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Shear behaviour of reinforced masonry: efficacy of FRP versus traditional technique

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ABSTRACT: The aim of this experimental work is to analyse and compare the shear resistance decay after long-term and environmental actions on brickworks structures reinforced by innovative (FRP) and traditional technique (strengthening mortar). Laboratory tests were carried out at the Non-Destructive Testing Laboratory of the Politecnico of Turin: ad hoc brickwork specimens were manufactured and reinforced by FRP and strengthening mortar (for jacketing walls). Test pieces were subjected both to static and to cyclic loading tests and to freezing-thawing thermo-hygrometric tests, in order to study durability and efficacy of strengthening techniques, and express a judgement on their long term compatibility with historical masonry, thereby avoiding the errors associated with materials that are not mechanically compatible.

1 INTRODUCTION

Masonry structures represent the largest part of the construction heritage in the world. As a matter of fact, monuments and historic building and also many houses, bridges and simple construction are realized in masonry material.

From a structural viewpoint, the masonry material is characterized by a very low tensile strength; thus, even reduced values of the tensile stresses can induce crack initation and hence damage of the material. Because of the limited tensile strength, masonry constructions often present diffuse fracture pattern. Moreover, masonry bearing and shear walls have been found to be voulnerable to earthquake. From a technological point of view, the strengthening of masonry structures has been accomplished adopting standard materials, mainly cement, concrete and steel, mortar, sometimes with the aim of changing the statics of the structure. Between these methods, one of the most common method used to strengthen masonry structures was to provide single or double-sided of mortar layer. This method is considered effective in increasing the strength, stiffness, and ductility of masonry buildings (Zarri 1993; Valluzzi et al. 2002; Grazzini 2004; Al-Salloum & Almusallam 2005; Antonaci et al. 2006; Bocca & Grazzini 2008).

Composite materials appear to be good candidades to substitute standard materials, since they are light, very simple to install and are also removable (Corradi et al. 2002). Moreover composite materials are characterized by high strength, good resistance to corrosion, durability and reduced installation and maintenance costs.

Thus, one promising technique to improve the overall strength of masonry structures and to reduce their seismic vulnerability is to retrofit the masonry walls using fiber reinforced polimer (FRP). This system consists of glass, carbon or aramidic fiber fabric combined with special epoxies to create a high strength , lightweight structural laminate.

Although there are many real examples of masonry structures reinforced using FRP (for example the Basilica of S. Francesco D'Assisi) (Croci & Viskovic 2000), several models which describes the FRP-masonry interaction (Luciano & Sacco 1996; Luciano & Sacco 1998) and mechanical analysis (Triantafillou, T.C. 1998; Foraboschi & Faccio 2000; Cecchi et al. 2004; Ascione et al. 2005), scarse informations exist about the durability of these materials. Unfortunately, their long-term behaviour remain unknown in several respects, especially when they are applied to damaged historical masonry structures.

The aim of this experimental work is to analyse and compare the shear resistance decay after the long-term and environmental actions on brickworks structures reinforced by innovative (FRP) or traditional (strengthening mortar) techniques. Laboratory tests were carried out at the Non-Destructive Testing Laboratory of the Politecnico of Turin: ad hoc brickwork specimens were manufactured and reinforced by FRP and strengthening mortar (for jacketing walls). On both specimens set, cyclic and freezing-thawing thermo-hygrometric tests were performed in order to simulate long-term and environmental actions, respectively. Subsequently, the shear test was carried out to investigate the resistance losses in term of shear capacity and thus expressing an opinion about durability and efficacy of strengthening techniques.

2 EXPERIMENTAL PROGRAM

In order to reproduce the environmental actions and to analyse the long-term behaviour of reinforced masonry specimens, a laboratory testings set are carried out. The effects of these actions on the reinforced masonry specimens were evaluated in term of shear loss resistance and deformability parameters dacay such as shear modulus, Poisson coefficient .

Two specimens sets are manufactured: the first one consists in Mortar Reinforced (MR) brickworks, the second one is reinforced with Carbon Fiber Reinforced Polimer sheets (CFRP).

Environmental actions were simulated on one MR and FRP reinforced specimen (MM02 and MF02) through a freezing-thawing thermo-hygrometric cycles. Specimens were subjected at 8 thermal cycles. Every thermal cycles during 25 hours: in Table 1 is summarize the scheme of the last one.

Long-term behaviour is carried out through a fatigue test one MR and FRP reinforced specimen (MM03 and MF08). A medium value was selected for loading cycles (50% of the static load) and test duration (100000 cycles – 1 Hz – ca 24h).

After these damage tests (fatigue and thermal cycles) the shear test was followed: it was carried out through a diagonal compressive test.

