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PROBLEMS RELATED TO THE USE OF FIBER REINFORCED CEMENTITIOUS MATERIALS AS STRENGTHENING OF MASONRY MEMBERS

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Abstract. *This paper gives the results of a series of tests carried out on brick columns and panels reinforced with Fibre Reinforced Cementitious Materials. Steel and glass fibres were used, and cement and lime mortars were employed as the matrices. The issue of durability of reinforced masonry structures, that is the transformation from sole masonry structures to hybrid ones, was investigated. Six brickwork columns (three unreinforced and three reinforced) and eighteen solid brick panels were built and tested (two unreinforced, 16 reinforced with steel cords or glass fibre). Tests were carried out in laboratory, and the results enabled the determination of the compression strength of the masonry before and after the application of the reinforcement, and before and after environmental effects. The main goal of the durability testing was to verify whether the artificial ageing process hinders the resistance. At the end of the cycles, a first visual observation was performed in order to evaluate if superficial alterations took place, such as efflorescence or micro cracking due to the immersion in the sodium chloride (NaCl) solution. The aged reinforced specimens appear to have a losses that range from 4% to 25% of the ultimate load, depending on the type of reinforcement and mortar used, although scattering of results confirm the need of more extensive testing.*

1 INTRODUCTION

Structural enhancement of masonry elements, built with natural stones or clay bricks, is frequently necessary; in particular, compressed members, as columns, are prone to brittle failure under seismic forces or static overloads. Recent earthquakes in Molise (2002), Umbria

(2009), Abruzzo (2009) and Emilia-Romagna (2012) have shown that masonry structures are extremely susceptible to the forces imposed during such events [1-2]. Thus, there is an urgent need to upgrade these deficient masonry elements to meet the current design standards in seismic regions. Steel jacketing and reinforced concrete (RC) have been extensively used in Europe, particularly Italy, to retrofit masonry columns and have proved to be effective, but have some drawbacks [3-4]. Such techniques are in fact often non-reversible, expensive and add mass to the structure. Such issues have led researchers to investigate new retrofit solutions using innovative materials such as Fibre Reinforced Polymers (FRP) [5-9] or Steel fibre-Reinforced Polymers (SRP) [10-12] composites in the form of bonded surface reinforcements. Wrapping with FRP or SRP reinforcement offers the designer an outstanding combination of properties, including ease of handling, speed of installation and high strength-to-weight ratio [13-15].

On the other hand, some considerations advise against the use of such techniques. In fact, frequently natural masonry blocks are subjected to moisture entrapment from the ground, released through the external surface during their service life; for that reason it is not always recommendable to apply continuous epoxy-bonded jacketing, inhibiting the material transpiration. As a result of such considerations, beside the “traditional” FRP/SRP wrapping this paper presents the results of a second experimental investigation in a series dealing with the possibility of application of Fibre Reinforced Cementitious Matrices (FRCM). This gives a promising technique that may represent a new opportunity in the field of restoration, since it is reversible, aimed at integrating the masonry rather than transforming it and compatible with the preservation of the building materials.

In this paper, the structural validity of FRCM materials has been analysed by doing compression tests on FRCM-confined columns. Subsequent experimental work focused on the durability of FRCM reinforced elements. After an initial period of durability testing solely on the fibres, with and without their polymeric matrix, attention turned to research that would prove whether the degradation of the FRP system when applied to structural support would increase damage or simply result in not providing the structural reinforcement it had been designed to give. There were cases in which the degradation which started in the FRP system caused mould or other aggressive attacks to the underlying structural system, provoking more damage than if the FRP had not been present [16]. From the data analysed in previous experimental campaigns [17], the more aggressive durability testing performed on FRCM specimens consisted in wet/dry cycles in a 5% sodium chloride solution. Therefore this type of cycle was chosen for the durability on an FRCM reinforced structural element, in the attempt to verify whether the artificial ageing registered in the second experimental campaign described above had the same detrimental effects when the FRCM system was applied to masonry structures. Different schemes of reinforcement were here investigated, the difference consisting in the type of fibres, glass or steel, and the type of matrix, cement mortar or lime mortar.

2 MATERIALS

Small brick columns and panels were assembled, subjected to both compression loads and wet/dry durability cycles and tested in laboratory.

