FRCM for the in-plane shear strengthening of masonry panels with irregular texture

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ABSTRACT
Existing masonry buildings often exhibit a brittle behavior during seismic events due to the reduced in-plane shear capacity of piers. Inorganic composite materials are widely used for the seismic upgrading of masonry walls capacity, thanks to the good breathability and compatibility with the substrate. This work presents the results of an experimental program carried out on 17 limestone masonry panels with irregular texture typical of L'Aquila area and tested under diagonal compression. Three panels were used as control specimens; the remaining panels were strengthened with Fiber Reinforced Cement Mortar (FRCM) with anchors and two different lime-based mortars, one cement-free and one with a small cement content ratio, and coupled with two different grids (GFRP grid 40 × 40 mm and BFRP grid 6 × 6 mm). Single-sided and double-sided strengthening configurations were adopted, to investigate the reduction in strengthening effectiveness in the case of single-sided applications. The results showed that the FRCM system allowed a capacity increase by 65% in single-sided configuration and 140% in double-sided configuration. The matrix cement-content did not affect significantly the results. Conversely, the use of the BFRP grid, characterized by a 6 mm spacing, promoted the development of premature delamination problems.

1 INTRODUCTION

Existing masonry buildings in seismic areas are particularly vulnerable to heavy damage due to the reduced in-plane shear capacity of the piers (D'Ayala and Speranza 2003). This problem is even more accentuated in the case of poor quality masonry walls with a lack of transverse connections or with an irregular texture. Recently, the use of Fiber Reinforced Cement Mortar (FRCM) solutions for the in-plane shear capacity of masonry panels has been largely demonstrated via experimental tests. However, only few experimental programs available in literature investigated the effectiveness of such strengthening solutions for masonry panels with irregular texture (Balsamo et al. 2014, Corradi et al. 2014, Gattesco et al. 2015).

In the present work, the use of FRCM for improving the shear capacity of limestone masonry panels with irregular texture typical of the L'Aquila area was investigated on 17 panels under experimental diagonal compression tests.

2 EXPERIMENTAL PROGRAM

2.1 Specimens manufacturing

The experimental program involved 17 limestone masonry panels, of global dimensions 1200 × 1200 × 300 mm^3. The panels were made of rubble limestones, arranged randomly in the wooden formwork (Figure 1a). Bed joints of average thickness 10–15 mm were made with a lime-based mortar (Figure 1b). Due to the manufacturing process, the panels were characterized by an irregular texture, typical of existing masonry buildings in the L'Aquila area (Figure 1c). The specimens were built and cured as per site conditions and were strengthened after their curing period.

2.2 Strengthening configurations

The panels were strengthened with FRCM (Fibre Reinforced Cement Mortar) in both single-sided (SS) and double-sided (DS) configurations.

(a)

(b)

(c)

Figure 1. Specimens manufacturing process: (a) layer of stone, (b) bed-joint mortar, (c) masonry panel after curing.

Mechanical anchors were adopted to improve the weak horizontal connection caused by the irregular texture of the masonry in all SS and SD panels.

Two classes of matrix were herein investigated: a lime-based cement free mortar, named lime mortar in the following, and a lime-based mortar containing 20% of cement, called cement-lime mortar in the next. The average thickness of the mortar is 25 mm per each side.

The grid adopted for the strengthening of 12 panels consisted of a pre-coated GFRP balanced grid with spacing 40 x 40 mm (unit weight 270 g/m^2). GFRP bars were used as anchors (five per side), with a penetration length of 200 mm.

The remaining 2 specimens were strengthened in double-sided configurations with a pre-coated BFRP balanced grid of spacing 6 x 6 mm (unit weight 250 g/m^2), to investigate the role of the grid in the overall behaviour of FRCM strengthened specimens. In this case, the anchors adopted were steel spikes with diameter 5 mm. The experimental program is summarized in Table 1. The labels are in the format XyJ_n, where X is the mortar (L=lime; CL=cement-lime), y is the configuration (1=single-sided; 2=double-sided), J is the grid (G=GFRP, B=BFRP), n in the specimen number.