Table 1. Scheme of the freezing-thawing thermo-hygrometric cycle

Time (h)	12	0,5	12	0,5
Temperature (°C)	60	20	-15	20
Environment	oven	environment	freezer	environment

2.1 *Materials and Specimens*

The details about code and dimension specimens, reinforced pattern, brick size and reinforcement sequence are shown in Figure 1.

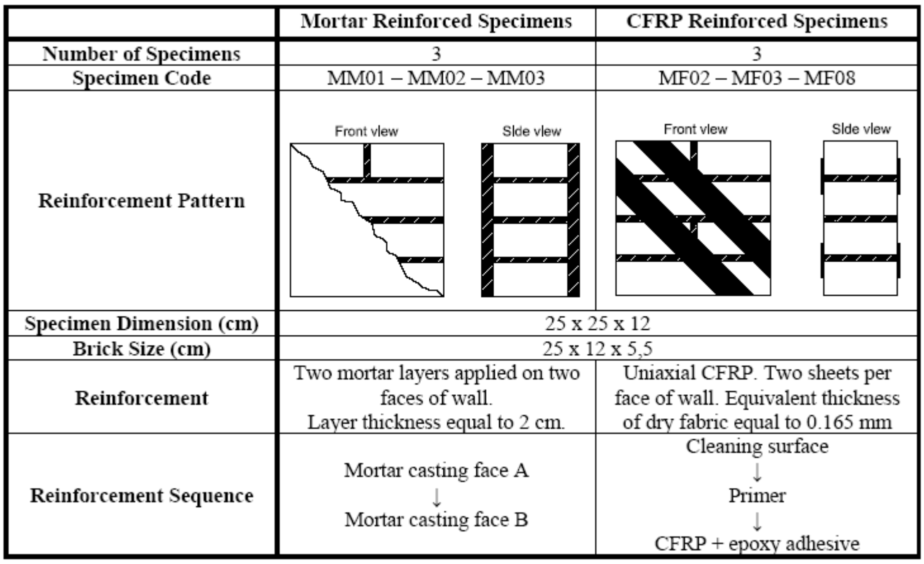
Table 2. Brick, Bed and Structural Mortar mechanical features

Material	Brick	Bed Mortar	Structural Mortar	CFRP material
Mortar Type	-	M5	M15	-
Compression Strength	16 MPa	7,5 MPa	18 MPa	-
Compression Strength after freezing test	18 MPa	-	-	-
Elastic Modulus	-	11000 MPa	16000 MPa	230000 MPa
Tensile strength	-	-	-	2500 MPa
Ultimate Tensile Strain	-	-	-	1,3 %

Each test piece was labeled with two code type: MM”X” and MF”X”. The first one stands for “Masonry Mortar” and the second one stands for “Masonry FRP” both followed by the order number “X”.

Reinforced masonry specimens was manufactured according to the materials given in Table 2.

Reinforced masonry specimens were water-cured for approximately 28 days before testing.



	Mortar Reinforced Specimens	CFRP Reinforced Specimens
Number of Specimens	3	3
Specimen Code	MM01 – MM02 – MM03	MF02 – MF03 – MF08
Reinforcement Pattern	Front view Side view	Front view Side view
Specimen Dimension (cm)	25 x 25 x 12	
Brick Size (cm)	25 x 12 x 5,5	
Reinforcement	Two mortar layers applied on two faces of wall. Layer thickness equal to 2 cm.	Uniaxial CFRP. Two sheets per face of wall. Equivalent thickness of dry fabric equal to 0.165 mm
Reinforcement Sequence	Mortar casting face A ↓ Mortar casting face B	Cleaning surface ↓ Primer ↓ CFRP + epoxy adhesive

Figure 1. Details of the reinforced specimens.

2.2 *Testing Arrangement*

Static and cyclic load were applied by means of a 250 kN servo-controlled material testing machine. Test arrangement is shown in Figure 2.

Every reinforced specimen was equipped by a couple of displacement transducers per face in order to measure the horizontal and vertical displacement.

Thermal cycles was carried out by means of a laboratory oven.

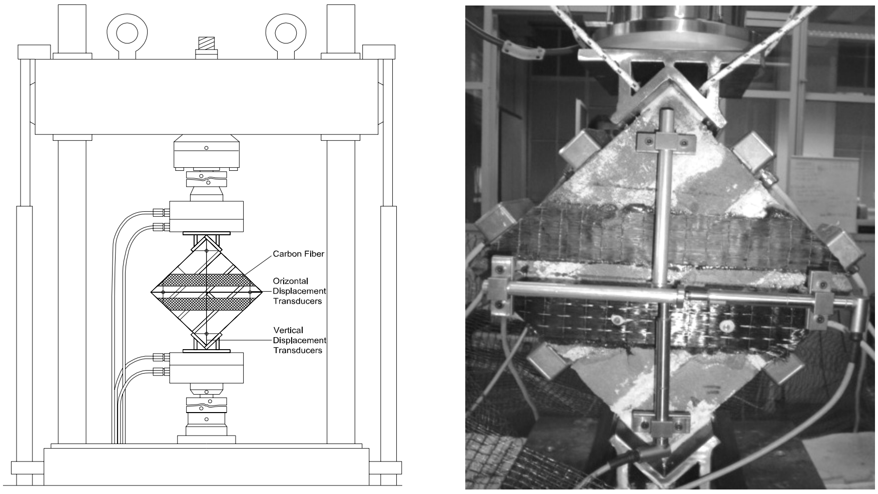


Figure 2. Static and cyclic loading test arrangement.

