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Sustainable Strengthening Techniques for Masonry Structures

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Abstract: Reducing the energy consumption is an important objective of the construction industry and this also applies for renovation, retrofit and refurbishment of existing buildings. Masonry buildings often need to be retrofitted and the use of Fibre Reinforced Polymeric (FRP) materials has proven to be a viable solution. With the inevitable declining of fossil fuels, carbon fibres and epoxy resins must be substituted with greener materials. This paper reports the results of several experimental investigations recently conducted by the authors using glass fibre meshes embedded into an inorganic matrix (known as FRCM: Fibre Reinforced Cementitious Matrix) to reinforce historic masonry constructions. This strengthening technique has been applied in laboratory to reinforce masonry wall panels, tile brickwork vaults and to construct masonry ring-beams at eaves level of existing buildings. The mechanical behaviour of the reinforced masonry elements have been significantly enhanced and test results demonstrate that is possible to avoid the use of more traditional composite reinforcements like high-strength carbon fibres and epoxy resins to bond the reinforcing materials to the masonry substrate.

Keywords: Sustainable strengthening techniques, GFRP grids, masonry walls, masonry tile vaults, ring beam reinforcement.

1. Introduction

In recent years, the conservation and protection of the architectural heritage of Europe became a priority and an important issue for architects and engineers. However the poor quality of the masonry material used to construct these historic structures often complicated the technicians' work. In many applications, the solution was to use composite materials, mainly carbon and kevlar fibres, bonded with strong adhesives (i.e. epoxy resins) to the masonry substrate (Bagherpour, 2012; Tinazzi et al., 2000; Triantafillou, 1998; Valluzzi et al., 2001; Verstrynge et al., 2015). Thanks to these fibrous materials, it is possible to provide the needed tensile strength to the masonry material enhancing its mechanical behaviour. Several solutions have been proposed to increase the lateral strength of masonry wall panels (Binda et al., 1997; Corradi et al.; 2014; Tumialan et al., 2001; Van Rickstal et al., 2001; Vintzileou et al., 1995), or the compressive strength of masonry columns (Aiello et al., 2007) or the capacity of vaulted structures (Alecci et al., 2016; Fagone et al., 2016; Gattulli et al., 2015).

The problem of durability or the sustainable characteristics of the investigated strengthening techniques have not been studied and considered. Composite materials exhibit several positive features which make them suitable as structural reinforcing elements (Corradi et al., 2015). FRPs are characterized by high tensile strength in the fibres' direction and by a linearly-elastic response up to failure. By using epoxy adhesives it was possible to transfer the loads from the masonry to the fibres and to protect the fibres from degradation due to environmental effects (Righetti et al., 2016).

However the conservation bodies often prohibit or limit the use of organic (epoxy) adhesives on listed constructions. Both carbon fibres and epoxy adhesives are made from a pitch derived from oil processing. Furthermore the inevitable declining fossil fuels and the increase of their cost facilitated the use of more sustainable reinforcements. These also meet the need for reducing the energy consumption and carbon emissions (Ercan, 2011; Kishali et al., 2010; Menezes et al., 2008). The use of glass-fibre composites embedded into a cementitious matrix can be an interesting solution in order to meet the above requirements. Fibreglass (GFRP) is a type of fibre-reinforced polymer where the reinforcement fibre is specifically glass fibre. This has been used in the construction sector since late 1980s, with applications on both new and existing masonry structures. Chiefly, its application was researched as a strengthening technique to improve the performance of masonry structures. However, GFRP cost (both the composite material and the epoxy adhesive) and the limited mechanical enhancement compared with conventional retrofitting methods, curtailed a widespread adoption for reinforcement of non-historic masonry constructions.