Compression tests were first conducted on FRCM reinforced columns. The results of compression tests show an interesting increase of load bearing capacity with respect to unreinforced columns and give useful indications on the correct application of the reinforcement. The columns were built using solid bricks and reinforced with different types of steel wires. The brick columns were 50 cm in height, were made of 8 courses of bricks and had two different cross sections: octagonal and square.

For wet/dry durability cycles, each panel was composed of five bricks (dimensions: 200x100x50 mm). Total panel's dimensions were 290x100x200 mm (Fig. 1). The test matrix is reported in Table 1.

Number of Specimens	Type of cementitious matrix for Reinforcement	Type of Reinforcement	N° of wet/dry cycles	
8	Lime	Steel (4)	0 (2)	75 (2)
		Glass (4)	0 (2)	75 (2)
8	Cement	Steel (4)	0 (2)	75 (2)
		Glass (4)	0 (2)	75 (2)
2	None	Unreinforced (2)	0 (2)	

Table 1: Test matrix. In parenthesis the number of specimens per type.

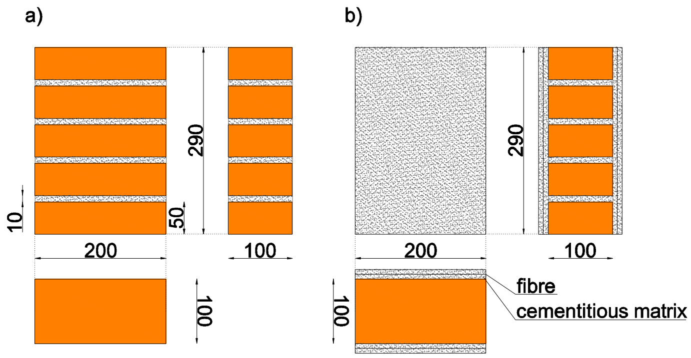


Figure 1: Graphic scheme (dimensions in mm) of the brick masonry panels, plan and elevation, a) unreinforced panel, b) reinforced panel.


a)

b)

Figure 2: UHTSS steel fibres: a) the coil, b) detail of a single cord.

Two panels from a total of 18 remained unreinforced, as control specimens. All other panels, 16 in total, were reinforced though steel or glass fibres placed on the wide faces of the panels (200x290 mm) with either lime or cement-based mortar, in the manner of reinforced plaster. The mechanical properties of the steel and glass fibres used in the investigation are illustrated in Table 2.

The steel fibres are made of UHTSS (Ultra High Tensile Strength Steel) cords, which are provided from coils available on the market (with the commercial denomination 3X2), produced by Hardwire llc. They are either brass coated or galvanized with zinc, for increased protection against corrosion. When lime-based mortar is utilized for repointing, it is best to use cords protected by zinc galvanizing The coils used for the steel cords are about 30 cm wide and variable in length, and consist of a series of cords laid out parallel to each other and held together by a polyester mesh (Fig. 2). The most interesting property of the cords used in the proposed system consists in the high bonding and compatibility between the cords and the mortar surrounding them, due to their small size (their average diameter is 1 mm) and shape. In fact, the cords are made by twisting five individual filaments together (three straight filaments wrapped by two filaments at a high twist angle). The specifications of the single cord are shown in Table 2. The mechanical properties of the metal cords were verified by tensile tests carried out on 8 samples. The results substantially confirmed the values given by the manufacturer on the technical sheet, with small variations of the failure load (1539 N) and of the deformation at failure (2.1%) .

Cord diameter (mm)	0.89
Sample size	10
Tensile failure load (N)	1539
Cross section area (mm^2)	0.62
Young’s modulus (GPa)	206.8 (16.4)
Tensile strength (MPa)	2479 (127)
Strain to failure (%)	2.1

Table 2: Mechanical properties of the steel fibres. Standard deviation in ( ).

Nominal dry section (mm^2)	3.8
Sample size	7
Tensile failure load (kN)	3.679
Tensile strength (MPa)	968.2 (85.93)
Young’s modulus (GPa)	74.2 (3.4)
Strain to failure (%)	1.3

Table 3: Mechanical properties of the GFRP grid. Standard deviation in ( ).