3 EXPERIMENTAL RESULTS

In this section, the experimental testing results are shown only in term of vertical displacement vs. load because the horizontal displacement vs. load trend is the same of the previous one.

The results of the diagonal compressive test are reported in Figure 3a which show the load vs. displacement curves for MR specimens after thermal and fatigue damage and in undamaged condition.

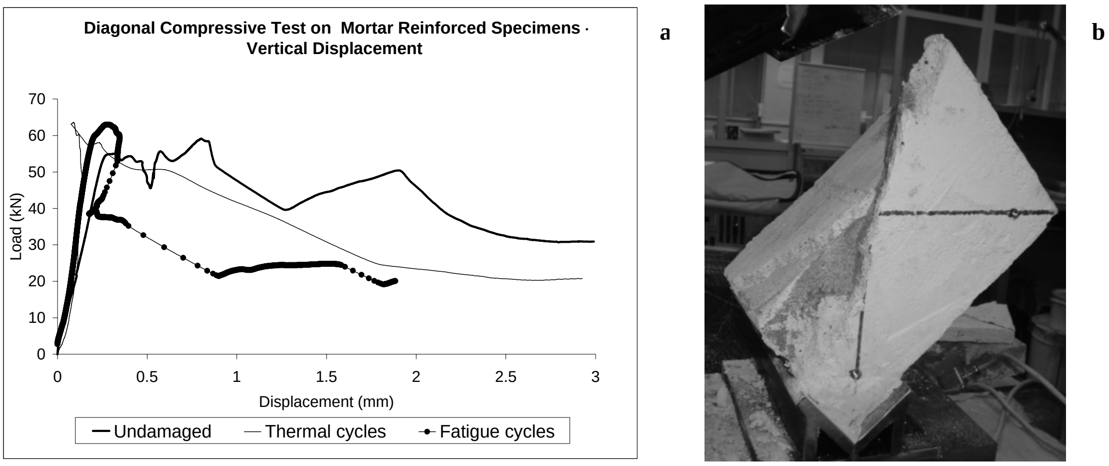


Figure 3. Diagonal compressive test on MR specimens after thermal and fatigue damage and in undamaged condition (a). MM02 specimen after collapse (b).

It can be observed that the maximum shear resistance for three reinforced brickwork was substantially unchanged. The mechanical behaviour was different between reinforced brickworks: ductile collapse for specimen subjected to the thermal cycles, brittle collapse for specimen subjected to the fatigue cycles. Failure mechanism was the same for these MR specimens, with a diagonal cracking in loading direction.

In Figure 4 are reported the results of the diagonal compressive test in terms of load vs. displacement curves for CFRP specimens after thermal damage and in undamaged condition.

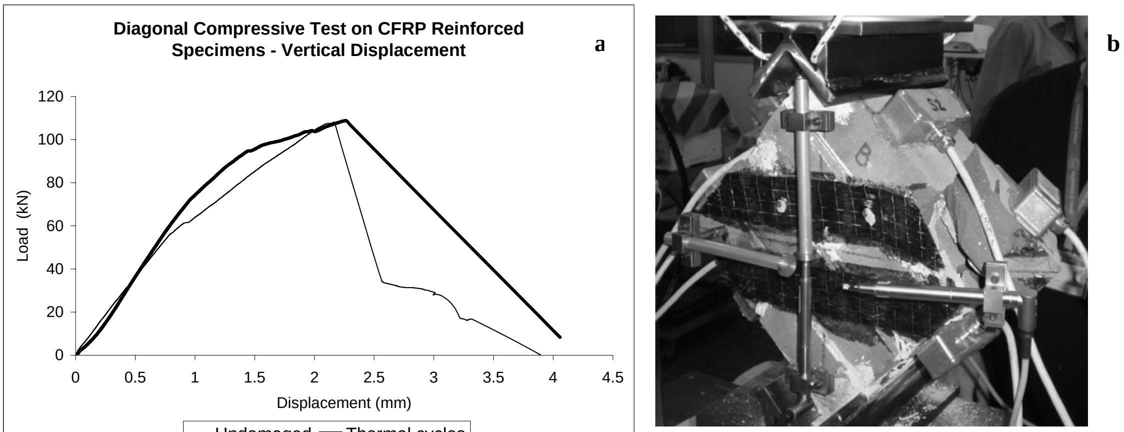


Figure 4. Diagonal compressive test on CFRP specimens after thermal damage and in undamaged condition (a). MF02 specimen after collapse for plate end debonding and ripoff failure mode (b).