The strengthening procedure consisted of: masonry pre-wetting; drilling of the holes for the mechanical anchors; first coating of mortar with average thickness 15 mm; application of the grid by hand-pressing; application of the anchors filling the holes with mortar; second coating of mortar with average thickness 10 mm.

Table 1. Experimental matrix.

Specimen	Configuration*	Mortar	Grid
C_1	control	-	-
C_2	control	-	-
C_3	control	-	-
L1G_1	SS	lime	GFRP
L1G_2	SS	lime	GFRP
L1G_3	SS	lime	GFRP
L2G_1	DS	lime	GFRP
L2G_2	DS	lime	GFRP
L2G_3	DS	lime	GFRP
CL1G_1	SS	cement-lime	GFRP
CL1G_2	SS	cement-lime	GFRP
CL1G_3	SS	cement-lime	GFRP
CL2G_1	DS	cement-lime	GFRP
CL2G_2	DS	cement-lime	GFRP
CL2G_3	DS	cement-lime	GFRP
CL2B_1	DS	cement-lime	BFRP
CL2B_2	DS	cement-lime	BFRP

*Configuration: SS=single-sided strengthening, DS=double-sided strengthening.

2.3 Material mechanical properties

Experimental tests were performed for characterising the compression and tension capacity of the mortars. The lime mortar achieved an average compressive strength of 6.6 MPa (*CoV*=1.1%) and an average flexural strength of 14.5 MPa (*CoV*=8.8%). The cement-lime mortar achieved an average compressive strength of 5.8 MPa (*CoV*=5.2%) and an average flexural strength of 14.2 MPa (*CoV*=14.3%).

The mechanical properties of composite grids were provided by the manufacturer. In particular, the GFRP grid had a tensile strength of 1480 MPa, with elastic modulus of 33 GPa and a resisting area of 36 mm^2/m. Conversely, the BFRP grid was characterized by a tensile strength of 1542 MPa, with elastic modulus of 89 GPa and a resisting area of 39 mm^2/m.

2.4 *Test set-up*

An ad-hoc designed set-up for off-site tests was used for performing the diagonal compression tests. The specimens were tested under displacement control to allow monitoring of the post peak response with displacement rate 0.02 mm/s. Four linear variable displacement transducers, two per each side of the panels, were installed along the two diagonals to monitor the in-plane displacements along principal directions over a gauge length of 400 mm. More details about the test set-up and the instrumentation can be found in Del Zoppo et al. 2019a.

3 *EXPERIMENTAL RESULTS*

The experimental results in terms of peak shear stress, τ, are summarized in Table 2 for control and strengthened specimens. The peak shear stress was calculated according to ASTM E 519-07 (2007), as:

$$\tau = 0.707 P / A_n \tag{1}$$

where P is the experimental diagonal load and A_n is the net area of the specimen (i.e. $A_n = 0.5(w + h)t$ with w the panel width, h the panel height and t the panel thickness).

The shear stress-strain curves for panels strengthened with lime or cement-lime mortar are depicted in Figure 2a and b, respectively.

The experimental results are also presented in the next in terms of observed damage pattern and failure mode for each class of specimens.

Table 2. Experimental peak shear stresses.

Specimen	P_{max} [kN]	τ_{max} [MPa]	$\tau_{max,average}$ *(CoV)* [MPa]
C_1	185	0.36	0.39 *(11%)*
C_2	192	0.38	
C_3	226	0.44	
L1G_1	295	0.58	0.64 *(10%)*
L1G_2	322	0.63	
L1G_3	362	0.71	
L2G_1	498	0.98	0.95 *(3%)*
L2G_2	476	0.94	
L2G_3	474	0.93	
CL1G_1	290	0.53	0.60 *(16%)*
CL1G_2	391	0.71	
CL1G_3	316	0.57	
CL2G_1	467	0.92	0.90 *(1%)*
CL2G_2	458	0.90	
CL2G_3	456	0.90	
CL2B_1	477	0.92	0.92 *(1%)*
CL2B_2	471	0.91	