In the early 2010s, the use of specialized non-organic matrices (i.e. cementitious or lime-based mortars) was studied in order to foster improved long-term behaviour, provide reinforcement reversibility, meet the requirements of conservation bodies and use more compatible reinforcement materials with historic masonry (Lanas et al., 2003). This retrofitting method, known as FRCM (Fibre Reinforced Cementitious Matrix) is not labour-intensive, eliminates the need for an epoxy system to bond the fibres to the masonry and it is environmentally-friendly as it employs renewable and biodegradable resources. The adoption of non-organic matrices raises inherently less concerns regarding durability, production cost and health and safety restrictions compared to epoxy resins. The porosity of the specialized mortars allows walls and vaults to breathe, preventing damp and condensation problems. This reinforcement technique can be also listed within sustainable restoration techniques for historic constructions based on its non-invasiveness, non-energy consuming and reversible characteristics. It is also important to note that a key advantage of FRCMs is their inherent non-combustivity outperforming FRP systems during fire or high temperatures. Non-organic mortars present superior strength retention at elevated temperatures and can effectively protect the embedded fibrous reinforcement.

FRCMs have been used over the last recent years for seismic retrofitting of historic masonry constructions (Borri et al., 2016; Cascone et al., 2016; Gattesco et al., 2014; Koutas et al., 2014-2015; Papanicolaou et al., 2008; Tetta et al., 2015). These studies have demonstrated that the use of FRCMs can produce a significant enhancement of the mechanical properties of masonry structural elements. However non-organic matrices are not well established in applications involving the bonding of composite materials on masonry substrates (Carozzi et al., 2016). It is known that their mechanical properties are significantly weaker compared to epoxy adhesives.

This paper presents work to discuss and identify the fields of application of FRCM reinforcements for historic masonry structures. Test results of previous experimental campaigns are concisely reported and analysed. Three different fields of application are presented: strengthening of wall panels using thermal-insulating mortars, reinforcement of tiled thin vaults and the study of masonry ring-beams reinforced with GFRP grids inserted in the horizontal mortar joints. For all three applications the FRCM system is made of a GFRP grid bonded with an inorganic mortar. FRCM reinforcements can be expected to have a direct effect on the structural behaviour of the masonry elements and different series of tests have been designed to analyse this effect. All test series used test pieces constructed at full size, by masons familiar with the traditional historic methods of construction.

2. GFRP grid

The fibrous material used in this study to reinforce the masonry elements is a GFRP grid with a mesh size of 66x66 or 33x33 mm (Figure 1). The GFRP grid is made up of continuous fibre filaments embedded in thermosetting epoxy vinyl ester resin matrix. The glass fibre is an Alkali Resistant (AR) material and it is particularly suitable for application with inorganic cement- or lime-based mortars. Similarly to a woven fabric, glass grids are made up of a weft (the yarn going across the width of the grid) and a warp (the yarn going down the length of the loom) (Figure 2). The weight densities of the GFRP grids were 0.5 and 1 kg/m^2

for 66x66 and 33x33 mm mesh sizes, respectively. Both grids were characterized by a dry glass fibre section of 3.8 mm^2 in the weft and warp directions.

Specimens were extracted from the grid and the mechanical characteristics were analysed via tensile test according with ASTM D3039. Test results are shown in Table 1.

Table 1 – Mechanical properties of GFRP grid

	Sample size [-]	Tensile strength [MPa]	Young's modulus [GPa]	Elongation at failure [%]
Warp	15	634	39.63	1.60
Weft	13	558	35.72	1.56

The used mortars are different both in composition and in mechanical properties and have been mechanically characterized. In the following sections the mechanical properties of the mortar are given for each application.

