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FRCM retrofitting techniques for masonry walls: a literature review and some laboratory tests

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Abstract

The experimental characterisation of externally bonded composite materials as strengthening solutions for masonry structures, such as basalt textile reinforced mortar (BTRM) or fiber reinforced concrete (FRC), has been receiving increasing attention due to their outstanding mechanical performance. Several studies have been demonstrated the efficiency of this retrofitting solution for increasing the mechanical strength and the displacement capacity of masonry material.
In this paper the state-of-art of the most relevant achievements in the experimental investigations and numerical analysis of retrofitted masonry wall have been critically reviewed. Firstly, a detailed collection of several experimental tests using different textile reinforced mortar and/or fiber reinforced mortar has been conducted. Special focus has been given to the test set-up and load configuration type adopted for experiments. Subsequently, several modelling techniques have been treated in order to detect the best approach simulating the interaction between reinforcement system and masonry ranging from macro and micro modelling, concentrated and diffused plasticity model and diverse constitutive laws.
Finally, an overview of some original experimental outcomes from laboratory tests is presented. This results will play a major role in for the validation of the numerical models for the prediction of the shear strength and the ductile behavior of reinforced masonry that will be developed in a further step of this research.

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Keywords: Review, retrofitting, masonry, textile reinforced mortar, fiber reinforced concrete, experimental investigations

1. Introduction

Aspects related to the modeling of masonry structures are of particular interest, both for the professional activity of the engineer and for research (see e.g Ferretti et al. 2021 and 2022). Several review papers or entire book chapters emphasized the crucial role played by this topic into the structural engineering field, as reported by Beyer et al. (2022) and Sarhosis et al. (2016). In the last decade, several retrofitting techniques, as Fiber reinforced polymer (FRP) or textile reinforced mortar (TRM), became widespread and received special attention by engineers (see e.g. Bertolesi et al. 2020, Formisano et al. 2021 and Facconi et al. 2016). While the former intends to make use of simplified but reasonably accurate models, detailed modeling is still necessary for the timely evaluation of the behavior of complex structures. In this respect, Cattari et al. (2021) provided an overview of the nonlinear modeling considerations for assessing the seismic response of unreinforced masonry structures, with particular emphasis on the effects that questioning modeling decisions might have on the outcomes of models considering extremely complex architectural configurations. In fact, numerical models are now the only instruments considered to be sufficiently effective to facilitate the seismic assessment of existing buildings, according to the specialized technical community. The study discusses many methods, from the widely used Equivalent Frame approach to more sophisticated methods including 2D and 3D Finite Element processes based on continuous, discrete, and micro-mechanical approaches. They drew attention to many potential future advances for various simulation levels, such as equivalent frame models. Additionally, a few challenging problems that are typical of the execution of nonlinear time history studies were highlighted, such as the ability to simulate the cyclic response or the capacity to accurately reproduce energy dissipation that is specially connected to ductility. Castellazzi et al. (2022) presented a comparison of the outcomes of nonlinear static analysis performed on a masonry building using various programs that operate in the fields of continuum and discrete macroelement modeling. The building was modeled after a real school that had been damaged in the Central Italy earthquake in August 2016. With regard to the dispersion of the results and to the potential consequences in the professional sector, the results provided some insights on the employment of continuum and discrete-macroelement modeling.

Within research studies which associating experimental and numerical approaches to deep the structural behavior of masonry elements, an experimental research on the mechanical performance of retrofitted brick masonry walls under an in-plane cyclic shear test was presented by Garcia-Ramonda et al. in (2022). Unreinforced and retrofitted with Basalt Textile Reinforced Mortar configurations of the specimens were tested. The examination of the reinforced walls put through shear compression tests also made use of a sophisticated computational model. As a continuous nonlinear homogeneous macromodel, the brickwork was modeled. The capacity of the model to predict the in-plane behavior of retrofitted brick masonry walls was examined by comparing the numerical results with the experimental results ones. Salsavilca et al. (2020) examined the behavior of the link between the composite layer and the substrate given by a Peruvian masonry, when structural element were retrofitted by Steel Reinforced Grout. Additionally, a characterization of the retrofit materials using compression tests on the mortar and direct tensile tests on the fiber was reported. In order to create a cohesive material law, design bond parameters were also obtained using an analytical model. Bellini et al. (2018) have provided an experimental campaign and a numerical analysis devoted to the research of the out-of-plane behavior of masonry walls reinforced with Fiber Reinforced Cementitious Matrix. In order to examine the behavior of strengthened masonry walls under out-of-plane horizontal activities, such as, for example, seismic actions, they discussed the failure modes and capacity of the strengthening system. The outputs of nonlinear studies carried out on simplified finite element models of the walls were discussed and compared with the results of the present study. In order to develop trustworthy code recommendations that result in the safe design of reinforced masonry structures, a proper assessment of the flexural capacity of the strengthened walls is necessary.

