to 4% depending on the specimens' aspect ratio and retrofit configuration.

Instrumentation included 40 displacement transducers to monitor in-plane deformations, rigid body movements, and potential out-of-plane displacements. Digital Image Correlation (DIC) was employed to capture detailed strain and displacement fields, with a white-and-black speckled pattern applied to the specimen surfaces for optical tracking. Forces were recorded using load cells mounted on the actuators, and high-accuracy displacement sensors monitored lateral actuator movements.

EXPERIMENTAL RESULTS

The quasi-static cyclic tests performed on squat and slender masonry walls demonstrated distinct behavioral improvements depending on the geometry of the specimens and the retrofitting configuration applied. The results revealed clear trends in the effectiveness of the retrofits in terms of lateral strength capacity and displacement capacity, with notable differences between the configurations and the failure modes of the walls.

Squat masonry walls exhibited a shear failure mode featuring diagonal cracks with severe damage in the intersection as shown in Figure 4. The application of CRM on both sides of the specimen led to the most significant improvement in structural performance. This configuration doubled the lateral strength capacity of the squat walls when compared to the SQ_URM specimen. Additionally, the displacement capacity at 20% strength loss, ultimate displacement δ_u, improved by a factor of 1.5, allowing the ultimate drift to increase from 0.5%, which corresponds to the ultimate drift according to the building code [10] for URM masonry piers failing in shear, to a value of 0.7%. Comparatively, applying CRM to only one side of the squat walls produced a smaller, though still significant, improvement. The lateral strength capacity increased by a factor of 1.4, and the ultimate displacement δ_u rose by a factor of 1.2, with the ultimate drift improving to 0.6%. Evidencing that the enhancement is only proportional to the number of sides strengthened in terms of carrying capacity and not displacement.

Comparing the two strengthened configurations it can be stated that the addition of reinforcement, to achieve a symmetrical configuration, led to an additional 30% increase in both strength and displacement capacity.

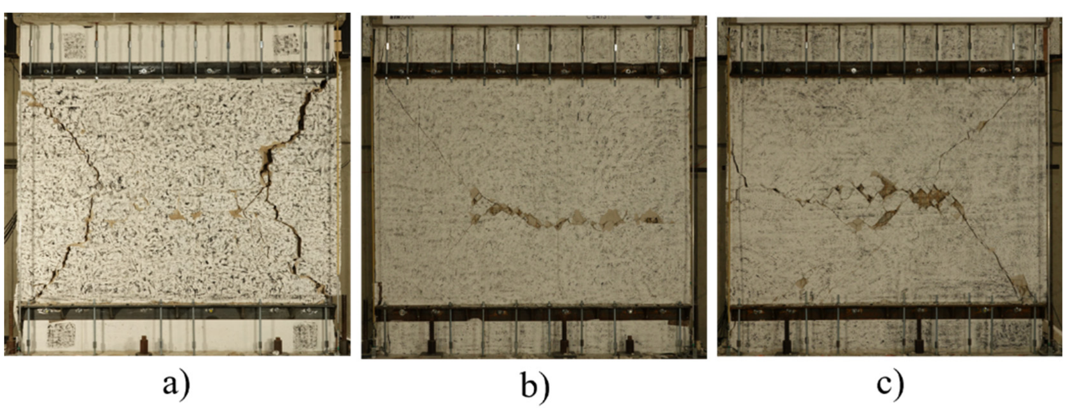
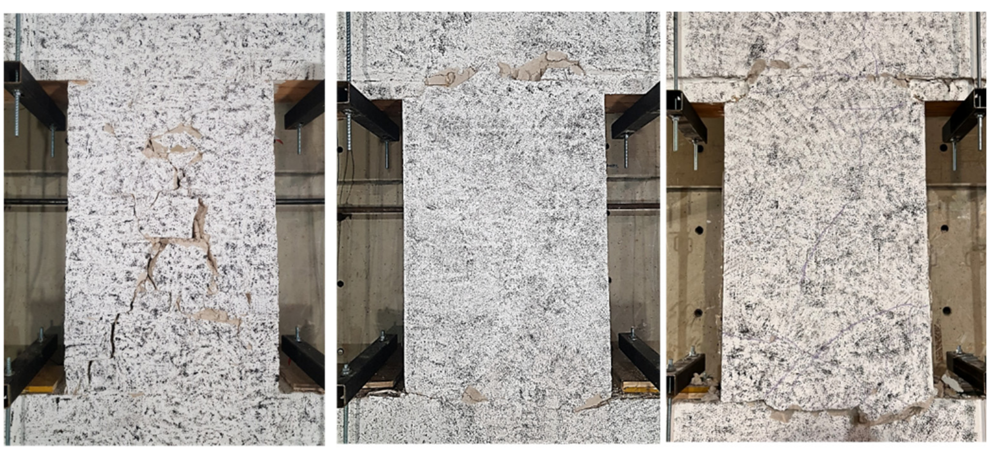