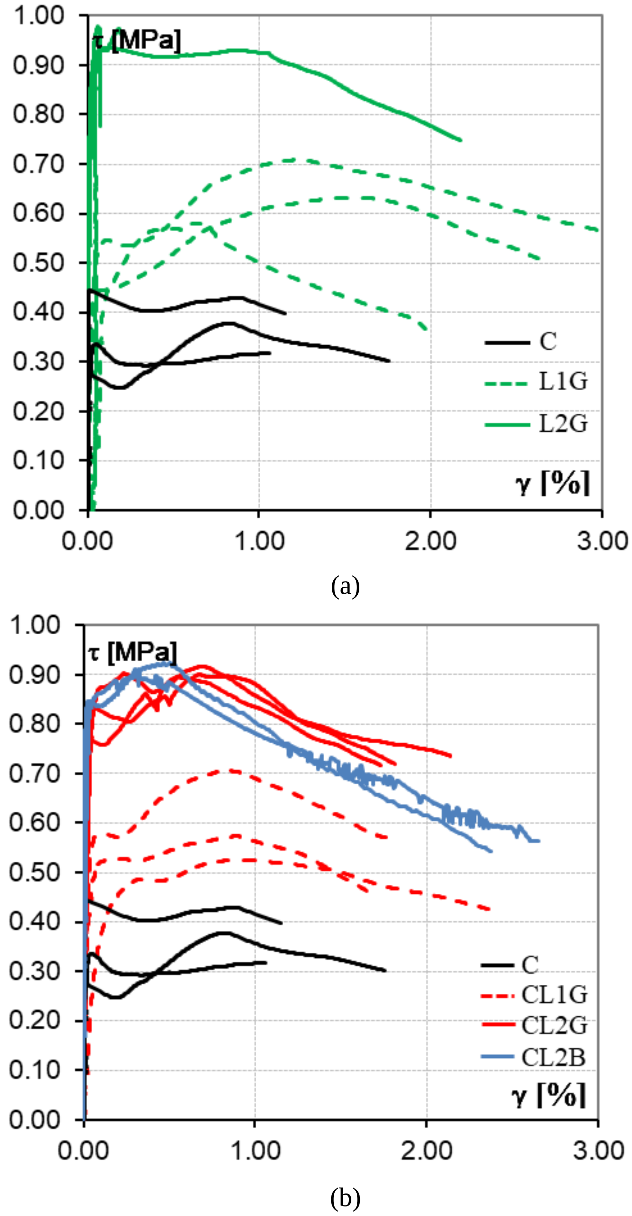


Figure 2. Shear stress-strain capacity curves for FRCM with lime mortar (a) or cement-lime mortar (b).

3.1 *Control specimens*

The three control specimens of limestone masonry with irregular texture exhibited a diagonal tension failure with the development of a single large crack following the bed-joints along the compressed diagonal, see Figure 3a. No toe crushing phenomena were observed at failure.

The control specimens achieved quite high peak shear stresses for a masonry with irregular texture, with an average peak shear stress, τ, of 0.39 MPa and a coefficient of variation CoV=11%.

3.2 *Single-sided strengthened specimens*

Six specimens were strengthened with FRCM in single-sided configuration with anchors, out of which three were reinforced with a lime mortar and other three with cement-lime mortar. The same GFRP grid was adopted for all specimens in single-sided strengthening configuration.

In terms of failure mode, all the specimens in single-sided configuration developed some cracks along the compressed diagonal, in a pattern compatible with the diagonal-tension failure (Figure 3b). The specimens didn't show any premature delamination or debonding problem before failure. Furthermore, any significant out-of-plane deformation due to the asymmetrical reinforcement was recorded during the diagonal-compression tests.