In recent years, several researchers have developed intensive laboratory work in order to investigate the actual

behavior of differently consolidated masonry elements.
Incerti et al. (2019) conducted an extensive experimental campaign to evaluate the efficacy of the same strengthening technique when it was applied to two different masonry typologies. Four masonry samples made of hydraulic lime-based mortar and clay bricks were put through various testing using the Flemish bond and header bond textures. Benefits seen in the samples' capacity, shear stiffness, and ductility were examined in light of variations in building typologies. Moreover, comparisons were made with the theoretical findings from the Italian Guidelines CNR DT 200.
An experimental examination of the structural behavior of masonry walls strengthened with Textile Reinforced Mortar to increase their in-plane shear strength and deformation capacity (ductility) was presented by Garcia-Ramonda et al. (2020). Ten clay brick and lime mortar masonry samples retrofitted with three alternative technologies were diagonally compressed tested as part of the experimental program. On the inner face of the wall, continuous basalt Textile Reinforced Mortar, discrete bands of unidirectional steel Textile Reinforced Mortar, and continuous basalt Textile Reinforced Mortar were used. On the outer face of the wall, bed joints structural repointing was done with near-surface mounted helical stainless-steel bars. Testing of several specimens in both their unreinforced and repaired configurations revealed an improved increase in shear resistance and ductility, making them acceptable for seismic retrofitting and post-earthquake repair.
In a subsequent paper, Garcia-Ramonda et al. (2022) offered an experimental program on masonry walls consisting of handmade solid clay brick and hydraulic lime mortar. Reversed cyclic shear compression tests were performed on the specimens in a variety of configurations, including unreinforced, repaired and retrofitted by using Basalt Textile Reinforced Mortar. According to the experimental findings, the suggested solutions for seismic retrofit and post-earthquake restoration of existing masonry buildings increased resistance, ductility, and energy dissipation in comparison to unreinforced masonry shear walls. Furthermore, they helped to clarify the failure mechanisms and displacement capabilities of the behavior of masonry walls subjected to cyclic horizontal displacements.
For shear masonry walls formed of handmade solid clay brick and hydraulic lime mortar, Garcia-Ramonda et al. (2022) proposed an experimental investigation on the usage of steel reinforced grout as an in-plane strengthening solution. On reinforced walls made of sheets of low-density steel, cyclic shear compression tests were performed. The retrofitting was applied in a strip arrangement to both faces of the walls. In terms of failure mechanism, load-bearing capacity, energy dissipation, and ductility, the experimental program sought to investigate the impact of the number of textile layers on the in-plane response of strengthened masonry walls.
There is no doubt that the existing literature is full of laboratory insights into both the actual behavior of masonry components and the impact of various retrofitting methods. Parallel to this development, numerical simulation has also advanced to satisfy the design and verification requirements of reinforced or unreinforced masonry projects. Nevertheless, despite significant advancements, there are still some areas that require some research and advancement. One of these is unquestionably the transition from complex nonlinear modelling of masonry parts in simplified equivalent frame approach with and without retrofitting operations (see e.g. Cattari et al. 2021). The element's cyclic reaction and the contribution that retrofitting measures make to ductility are still two specific characteristics of difficult challenges.
The goal of this contribution is to increase knowledge in this field. In order to highlight the effort in term of ductility with respect to the cyclic shear stress of Fiber Reinforced Cementitious Matrix or in the presence of axial compression, some laboratory results will be presented specifically on brick-and-mortar specimens not reinforced with Fiber Reinforced Cementitious Matrix.
These will serve as a prelude to the step in which the element's structural modeling through micromodeling will be explored in order to define a comprehensive, rich, and generalized database. The latter will serve as a tool to subsequently advance a model with concentrated elemental flexibility and retrofitting intervention.