Figure 4: Final crack pattern: a) SQ_URM, b) SQ_CRM1, c) SQ_CRM2

The slender masonry walls, on the other hand, exhibited a hybrid or flexural failure mode localized in the pier between the openings, a behavior characteristic of their higher aspect ratio [11]. This is illustrated in Figure 5, which provides a zoomed-in view of the area of interest. Interestingly, in specimen SL_URM, the failure mechanism initially followed a rocking behavior, transitioning in the final loading cycles to a shear failure mode, evidenced by diagonal cracks in the pier between windows (see Figure 5a). Unlike the squat specimens, where diagonal cracks widened significantly, the cracks in the slender specimen remained narrow, allowing the structure to continue carrying load through the diagonal strut. These findings align with the analytical predictions presented in [7] which anticipated that failure in slender specimens would occur as a combination of flexural and diagonal cracking modes.

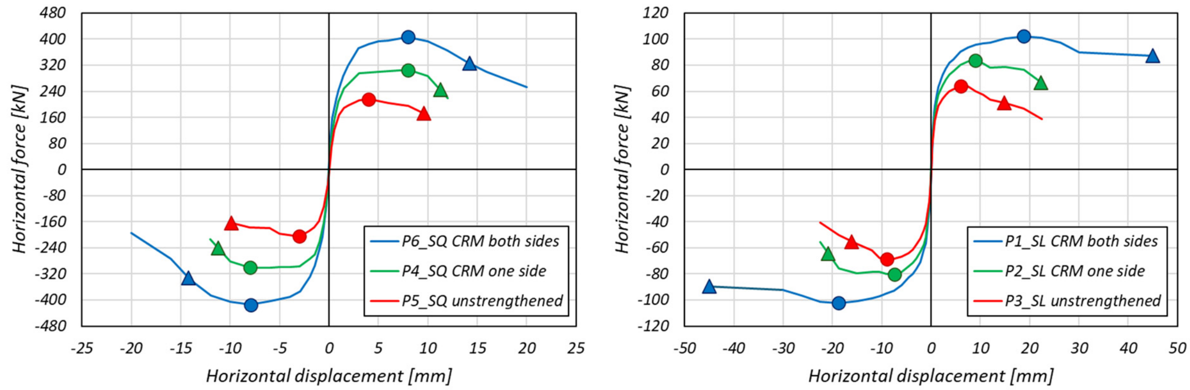
Slender specimens with CRM applied on both sides exhibited a lateral strength capacity increment by a factor of approximately 1.5, which is similar to the performance observed in the squat specimens. However, the ultimate displacement δ_u showed an exceptional improvement, with an increase by a factor of 3.0, raising the ultimate drift from 1.0% to 3.0%. Such drift corresponds to 3 times the 1.0% limit prescribed by the current building codes for masonry piers failing in flexure [10]. When CRM was applied to only one side, the lateral strength capacity improvement was more modest, with an increase by a factor of 1.2. The ultimate displacement also improved, though less markedly, with a factor of 1.4 and an ultimate drift of 1.4%. Interestingly, the application of symmetric strengthening solutions led to a load capacity increase of only 20% compared to the single-sided solution. However, the effect of the symmetric strengthened configurations was even more pronounced in terms of displacement capacity, showing a remarkable improvement by a factor of 2 over the single-sided solution. The disparity between the performance of single-sided and double-sided CRM applications in slender walls emphasizes the critical role of symmetric reinforcement in achieving both strength and deformation improvements under cyclic loading.

Near the end of the test, all retrofitted specimens, regardless of their aspect ratio, exhibited delamination of the reinforcement layer from the stone masonry along with the rupture of the glass fiber mesh. This delamination of the CRM jacketing may have been influenced by the roughness of the stone masonry surface and could potentially be mitigated by increasing the number of connectors. Additionally, in the final loading cycles, both slender specimens strengthened with CRM developed a sliding shear interface at the base of the pier, extending across its entire length (see Figure 5b-c). This phenomenon was accompanied by the detachment of the CRM layer, leading to masonry crushing and subsequent crumbling as the reinforcement separated from the substrate.



a) b) c)