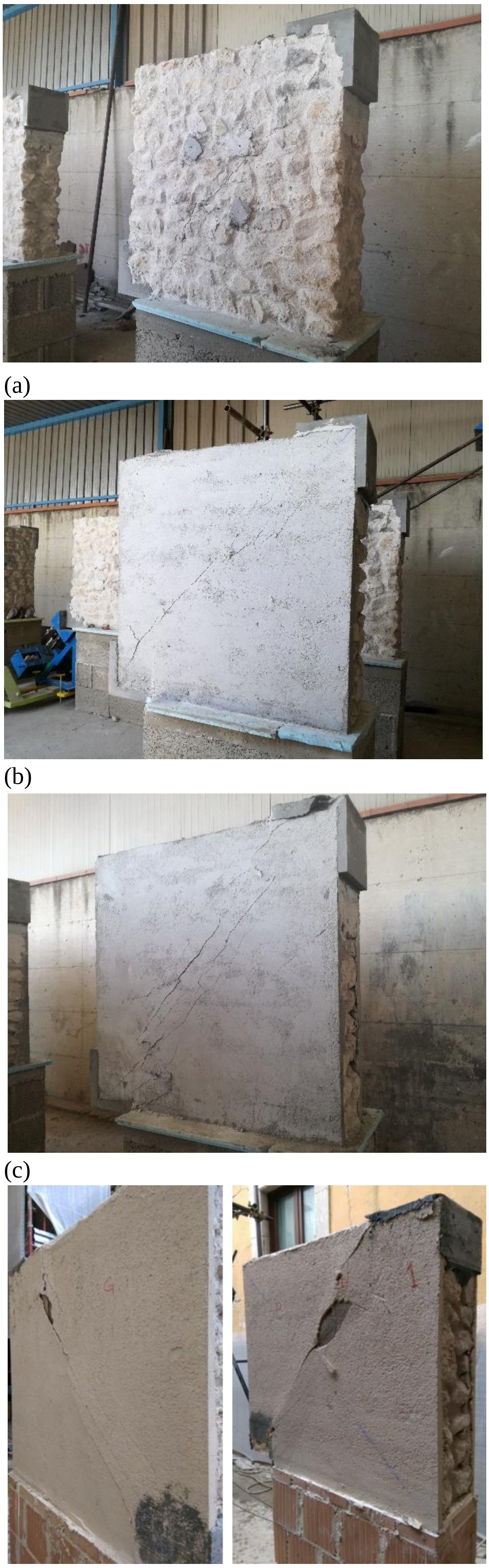
Specimens reinforced with the lime mortar experienced an average peak shear stress of 0.64 MPa, with a *CoV*=10%. Similarly, specimens strengthened using a cement-lime mortar achieved an average peak shear stress of 0.60 MPa, with *CoV*=16%.

3.3 Double-sided strengthened specimen

The specimens strengthened in double-sided configuration with the GFRP 40x40 grid experienced a diagonal-tension failure, with the development of several cracks along the compressed diagonal before the failure (Figure 3c). Similarly to what observed for the single-sided specimens, no delamination, debonding or local failure mechanisms were detected during the tests up to failure.

In terms of capacity, the specimens strengthened with the lime mortar achieved an average peak shear stress of 0.95 MPa (*CoV*=3%). Specimens strengthened with the cement-lime mortar attained an average peak shear stress of 0.90 MPa (*CoV*=1%).

Conversely, in specimens strengthened using the BFRP 6x6 grid, premature delamination problems occurred during the test for both specimens tested, with partial detachment of the second coating of mortar, see Figure 3d. This can be partly related to the higher elastic modulus of the BFRP grid if compared to the GFRP one, and partly related to the very small spacing of the BFRP grid that could reduce the bond between first and second layer of mortar. In terms of average peak shear stress, the specimens achieved a τ of 0.92 MPa with a *CoV*=1%.



(a)

(b)

(c)

(d)

Figure 3. Damage pattern at failure for: control specimen (a), single-sided strengthened specimen (b), double-sided strengthened specimen with GFRP grid (c) and double-sided strengthened specimen with BFRP grid (d).