The fiberglass grid (Glass Fiber Reinforced Polymer: GFRP) used in this research program was manufactured using AR-glass (Alkali-Resistant) fibers and a polyester resin. Specimens extracted from the composite mesh have been measured with a tensile modulus ranging from 71.1 to 79.8 GPa. The mesh has a nominal cross section dry fibre-area of 3.8 mm^2 both in the vertical (weft) and horizontal (warp) direction and has an opening of 66 mm in both directions (Fig. 3). The main mechanical characteristics of GFRP material measured via tensile tests, are shown in Table 3.


a)

b)

Figure 3: GFRP grid: a) the grid, b) detail of the joint.

The lime and cement mortar used as cementitious matrices for the FRCM system are described in Table 4. The mortar used in the assembly of the panels was a cement mortar, hand mixed (lime, cement 32.5 MPa, sand) with proportions in weight 1:1:6 (PCement, Tab. 4). This mortar was used solely in the building of the panels, and not in their reinforcement. Small cubic specimens of bricks, 5.5x5.5x5.5 cm in size, were tested in compression (Tab. 5).

Once the panels were assembled with the cement mortar described above, they were left to cure for 60 days in a humidity free environment at room temperature (circa 19°). Once curing was completed, the panels were reinforced, in number and type of reinforcement as described in Table 1. A layer of cementitious matrix was applied to the surface of the panel, covering the entire façade evenly. The reinforcement was then applied and pressed to ensure attachment to the applied layer of mortar. A second layer of mortar was applied, thus covering the fibre. The reinforced panels were left to cure again for another 60 days and in order to ensure complete curing, in order to avoid that this process could occur during the artificial ageing cycles.

Mortar Type	Average Flexural Strength (MPa)	Average Compressive Strength (MPa)
Lime	0.17	0.52
Cement	0.42	4.05
PCement	0.25	0.62

Table 4: Average values of flexural and compression strength obtained through testing on mortar specimens.

	Average maximum compression load (kN)	Average compressive strength (MPa)
Clay bricks	142.15	47.04

Table 5: Average compressive strength found for solid clay bricks used to build the panels.

3 ARTIFICIAL AGEING METHOD

Once curing was complete, wet/dry cycles on eight reinforced panels commenced. The cycles consisted in a wet period, during which the specimens were immersed in a solution of sodium chloride (NaCl) at 5%, followed by a dry period, during which the specimens were placed in a ventilated oven at 35°C. These specimens required a period of 45 minutes for complete sorption to occur. This amount of time was determined through weighing the specimens dry, and then after having been immersed in the NaCl solution at intervals of 5 minutes. Once the registered weight was stable, thus indicating that sorption was at maximum values, the time elapsed was considered to be the necessary amount for a complete wet cycle. The panels were immerged with the 5% NaCl solution at a level which covered the specimens for at least 2.5 cm and then placed in the oven and left to dry for 24 hours. One cycle duration of 75 days was chosen for all aged specimens.

4 TEST METHOD

4.1 Columns

For compression testing, six brick columns were subjected to axial compression tests in order to determine the efficacy of the confinement with steel fibres in terms of load bearing increase, ductility and axial stiffness. Testing was conducted through an oil-hydraulic Metrocom type press with a 3000 kN load cell with load increases of 5-7 kN/sec. Figure 4 shows the two types of columns tested while Figure 5 gives the cross-section dimension. The steel cords were glued by using a cement-based mortar. Reinforcement was executed in the following steps: a) cleaning of the column surfaces of all inconsistent material to improve the adhesion between mortar and masonry; b) application of a first layer of mortar; c) application of a unidirectional FRCM sheet; d) application of a second layer of cementitious mortar. All specimens were wrapped with orientation perpendicular to their axis.


a)

b)

Figure 4: Brick columns: a) octagonal cross section, b) square cross section.

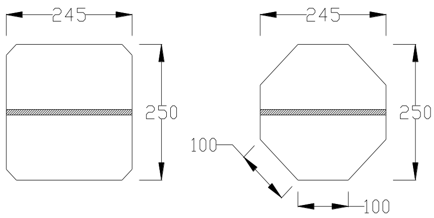


Figure 5: Column cross section (dimensions in mm).