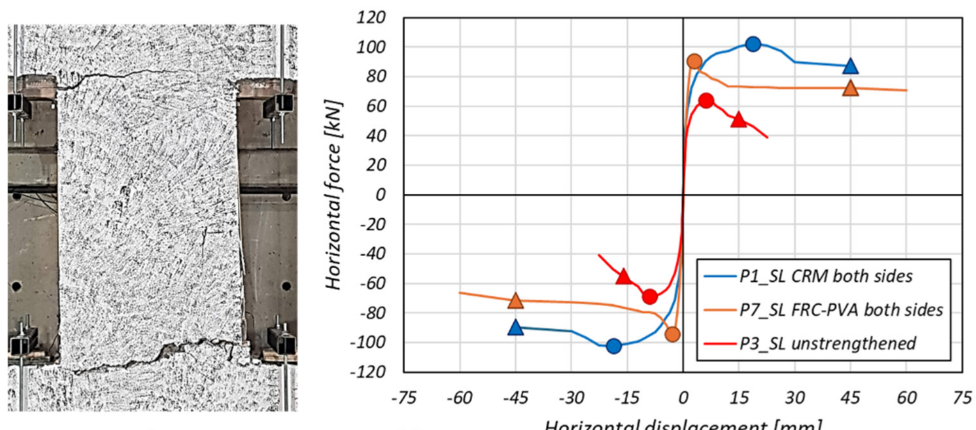
Figure 5: Final crack pattern of the area of interest: a) SL_URM, b) SL_CRM1, c) SL_CRM2



a) b)

Figure 6: Force-displacement envelope curve: a) squats specimens, b) slender specimens

An alternative strengthening configuration for slender walls was the application of FRM retrofit on both sides. As shown in Figure 7, the failure mechanism observed in this case was similar to that of the CRM-retrofitted specimens. However, the FRM solution exhibited a stiffer response, reaching peak load at a lower displacement. Despite these differences in stiffness and peak load displacement, both strengthening strategies demonstrated comparable ultimate displacement capacity. At a 20% strength loss, the FRM-retrofitted specimens achieved a displacement increase by a factor of 3.0, reaching the same ultimate drift of 3.0% as the CRM solution. The similarity in deformation capacity suggests that both retrofitting techniques effectively enhance the in-plane behavior of slender walls, with CRM offering a marginally greater strength enhancement.



a) b)

Figure 7: a) Final crack pattern of the area of interest, b) force-displacement envelope curve

Conclusion

This paper provides an overview of the ERIES-RESTORING project, which investigates the behavior of existing rubble stone masonry buildings strengthened with CRM and FRM through a series of quasi-static cyclic in-plane shear-compression tests on six full-scale specimens. The characterization tests were first conducted at the DICAr of the University of Pavia, followed by the quasi-static cyclic tests at the EUCENTRE Foundation laboratories in Pavia, Italy.

The experimental campaign examines two aspect ratios—squat and slender—and four masonry configurations: unreinforced (bare) walls as a reference, CRM strengthening on one side, CRM strengthening on both sides, and FRM strengthening on both sides. The CRM system consists of a glass-FRP mesh embedded in natural hydraulic lime mortar, compatible with historical masonry, with connectors providing transverse confinement. The FRM solution, using a polymeric fiber-reinforced mortar, was applied to both sides of a single pier. All specimens were tested under double-fixed conditions. For slender specimens, the tests included adjacent spandrels to evaluate CRM performance in piers between windows. Squat piers represented solid walls or those with widely spaced openings, featuring top and bottom R.C. beams anchoring the GFRP mesh.

As expected, slender specimens exhibited a hybrid flexural failure, with CRM jacketing showing signs of delamination followed by masonry crushing at the corners of the openings. However, the CRM retrofit significantly improved the displacement capacity, achieving an ultimate drift ratio of 3% when applied to both sides—three times the 1.0% limit prescribed by current building codes for flexural failure in masonry piers, and achieving 1.4% drift when applied to one side. The retrofitting also enhanced lateral strength capacity by factors of 1.2 and 1.5 for CRM on one or both sides, respectively. The slender specimens with FRM on both sides showed improvement factors of 1.4 for lateral strength and 3.0 for displacement capacity. In contrast, squat specimens displayed higher lateral strength but failed in shear, with more limited improvements in displacement capacity. The strength was improved by factors of 1.4 and 2.0 for CRM on one or both sides, respectively, and the displacement capacity by factors of 1.2 and 1.6, respectively.

Finally, regardless of the aspect ratio, the results highlight that the application of one or two faces of retrofit leads to a proportional improvement in peak load and overall load-carrying capacity. Both single- and double-sided strengthening configurations exhibited a clear correlation between the amount of reinforcement and the increase in strength. However, this proportional trend did not extend to displacement capacity. While single-sided retrofitting provided only a slight improvement in deformation capacity, the double-sided solutions demonstrated a remarkable enhancement.

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