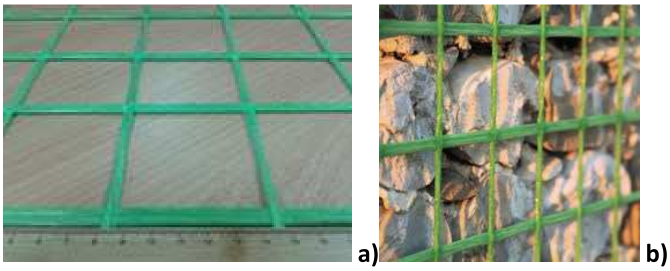

Figure 1 –GFRP grid: a) 66x66 mm mesh size; b) 33x33 mm mesh size

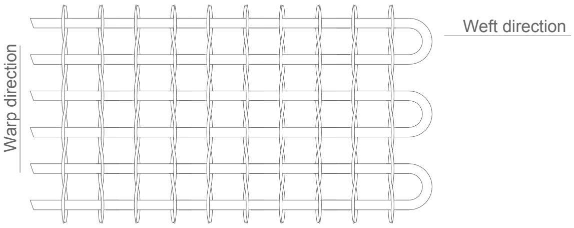

Figure 2 – Schematic layout

3. Possible applications for FRCM reinforcements

This section examines the results of previous studies undertaken by the authors using GFRP grids embedded into an inorganic matrix to reinforce three different masonry structural elements: wall panels, tiled vaults and ring beams.

3.1 In-plane reinforcement of wall panels

Masonry walls are often prone to be damaged when subjected to horizontal actions produced by earthquakes. In order to increase their in-plane capacity an innovative strengthening technique has been investigated. The aim is to increase both the mechanical properties and the energy efficiency of the load-bearing walls. It consists in inserting a GFRP grid into a thermal-insulating mortar jacketing. The application of a thermal-insulating mortar is useful in order to reduce the building energy consumption over its lifetime and increase the thermal insulation of the walls. Reinforcement was applied using a multi-stage process. After removing the original plaster, the original bed-joint were repointed by using new mortar (Figure 3) and the wall surface was ground to obtain a near smooth surface. To connect the GFRP-reinforced mortar layers and confine the wall panel two GFRP L-shaped bar joined together using epoxy past were used (Figure 4). Approx. 5 L-shaped connectors have been used for each wall panel.

Figure 3 – Mortar joints repointed with new mortar

Figure 4 – Detail of the GFRP L-shaped bar

After the application of the GFRP grid, a second layer of thermal insulating mortar (each mortar layer has a thickness of approx. 50 mm) is applied in order to cover the grid (Figure 5). The test elements were constructed in laboratory as free-standing square wall panels 1.17 m high and 0.25 m thick (two wythes). In order to investigate the effectiveness of this retrofitting technique, the wall panels have been tested in shear (diagonal tension test) in accordance with ASTM E519 and RILEM TC 76-LUM standards. Results are presented in detail in Borri et al. (2015). Four different non-cement based thermal insulating mortars have been used in the reinforced panels. Table 2 describes the mechanical characteristics of the bricks and mortars used for the construction of the masonry panel. The mechanical characteristics of the thermal insulating mortars are also reported in Table 2. These mortars are identified by the letter designations RO, D, R2 and C.

Figure 5 – Application of the mortar

Table 2 – Mechanical properties of the materials used to build the masonry panels

	Mortar*	Bricks	RO	D	R2	C
Compressive strength (MPa)	0.85	21.58	0.72	0.66	0.87	2.70
Sample size (-)	19	10	4	4	4	4
Coefficient of variation (%)	18	21	14	12	5	7
Indirect tensile strength (MPa)	0.18	-	0.13	0.14	0.23	0.43
Sample size (-)	19	-	4	4	4	4
Coefficient of variation (%)	31	-	16	10	5	0.4
Young’s modulus (MPa)	12640	-	1130	580	1030	2396
Sample size (-)	4	-	4	4	4	4
Coefficient of variation (%)	21	-	24	16	11	15

* Used for panel construction

Thermal conductivity (λ) values for the used mortars have been experimentally analysed. The obtained results are shown in Table 3: mortars exhibited values between 0.074 and 0.275 W/mK. The mortar with the smallest value of thermal conductivity was RO while the one with the highest was C-type (0.275 W/mK). Methods and results are reported in detail in Buratti et al. (2016).

Table 3 – Thermal conductivity values of the analysed mortars

Samples	**λ (W/mK)**
RO	0.074
D	0.123
R2	0.130
C	0.275

Two unreinforced and eight reinforced solid clay brick panels have been tested in shear. Figure 6 shows the test setup: the load is applied along a panel diagonal using a hydraulic jack. Two Linear Variable Differential Transformers (LVDTs) have been installed along the diagonal of both wall facades to record elongations and shortenings. Figure 7 shows the test arrangement.