4.2 Panels

Testing was carried out through eccentric compression loading. One of the objectives of this campaign was to study the behaviour of the fibres and the bonding, in an aged condition. By comparing the position of the central core of inertia with the compressive load, it was possible to verify that the compressive and tensile stresses were actively being applied to the brick panels. Loading was applied through a load cell (TCLP–10B Tokyo Sokki Kenkyujo Co, Ltd.) with a maximum capacity of 100 kN applying pressure on a steel cylinder positioned at 50 mm to the right of the central axis of the panel.

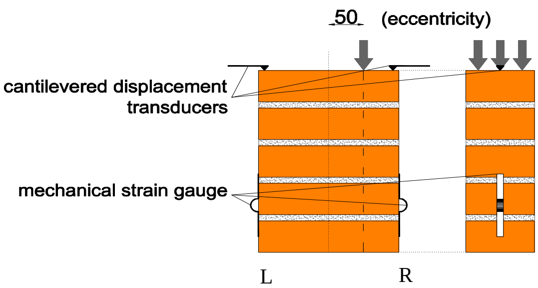


Figure 6: Graphic scheme of the positions of the mechanical strain gauges and transducers during testing (mm), with Left Hand (L) and Right Hand (R) sides indicated (dimension in mm).

Figure 7: Mechanical Strain Gauge.

The steel cylinder is the same width of the panel, ensuring that the load is applied only on the masonry structure and not on the FRCM reinforcement. Deformations were recorded through two mechanical strain gauges on the short sides of the panels and two cantilevered displacement transducers (CE-10 Tokyo Sokki Kenkyujo, Fig. 6). The two displacement transducers attached to the upper face of the panels measured the vertical displacement of the panel during loading. The second typology was applied for recording relative movements between the two extremities of the gauges. Omega-shaped (Fig. 7), the ends of these strain gauges are attached to the specimens and their hemispherical central part allows these ends to follow the displacements of the specimen.

5 RESULTS

5.1 Compression tests on columns

The specimens were subjected to axial monotonic load until failure occurs. The first three tests were conducted on unreinforced columns in order to obtain the average compressive strength of the columns, which resulted in 719 kN. Considering the area of the octagonal transversal section of the columns, 512 cm^2, the compressive strength is approx. 14 MPa. A similar value was measured for square cross section (14.8 MPa).

For octagonal cross-section columns confined by steel composites, the FRCM reinforcement (specimens 2&3) requires the application of a significant thickness of cementitious mortar, up to 5cm, which in some cases may be incompatible with the requirement of an unvaried transversal section. The compression testing on the reinforced columns show an increase of maximum load of 28% compared with unreinforced columns (Tab. 6).

Sample	Cross Section	Rinf.	Compression strength (MPa)	Failure load (kN)	Axial stiffness (MPa)
1	octagonal	no	14.0	719	2034
2	octagonal	steel	21.3	1089.8	2306
3	octagonal	steel	14.7	755.9	1462
4	square	steel	16.9	1020	2033
17	square	no	15.6	945	1745
18	square	no	14.0	847	2576

Table 6: Results of compression tests.

Figure 8: Compression test (reinforced column).

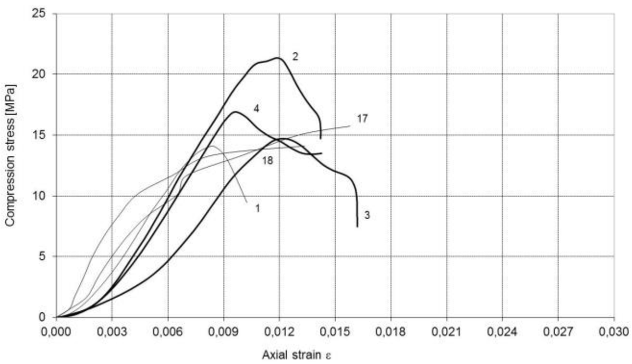


Figure 9: Stress vs. axial strain response.

For columns with a square cross-section, the effectiveness of the reinforcement is smaller (13.8%). This is mainly due to the stress-concertation near the columns corners. The flexural stiffness of the steel cords also prevent an adequate bonding of the fibres to the masonry surface and this partially compromises the confinement effect of the FRCM reinforcement.