2. Experimental investigations on masonry with Fiber Reinforced Cementitious Matrix (FRCM)

With the aim to understand the effectiveness of the specific retrofitting system on different masonry typologies, three experimental campaigns will be described. N. 38 squared masonry panels were realized within the extended experimental campaign. Two different masonry materials were investigated. Full bricks and tuff materials were considered by using blocks and lime-based mortar to reproduce masonry textures typical of the Italian built heritage. Specifically, N. 8, n.18 and n.12 samples for each masonry panel material were subjected to uniaxial compression

tests, diagonal compression tests and out-plane bending tests respectively with the aim to evaluate the efficiency of the strengthening system and the influence of the masonry quality on the shear and bending behavior of the samples. The masonry typologies on which this strengthening technique can be applied are extremely variable, it can be affected by the nature of the components, the characteristics of the mortar and those of the masonry material. For all these reasons, the considered experimental investigations can be assumed as representative of the most common masonry typology constructed by clay bricks or sandstone and hydraulic lime-based mortar (class M5). Mainly, two different type of glass fiber reinforcements "OLY WALL M15" were investigated in experimental tests. Details concerning geometric and mechanical properties of bricks, cementitious mortar adopted for masonry joints and type of the glass fiber reinforcement are reported in Figure 1. Moreover, The FRCM strengthening layout was realized by a bi-directional basalt grid, embedded within two mortar matrix layers (overall thickness of 30 mm) and applied symmetrically on both sides of the masonry panels with a distance from the edge equal to 20 mm in order to prevent early debonding phenomena, as described in Incerti et al. (2015). Cold-drawn Helicoidal, realized using steel inox "Oly Chain" connectors with a diameter of 8 mm and maximum tensile strength equal to 10.5 kN, were adopted for each sample, aiming to anchorage the reinforcement layouts on the two sides of the masonry panels. In Table 1 and 2, characteristics of brick and mortar specimens and tested fiber grid are reported respectively.

Table 1. Characteristics of brick and mortar specimens.

	Type	Dimensions [cm]	Gross Density [kg/m^3]	Compressive strength [MPa]	Bending strength [MPa]
Solid Brick	Fired-clay	12x25x5.5	1700	30	-
Tufo	Sand-stone	25x37x11	1250	4.4	-
Mortar	Pre-mixed lime-based (M5)	0.04x0.04x0.16 (prismatic specimens)	1900	5	2

Table 2. Characteristics of the tested Fiber grid and Mortar matrix applied to the masonry samples.

	Type	Gross Density [kg/m^3]	Compression strenght [kN]	Tensile strenght [kN]	Flexural strenght [MPa]	Elastic Modulus [GPa]
Fiber grid 250	OLY WALL - 250	0.25	-	1.34	-	61
Fiber grid 550	OLY WALL - 550	0.55	-	2.42	-	67
Mortar Matrix	Pre-mixed lime-based	1550	15	-	4	-

In conclusion, an overview of the mechanical tests conducted for each specimen is pointed out in Table 3. In the following section, the results derived by the experimental tests are provided and some comparisons are carried out.

Table 3. Overview of the mechanical tests included within experimental campaign .