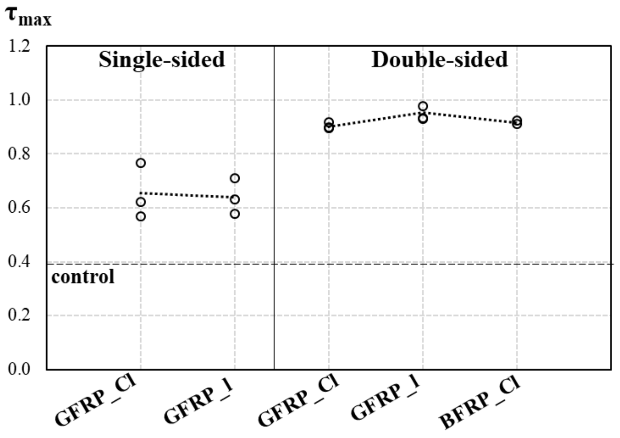


Figure 4. Effect of mortar/grid.

3.4 *Effect of the mortar composition/grid properties*

In Figure 4, the peak shear stresses achieved during the diagonal-compression tests are reported for each group of specimens, to underline the effect of the different mortar/grid adopted for the FRCM system, named GFRP_Cl (GFRP grid and cement-lime mortar), GFRP_l (GFRP grid and lime mortar) and BFRP_Cl (BFRP grid and lime mortar).

First of all, it is observed that the double-sided configuration probably helped in providing more stable results in terms of peak capacity with respect to the single-sided one. Indeed, a negligible variability of results was recorded for specimens in double-sided configuration.

In terms of mortar composition, specimens strengthened with lime or cement-lime mortar achieved almost the same peak capacity. Thus, from the present results, both mortars seemed to be equally compatible with the limestone masonry substrate. Panels strengthened in double-sided configuration with the lime mortar achieved a slightly greater average peak capacity with respect to the remaining panel adopting a cement-lime mortar.

About the specimens with same mortar but different grid, the same peak capacity was recorded for both sets of specimens (i.e. GFRP_Cl and BFRP_Cl). However, it should be noted that the two BFRP_Cl specimens experienced delamination problems that have caused failure of the system.

4 *CODES PROVISIONS AND ANALITYCAL FORMULATIONS*

Currently, the only codes regarding the design of strengthening solutions via FRCM are just the American ACI 549.4-R13 (2013) and the Italian CNR-DT 215 (2018). In particular, the American approach is based on the formulation provided for calculating the shear contribution of FRP and just consider the contribution of the grid. Conversely, the Italian guidelines provide two methodologies for defining the capacity increase due to the external shear reinforcement with FRCM.

The first one is an analytical approach for predicting the shear force carried out by the FRCM, as follows:

$$V_{FRCM} = 0.5 n_f t_f b_f \alpha \varepsilon_f E_f \tag{2}$$

where n_f is the number of grid layers, t_f is the equivalent thickness of fibres in the orthogonal direction to shear force, b_f is the panel length, $\alpha\varepsilon_f$ represents the effective strain at failure and E_f is the cracked FRCM elastic modulus, corresponding with the grid elastic modulus. The factor $\alpha = 0.8$ is used for taking into account the reduction of fibre tensile capacity due to the simultaneous shear interaction. In the case of single-side strengthening configuration, the computed shear force should be reduced by 30%.

Due to the lack of knowledge about the effective strain at failure for this kind of composite materials, the term $\varepsilon_f E_f$ representing the effective stress at failure condition was herein assumed equal to the grid ultimate tensile stress. The theoretical shear contribution of the FRCM was compared with the experimental one, evaluated as the difference between the peak shear force of strengthened specimen and the average peak shear force achieved by control specimens, are summarized in Table 3. It should be observed that the Equation 2 is only a function of the grid mechanical properties and did not take into account the matrix contribution or properties.

The comparison between theoretical and experimental results showed that the analytical model provided very safe predictions of the effective shear contribution given by the FRCM.

Table 3. Experimental shear stress increasing factor.