The collapse mode of reinforced columns (Fig. 8) includes the cracking of the masonry underneath the fibres and the subsequent bulging of the columns around the midpoint. Total collapse of the columns occurs for the rupture of the fibres once the masonry is completely cracked internally. Significantly, the rupture of the FRCM reinforcement does not occur at the corners of the columns, a typical collapse mode in FRP reinforced columns, but at the midpoint of the specimens once the tensile strength of the fibres has been exceeded. Figure 9 shows the compression stress vs. axial strain response of reinforced and unreinforced columns.

5.2 Compression tests on small panels

Values for both reinforced and unreinforced specimens remain within values that range from 35 to 50 kN (Fig. 10). The small variation between reinforced and unreinforced specimens may be due to the fact that the FRCM system is simply bonded to the façades of the panels without mechanical anchoring systems. While the ultimate loads values do not vary greatly, the collapse mechanisms are different.

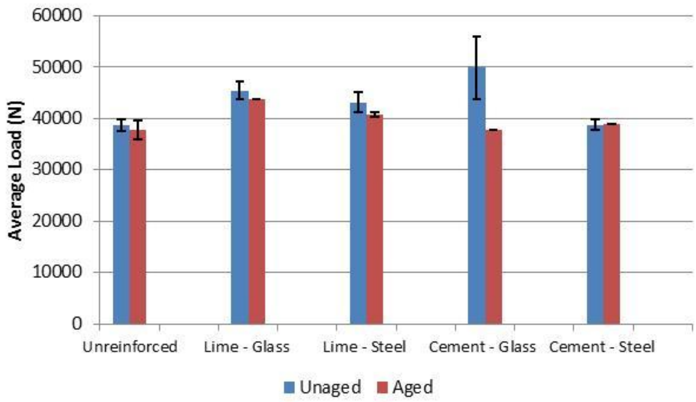


Figure 10: Average maximum loads for unaged and aged panels.

Unreinforced specimens fractured gradually. The average failure load of unaged specimen was 38.71 kN. The ageing process caused a negligible decrease of the panels' capacity of 2.3%. Cracks at first appear immediately below the point of load application, given by excessive compressive stress for a load of approx. 30 kN. At this point there is a drop in the load (Figs. 11-13). A secondary crack then appears at the bottom of the column opposite the loading point (Fig. 11a). This mechanism is not visible in the FRCM reinforced panels until the fibres detach completely from the side they are attached to, and even when detachment occurs it does not crack due to tensile strength; the rupture in reinforced specimens is abrupt and due to excessive compressive force as opposed to the gradual collapse verified in unreinforced specimens. The FRCM system does not prevent the masonry panel from cracking. The lateral shorter sides of the panels are free from reinforcement. Therefore when cracking of the bricks occurs, there may be a rotation of the elements shortly after the detachment of the fibres commences. This is the consequence of the eccentric compression, when the loads are outside the central core of inertia of the panel. The fact that the slate of FRCM detaches either completely or only partially makes little difference to the resistance of the panel; in fact, once the FRCM begins to detach, it is as if the fibre reinforcement is virtually non-existent.

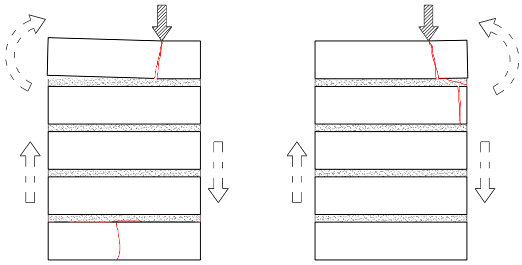
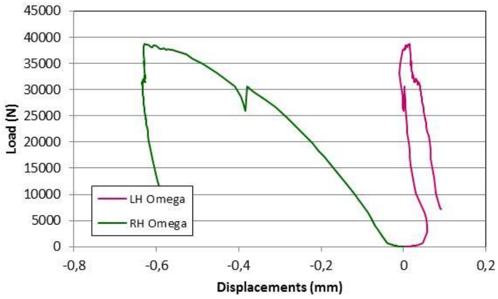
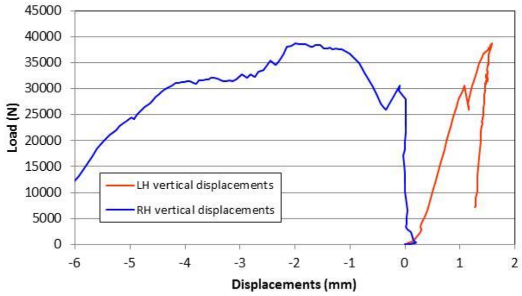


Figure 11: Graphic description of the cracks that occurred in unreinforced specimens; a) Specimen 1UR and b) Specimen 2UR.