Masonry typology	Compression test	ID sample	Diagonal compression test	ID sample	Out-plane bending test	ID sample
Unretrofitted	N.2 masonry panels with solid bricks (1.0x1.2x0.25 m^3)	M26 M27	N.3 masonry panels with solid bricks (1.2x1.2x0.25 m^3)	M23 M24 M25	N.3 masonry panels with solid bricks (0.8x1.2x0.25 m^3)	M28 M29 M30
	N.2 masonry panels with sand-stone (1.0x1.2x0.25 m^3)	T34 T35	N.3 masonry panels with sand-stone (1.2x1.2x0.25 m^3)	T31 T32 T33	N.3 masonry panels with sand-stone (0.8x1.2x0.25 m^3)	T36 T37 T38
Retrofitted with Glass fiber 250 + Connectors	N.2 masonry panels with solid bricks (1.0x1.2x0.25 m^3)	M13R M2R	N.3 masonry panels with solid bricks (1.2x1.2x0.25 m^3)	M1R M4R M6R	N.3 masonry panels with solid bricks (0.8x1.2x0.25 m^3)	M10R M14R M17R
	N.2 masonry panels with sand-stone (1.0x1.2x0.25 m^3)	T21R T22R	N.3 masonry panels with sand-stone (1.2x1.2x0.25 m^3)	T3R T5R T12R	N.3 masonry panels with sand-stone (0.8x1.2x0.25 m^3)	T11R T19R T20R
Retrofitted with Glass fiber 550 + Connectors	-	-	N.3 masonry panels with solid bricks (1.2x1.2x0.25 m^3)	M7R M9R M15R	-	-

		-	N.3 masonry panels with sand-stone (1.2x1.2x0.25 m^3)	T8R T16R T18R	-
Total	8		18		12

2.1. Experimental investigations: uniaxial compression tests set-up and results

N. 8 squared masonry panels were realized within the experimental campaign. For comparison reason, the experimental campaign included unretrofitted masonry panels for each typology mentioned-above. Details concerning the geometric properties of specimens are reported in Table 1 and Table 2. Simple compression tests were conducted adopting a force control approach with a loading rate of 2.0 kN/sec (UNI EN 1926:2007). Moreover, a neoprene layer, with a thickness of 1.0 cm, was applied on the application surface during the test in order to reduce friction phenomena acting on the upper side of the specimen. Therefore, the same procedure was conducted to the reinforced samples too aim at avoiding debonding phenomena due to the contact between the loading machine and the mortar matrix. Tests were conducted using displacement hydraulic controller MTS with a maximum capacity of 500 kN (see Figure 3). An imposed displacement rate equal to 0.01 mm/s was imposed to detect softening branch. Diagonal deformations were measured by linear potentiometers (tensile and compressive). The measurement instrumentation adopted consisted of:

- N.1 Pressure transducer HBM with maximum pressure of 500 bar;
- N.4 inductive transducer HBM for the vertical displacement between two target points on the steel frame and two target points on the panel surface;
- An acquisition control unit interfaced to a PC.

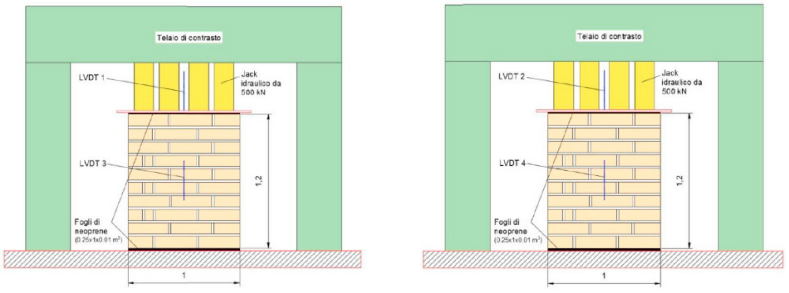
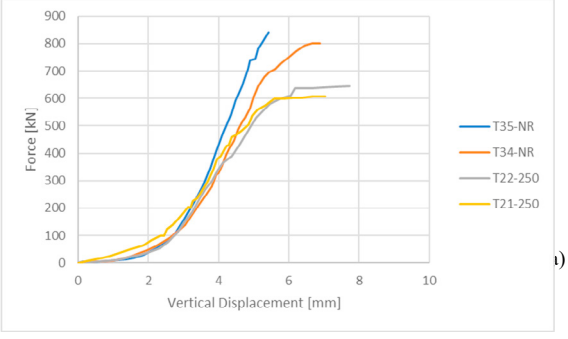


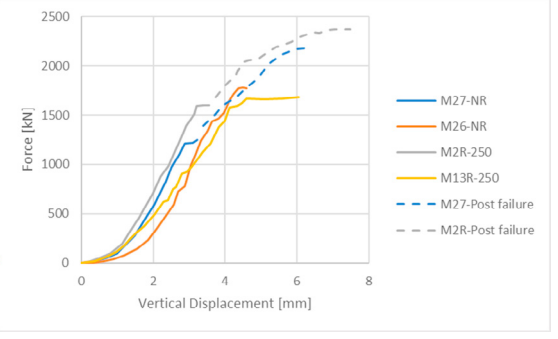
Fig. 1. Simple bending test set-up and measurement instrumentation adopted during the tests (dimensions are expressed in meters).