Configuration	FRCM	$V_{f,exp}$ [kN]	$V_{f,theo.}$ [kN]	$V_{f,theo}/V_{f,exp}$
SS	GFRP_Cl	93	*36*	*0.4*
	GFRP_l	88	*36*	*0.4*
DS	GFRP_Cl	*183*	51	0.3
	GFRP_l	199	51	0.3
	BFRP_l	193	58	0.3

The second method proposed by the Italian guidelines is a simplified approach based on empirical-based amplification factors. For instance, in the case of FRCM solutions in double-side configuration for masonry panels with irregular texture, an amplification factor for the shear stress $\tau/\tau_0 = 1.5$ is suggested.

Based on the experimental results herein discussed, the average τ/τ_0 ratios reported in Table 4 are greater than 1.6 in single-sided configuration and greater than 2.2 in double-side configuration.

Table 4. Experimental shear stress increasing factor.

	τ_{max}/τ_0 [-]		
Configuration	GFRP_Cl	GFRP_l	BFRP_l
SS	1.54	1.65	-
DS	2.29	2.40	2.32

The other test results available in literature on masonry panels with irregular texture reinforced with FRCM and tested under diagonal-compression were also collected and compared with the experimental results herein presented. In particular, 5 tests on limestone masonry panels typical of the L'Aquila region were presented in Balsamo et al. 2014. Gattesco et al. 2015 performed 8 experimental tests on cobblestone masonry panels with irregular texture and Corradi et al. 2014 carried out 8 experimental tests on rough hewn stone and pebble stone masonry panels with irregular texture. The main properties and experimental results were collected in Del Zoppo et al. 2019b and are also summarized in Table 5. The results of previous experimental tests are in accordance with the one herein presented. In terms of average amplification factors τ/τ_0, all the specimens achieved ratios greater than 2.3.

Table 5. Database of tests from literature on masonry with irregular texture.

Ref.	Configuration	t_{matrix} [mm]	Grid type	τ_{max} [MPa]	τ_{max}/τ_0 [-]
Balsamo et al. 2014	control	-	-	0.13	-
	DS	12	BFRP6x6	0.33	2.5
	DS	12	BFRP6x6	0.43	3.3
	DS	12	GFRP25x25	0.33	2.5
	DS	12	GFRP25x25	0.30	2.3
Gattesco et al. 2015	control	-	-	0.17	-
	control	-	-	0.19	-
	DS	30	GFRP66x66	0.58	3.2
	DS	30	GFRP66x66	0.57	3.1
	control	-	-	0.07	-
	control	-	-	0.08	-
	DS	30	GFRP66x66	0.32	4.3
	DS	30	GFRP66x66	0.35	4.7
Corradi et al. 2014	control	-	-	0.04	-
	control	-	-	0.04	-
	DS	30	GFRP66x66	0.34	8.4
	DS	30	GFRP66x66	0.44	10.8
	DS	30	GFRP66x66	0.46	11.2
	control	-	-	0.11	-
	DS	30	GFRP66x66	0.45	4.1
	DS	30	GFRP66x66	0.57	5.1
	DS	30	GFRP66x66	0.43	3.9

5 CONCLUSIONS

The effectiveness of the in-plane shear strengthening with FRCM system was investigated on 17 limestone masonry panels with irregular texture typical of the L'Aquila region. FRCMs with diverse mortars and grids were tested and their influence was evaluated in both single-sided and double-sided strengthening configurations. Mechanical anchors were used in both configurations.

The results showed that the FRCM is an effective solution for increasing the in-plane shear capacity of masonry panels with irregular texture. In particular, panels in single-sided configuration achieved a shear capacity increase up to 65%. Conversely, panels in double-sided configurations experienced an increase up to 140%.

The mortar composition did not play a significant role in the overall behaviour of the specimens. Conversely, premature delamination problems occurred when a grid with high axial stiffness and small spacing was used.

The comparison between the experimental results from this experimental program and from others available in literature showed that the FRCM system in double-sided configuration is able to provide on average shear stresses greater than 2.3 times the original shear capacity.

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