It is possible that strain gauges and transducers register concurrently opposing displacements. Due to the position of the instruments separated by two bricks which may rotate and move in directions other than those of the two bricks the gauges are glued to (Fig. 14), displacements may have opposing sign when referring to one side of the specimen. In the testing condition, the larger displacement has been recorded under the loading point. After collapse, vertical cracks appeared with elongations of the right side (Fig. 15).





Figures 12 and 13: Load - displacement diagrams for Unreinforced Specimen 1; values given by cantilevered vertical displacement transducers and Omega transducers.

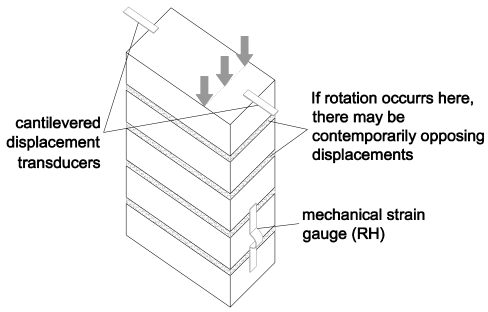


Figure 14: Axonometry of panels with strain gauges and displacement transducers. The mortar layers where possible rotations may lead to discording diagrams are highlighted.

The application of the FRCM reinforcement always caused an increase in the panel capacity. The application of the reinforcement is moderately able to absorb the tensile stresses and to partially prevent brickwork from cracking near the bed joints. The use of a cementitious mortar to bond the GFRP reinforcement increased the panel capacity of 29% compared to unreinforced specimens. The use of a lime-based mortar for both GFRP and steel reinforcements caused a limited increase of the panel capacity between 11.5 and 17%: this is probably due to the small tensile and shear strength of this mortar.

As for the differences in behaviour between aged and unaged specimens, none of the values of the aged specimens differed greatly from those of their unaged control specimens, as is clearly shown in Figure 10. However the ageing process caused a significant reduction of the panel capacity.

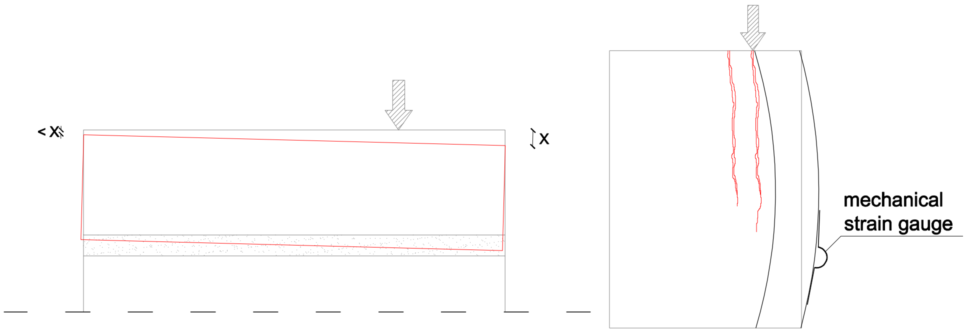
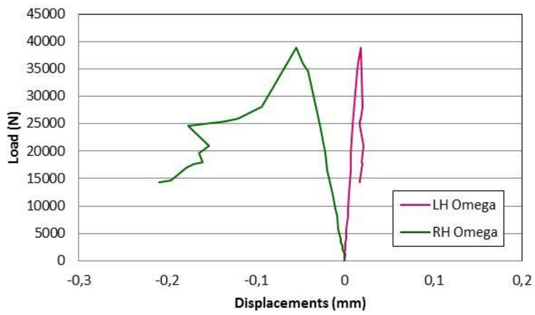
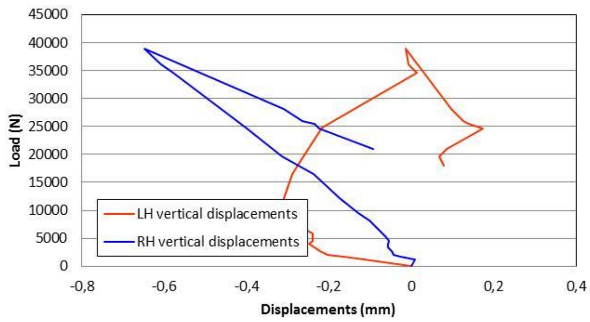