In Figure 2, it is reported a plot in which behaviors of “sandstone” and “solid brick” masonry panels, both unretrofitted and retrofitted with the two investigated type of reinforcement are depicted with the aim to observe the effectiveness of the strengthening systems and the influence of the specimens’ texture and material.

a)



b)



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2.2. Experimental investigations: Diagonal compression tests set-up and results

N. 18 squared masonry panels were realized within the experimental campaign. For comparison reason, the experimental campaign included unretrofitted masonry panels for either “sandstone” and “solid brick” typology. Diagonal Compression tests were conducted adopting a force control approach with a loading rate of 1.0 kN/sec (ASTM E519-07, “Standard Test Method for Diagonal Tension in Masonry Assemblages”). The edges of the specimens are positioned at the level of steel angular profile (15x25 cm^2) which are connected to a contrast steel frame as depicted in Figure 3.

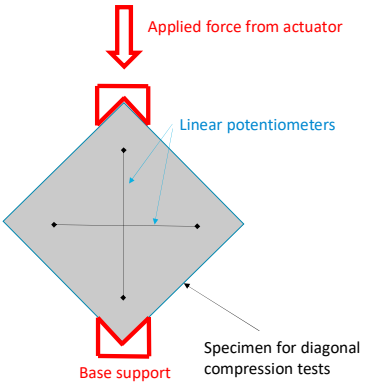

Fig. 3. Diagonal compression test setup

The same measurement instrumentation described in the previous section was adopted. However n.4 inductive transducers were placed along the compressed and tensioned diagonals of each specimen. Then, the samples were loaded in continuum using hydraulic actuators with a maximum capacity of 3000 kN. In Figure 4, results of the conducted test are provided in terms of shear force-shear deformation (F-γ) for both masonry typologies.

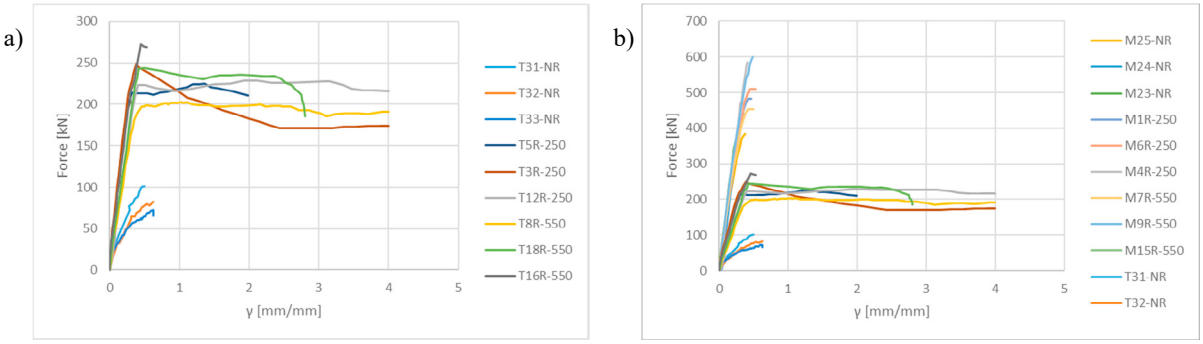

Fig. 4. Results of diagonal compression tests for (a) sandstone and (b) solid brick masonry panels

2.3. Experimental investigations: Out-plane bending tests set-up and results

N. 12 squared masonry panels were realized within the experimental campaign. For comparison reason, the experimental campaign included unretrofitted masonry panels for either “sandstone” and “solid brick” typologies. Out-plane bending tests were conducted adopting a force control approach with a loading rate of 0.3 kN/sec (EN 1052-2:2016). The bottom side of the panel was placed on a steel plate, edges of the specimens were contrasted by tubular steel beams by simulating cylindrical hinges during the loading phase and an actuator at the level of the middle height of the specimen was installed for transferred the out-plane bending to the structure. The same measurement instrumentation used for the previous cases within the experimental campaign was adopted with the

exception of the number of inductive transducers which were increased by n.1 unit with the aim to detect and monitoring the displacement points at 1/3 and 2/3 of both side of the panel and at the middle height in correspondence to the face in which actuator did not act (see e.g. Figure 5).