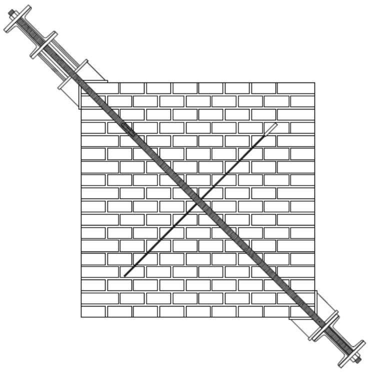

Figure 6 – Diagonal tension test layout

Figure 7 – Arrangement of the instruments during the test

Test results are reported in Table 4 in terms of maximum diagonal load (P), shear strength (τ), load capacity increment (ΔP) and shear modulus (G). The letter designation UR is used for unreinforced panels while RO, D, R2 and C are used to identify the type of thermal insulating mortar. All wall panels have been reinforced with a GFRP grid (66x66 mm mesh size) applied on both panels' sides.

Unreinforced panels failed by opening of diagonal cracks in the mortar joints along the compressed diagonal (Figure 8). Failure initiated in the central area of the masonry wall panel and extended towards the specimen corners. After the appearance of the diagonal cracks, the force dropped very gradually and the wall panel started to slid on the stepped cracks. A similar failure mode occurred for the reinforced panels: the diagonal cracking was followed by the detachment of the GFRP grid from the masonry substrate (Figures 9-10). Test results highlighted that shear capacity of reinforced specimens is mainly linked to the tensile strength and stiffness of the thermal insulating mortar: the load capacity increment is remarkable only for panels reinforced with mortars characterized by high mechanical characteristics (R2 and C types). The shear stress (approx. 3.15 bigger than the shear strength, see Borri et al. (2015)) – angular strain responses of both unreinforced and retrofitted wall panels are shown in Figure 11.

Table 4 – Test results on wall panels

Panel designation	Maximum diagonal load P (kN)	Shear strength τ (MPa)	ΔP (%)	Shear modulus G (MPa)
UR_1	204.5	0.234	-	4466
UR_2	197.7	0.226	-	3691
RO_1	202.9	0.232*	0.8	4247
RO_2	228.3	0.261*	13.5	5412
D_1	236.4	0.271*	17.6	3981
D_2	258.5	0.296*	28.5	4127
R2_1	315.6	0.361*	56.9	3528
R2_2	325.5	0.373*	61.9	-
C_1	431.4	0.494*	115	3431
C_2	420.3	0.481*	109	-

* Calculated using a wall thickness of 250 mm

Figure 8 – Failure mode for unreinforced panel

Figure 9 – Failure mode for panel reinforced with mortar type RO

Figure 10 – Detail of the GFRP mesh after cracking

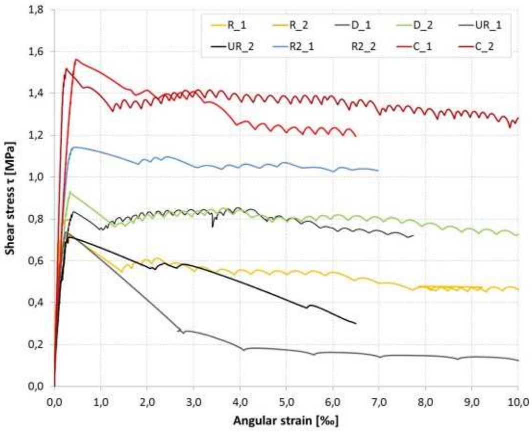

Figure 11 – Shear stress vs. angular strain for unreinforced and reinforced specimens

3.2 Reinforcement of tiled vaults

Masonry arches and vaults are common in historic masonry buildings. Due to several factors such as degradation of the material, increased service loads due to structural modifications, seismic actions, these structural elements often need to be retrofitted or repaired. In a single-ring arch, the critical failure mode is defined as “hinge mechanism” (Figure 12). It is characterized by flexural cracks along the mortar joints at the hinge positions. The hinges alternate between the extrados and the intrados of the structure.