Figure 15: The upper section of the panel, showing larger displacements on the right side of the panels, and a graphic scheme of elongations that might occur in the right side of specimens.

Again, the ageing process on panels reinforced using a lime-based mortar caused a limited decrease of the panel capacity (approx. 5%) and this demonstrated that both the steel and GFRP reinforcement can be used to reinforce wall panels without significant ageing problems. However the oxidation of the steel fibers is another aspect to consider, when steel fibre - Cement matrix are used to reinforce masonry members. However since the number of specimens tested was limited, results should be confirmed by a larger experimental programme. However, the emerging line seems quite correct. As may be inferred by the following graphs, all of the reinforced panels reach their ultimate load abruptly (Figs. 16-17), with no substantial differences between aged and unaged specimens.





Figures 16 and 17: Load - displacement diagrams for Steel Fibre - Cement Matrix Specimen 4 after 75 wet/dry cycles; values given by cantilevered vertical displacement transducers and Omega transducers.

Some other considerations can be made from the observation of the photographic survey conducted during testing which seem to be relevant to all unaged specimens. From physical observations of the aged specimens, the most evident effects of the ageing cycles is in the efflorescence of the saline solution on the surface of both the brick structure, visible at the sides of the panels, and the cementitious matrix covered faces of the panels. The glass fibres did not show any signs of degradation after the artificial ageing cycles were complete, while the steel fibre reinforced specimens began to show rust on the surface of the matrix used to cover them as soon as the 5th cycle. By the end of the 75 wet/dry cycles, the rust was heavily distributed throughout the matrix surface. However, rust was not detected on the surface of the masonry once the reinforcement detached after testing, and no other kinds of spots or smears were detected; the formation of mould, which could eventually cause the fibre reinforcements to detach from their structural supports, did not appear in the aged specimens.

6 CONCLUSIONS

The main inquiry of the present experimental campaign was aimed towards determining whether FRCM reinforced masonry panels are severely affected by artificial ageing, achieved in this particular case through wet/dry cycles in a 5% NaCl solution.

Sheet of steel or glass fibres (GFRP) can be easily applied as masonry strengthening. Preliminary compression tests demonstrated that it is possible to increase the compression capacity of brickwork columns by wrapping with FRCM systems using steel fibres. Increase in capacity up to 30% have been measured compared to unreinforced columns. However the shape of the cross-section could influence the effectiveness of the FRCM reinforcement.

It may be also noted that the FRCM system does not appear to be affected by the wet/dry cycles. While no substantial differences were found between the two types of specimens, due to the lack of anchorage of the reinforcement to the masonry substrate, the reinforced ones presented abrupt ruptures due to detachment of reinforcement, while the unreinforced ones collapsed in a more gradual manner. The degradation caused by the 5% NaCl solution appears only in saline efflorescence in all aged specimens, while in the steel fibre reinforced specimens rust was apparent from as soon as the 5th wet cycle. When the FRCM system was removed from the surface of the masonry panels after testing, no mould formations were detected. Regarding the resistance of the FRCM system to the tensile strength to which the panels were subjected as a consequence of eccentric compression, cracks caused by tensile stress did not appear in reinforced specimens, leading to the conclusion that the fibres successfully absorbed such stresses.

From the results of testing in the present campaign and the observations conducted throughout the cycles, it can be stated that FRCM reinforced panels are not affected by wet/dry cycles as regards the ultimate load carrying capacity. However, the superficial degradation of the specimens, in particular of those reinforced with steel fibre, must be addressed in order to avoid the detachment of the FRCM.

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