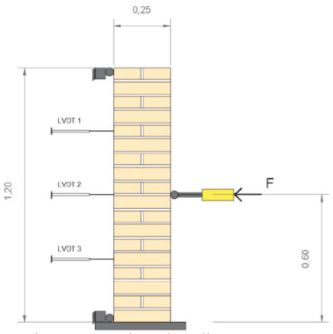

Fig. 5. Out-plane bending test set-up

Also for this case, in Figure 6 all the results of the experimental tests conducted by the authors are reported. With respect to the previous results obtained by bending and diagonal compression tests, specifically for this case, the outcomes derived by the experimental campaign were summarized in terms of maximum load achieved during the test, average of the maximum load considering specimens with the same type of reinforcement, texture and material.

Table 4. Results of Out-plane bending tests for sandstone and solid brick masonry panels. In the column dedicated to the average maximum loads, the coefficient of variation is reported within brackets.

ID Sample	Maximum load [kN]	Average maximum load [kN]	Masonry typology
T36	2.5	1.90 (28.0 %)	Unreinforced Sandstone
T37	1.44		
T38	1.77		
T11R	43.12	40.97 (5.34%)	Sandstone reinforced with 250 grid
T19R	38.74		
T20R	41.05		
M28	9.09	11.06 (17.45%)	Unreinforced Solid brick
M29	12.95		
M30	11.16		
M10R	41.85	41.01 (10.21%)	Solid brick reinforced with 250 grid
M14R	44.72		
M17R	36.47		

3. Conclusions

In this paper, an extensive literature review and the results of an extended experimental campaign were presented. Different masonry typologies with FRCM reinforcements were investigated with the aim to select the best retrofitting techniques for each scenario. Three different experimental tests were conducted. The outcomes of the diagonal compression test confirmed the efficiency of FRCM composites as a valuable strategy for improving the shear behavior of masonry panels and the global ductile behavior too. Specifically, from the comparisons between the unretrofitted specimens (T35-NR and T34-NR) and the reinforced ones (T22-250 and T21-250) a little improvement in term of ultimate deformation state was detected when the simple bending test was conducted. Similarly, reinforced solid brick panels (M2R-250 and M13R-250) received a negligible benefit from the reinforcement. Moreover, in the samples M2R and M27 when the maximum load equal to 600 kN was applied,

independently by the presence or not of the strengthening layout, a vertical crack split the specimen into two different parts. The results derived from the compression diagonal tests confirmed the benefic effect of the reinforcement and, with specific regard to simples retrofitted with 550 glass grid, a percentage increase equal to 179% and 40% was relieved with respect to the unreinforced specimens respectively. From diagonal compression tests it was noticed that for sandstone and solid brick panels the FRCM reinforcement gave rise to a significant increase of ultimate displacement of the order of about 800% in comparison to that of unreinforced specimens. For both panel types the contribution given by the two different reinforcement types (fiber grids 250 and 550) was very similar in terms of both ductility and ultimate strength. However, the maximum benefits deriving from FRCM strengthening was observed in the out-plane bending tests. In fact, the highest value of maximum load was recognized during these tests, for which the strength of the specimens was increased of 2056% and 270% with the only addiction of 250 glass grid reinforcement. For these specimens the results appear to be very reliable, since the coefficient of variation was very small if compared to the unreinforced walls (5.34% instead of 28.00% for sandstone panel and 10.21% instead of 17.45% for solid brick panel).

This first research preludes a subsequent analysis phase devoted to masonry modeling aiming at defining a comprehensive, rich, and generalized database. It would serve to develop a concentrate plasticity model for new equivalent frame modelling approaches.

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