It was not possible to test at diagonal compression the CFRP specimen subjected to the fatigue cycles, because after 33700 cycles it was collapse for plate-end debonding failure. No significant changes were found in term of maximum shear resistance for specimen subjected to the thermal cycles respect the specimen in undamaged condition. Likewise the ultimate displacement. The effect of the thermal cycles has been found on the slope of the pre-peak load vs. displacement curves. A marked nonlinearity after elastic phase the specimen subjected to freezing-thawing cycles had shown respect the specimen in undamaged condition. In the case of the freezing-thawing cycles an embrittlement was observed. From the curve of Figure 4, it has been possible to note an increment of the shear modulus and of the Poisson coefficient. Failure mechanism was the same for undamaged and thermal cycles conditions: both CFRP specimens were collapsed for plate end debonding and ripoff failure mode.

In Figure 5 are reported the results of the diagonal compressive test in terms of load vs. displacement curves for CFRP and MR specimens after thermal cycles.

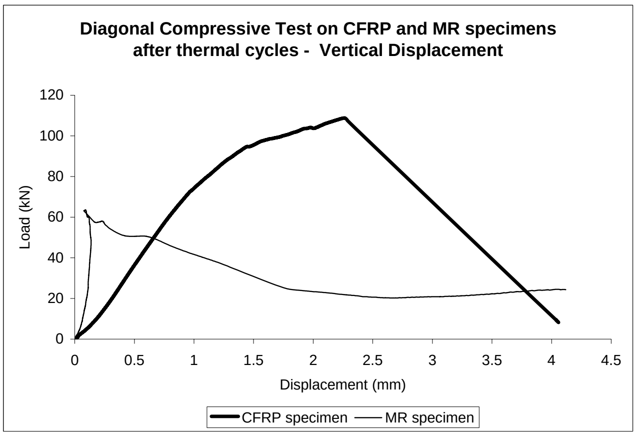


Figure 5. Diagonal compressive test on CFRP and MR specimens after thermal cycles.

From the curves of Figure 5 it possible to evaluate the collapse loading, the ultimate strain and the elastic modulus of the CFRP and MR specimens damaged with thermal cycles as shown in Table 3. Moreover, it is possible to highlight the following points:

- the maximum shear resistance of the CFRP brickwork was considerably higher than MR brickwork;
- MF brickwork has shown a wider ultimate strain than “MM” brickwork due to an high resistance of the CFRP sheets;
- CFRP brickwork shown a brittle shear behaviour respect MR brickwork which shown a ductile shear behaviour;
- it was not possible to compare the fatigue behaviour of the CFRP and MR brickwork because the first one was collapsed before the end of the cycles expected. It can be pointed out the significative influence of the delamination effect on the mechanical response of the reinforced masonry;
- in the MR brickwork, fatigue cycles had led an adhesion loss between reinforcement and masonry support but the shear capacity did not provide marked variations. The great stiffness of the CFRP composites did not allowed to increase the shear capacity in term of cyclic action.

Table 3. Results from the curves of Figure 5

Specimen Code	Collapse Load (kN)	Ultimate Strain	Elastic Modulus (MPa)
MM02	63,63	1,59E-03	1377,16
MF08	108,85	8,12E-03	616,69

4 CONCLUSIONS

An experimental laboratory research to evaluate the durability on reinforced masonry panels is presented. Two brickwork specimens sets was reinforced with two techniques: an innovative technique, the CFRP sheets, and one traditional technique, strengthening mortar. A comparision between these two reinforced techniques was performed in order to evaluate their goodness under long term and thermal actions.

The reinforced materials with low stiffness and strength features (mortar reinforced method) under thermal and fatigue cycles have shown a good behaviour under long-term actions with a marked softening branch in the load vs. displacement curve.

About CFRP reinforced method has shown great shear capacity with a poor ductility and low energy dissipation capacity. This one can lead some problems in term of long term behaviour. Moreover debonding phenomena affects significantly the reinforced material behaviour, reducing the mechanical response of the specimens. The last one was well observed in the fatigue test, where the CFRP reinforced specimen has collapsed suddenly with a brittle failure.

Aim of the future development of the research is to perform experimental laboratory testing on to reinforced brickwork, both mortar and CFRP retrofitting, especially with fatigue test order to investigate better the CRFP reinforced brickwork behaviour in relation to the mortar strengthening specimens. Moreover it will be important to compare the experimental results with the numerical one through a FEM model.

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