The reinforcing technique studied could be considered as an evolution of a traditional Spanish building technique (*Tabicada* technique) (Figure 13). It consists in building vaults with several layers (typically two or three) of thin bricks alternated with layers of mortar. Bricks were arranged in diagonal direction in order to cover the mortar joints of consecutive layers (Figure 14).

The innovative aspect of the technique is to reinforce the mortar joints by applying the 66x66 mm GFRP mesh on the extrados of each bricks’ layer (Figure 15).

In order to evaluate the effectiveness of a reinforced technique for masonry arches using GFRP meshes, 17 masonry arch specimens have been built using two or three tile layers respectively. Arches had a span of 2000 mm with a corresponding height of 700 mm above springer level. Two types of mortar have been used. The flexural and compressive strengths of type 1 mortar were 0.58 and 0.16 MPa, respectively. The mechanical characteristics of type 2 mortar were 5.25 and 1.96 MPa. Specimens were tested by applying a vertical compression load at the keystone. Test results are shown in Table 5. All test specimens are indexed by an alphanumeric code: in this nomenclature DR refers to Double-Ring and TR to Triple-Ring arch; the second part of the code refers to the type of strengthening (UT for Unreinforced; IT for reinforced arch with GFRP grid placed into the mortar bed joints; OT for reinforced arch with GFRP grid placed both into the mortar bed joints and at the extrados of the arch); and the third part of the code refers to the identification number of the specimen.

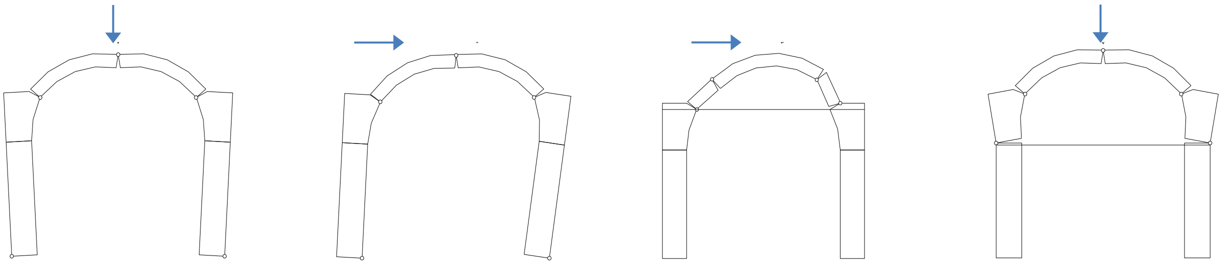

Figure 12 – Hinge mechanism for arch structures

Figure 13 – Examples of Tabicada technique

Test results are shown in Table 5. All test specimens are indexed by an alphanumeric code: in this nomenclature DR refers to Double-Ring and TR to Triple-Ring arch); the second part of the code refers to the type of strengthening (UT for Unreinforced; IT for reinforced arch with GFRP grid placed into the mortar bed joints; OT for reinforced arch with GFRP grid placed both into the mortar bed joints and at the extrados of the arch); and the third part of the code refers to the identification number of the specimen.

The failure mode of unreinforced specimens was due to the formation of the four-hinge mechanism (Figure 16) while, the reinforced arches failed for the separation of the layers of tiles and GFRP reinforcement (Figure 17). Results are presented in detail in Castori et al. (2016).
Tests show that the use of composite FRCM strengthening increases the capacity the masonry arch samples and prevents the hinge mechanism. The application of the reinforcing material produced a capacity increase between 2 and 7 times for the double-layer arches (DR series) and approx. of 3 times for the triple-layer arches (TR series), compared with the unreinforced arches of the same series.

Table 5 – Tests results (masonry arches)

Arch designation	Mortar type	Failure load (kN)	Load point deflection (mm)	Failure mode
DR_UT_01	1	0.15	-	Mechanism
DR_UT_02	2	1.57	2.46	Mechanism
DR_IT_01	1	0.82	4.88	Ring separation + snap-through
DR_IT_02	2	3.52	26.53	Ring separation + snap-through
DR_OT_01	2	8.32	27.13	Ring separation + snap-through
DR_OT_02	2	10.54	3.21	Ring separation + snap-through
DR_OT_03	2	8.50	13.93	Ring separation + snap-through
DR_OT_04	2	7.49	8.64	Ring separation + snap-through
TR_UT_01	1	1.07	1.34	Mechanism
TR_UT_02	2	6.83	4.93	Mechanism
TR_UT_03	2	4.10	7.69	Mechanism
TR_IT_01	1	2.71	2.23	Ring separation + snap-through
TR_IT_02	2	8.46	17.60	Ring separation + snap-through
TR_IT_03	2	12.99	24.79	Ring separation + snap-through
TR_OT_01	2	16.66	14.04	Ring separation + snap-through
TR_OT_02	2	17.83	13.06	Ring separation + snap-through
TR_OT_03	2	13.16	9.90	Ring separation + snap-through

Figure 14 – Detail of unreinforced arch

Figure 15 – Detail od reinforced arch

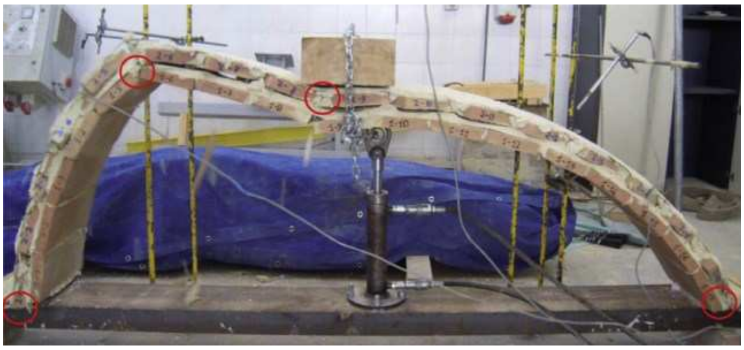

Figure 16 – Four-hinge mechanism

Figure 17 – Ring separation of the brick layers and GFRP reinforcement

The retrofitting technique was more effective for vaults made using weak mortar (Type 1); for example, in the IT series, the increases in capacity provided by mortar type 1 for double- and triple-layer arches were 145 and 29 % larger compared with the arches constructed with the mortar type 2. Tests also highlighted that the application of the grid reinforcement at the arch extrados (OT series) reduced the problem of the local buckling and avoided a premature collapse.

3.2 Ring beam reinforcement

It is known that ineffective wall-to-wall and floor-to-wall connections may facilitate out-of-plane collapse mechanisms in case of a seismic event. The separation of a masonry structure into separate components oscillating independently is the main consequence of a lack of connection. A catastrophic collapse of one or more wall elements or the failure of the bearing of the roof on its supporting wall then follows. In order to increase the quality of connections and achieve a box-like behaviour of the masonry structure against earthquakes, the application of a ring beam at the ground and eaves levels is an effective retrofitting method (Figure 18). This may improve the integrity of the masonry construction so as to prevent separation of individual wall panels and out-of-plane collapse mechanisms. FRCM could be also applied here, building a composites-reinforced masonry ring beam. The innovative reinforcing technique consists in removing a small section of the upper part of perimeter walls and rebuilt a masonry ring beam reinforced at the mortar bed-joints with the GFRP grid using recycled or new stone or bricks (Figure 19). This retrofitting technique may be also applied when the fair-faced appearance of the masonry must be preserved.

Figure 18 – Examples of reinforced concrete ring beams

As part of a previous study, described in detail in Sisti et al. (2016), six full-scale masonry beams were constructed and subjected to bending tests. Four stonemasonry specimens (length 5 m and square cross section characterized by side of 0.5 m), were built using 3 layers of stones and 4 layers of GFRP grid embedded in a ready mix hydraulic lime-mortar (type CM) (Figure 20). The remaining two specimens (length 5 m and cross section of 0.4 x 0.33 m), were built using 4 layers of clay bricks and 5 layers of GFRP mesh embedded in a ready-to-use cement-based mortar (type MI) (Figure 21).

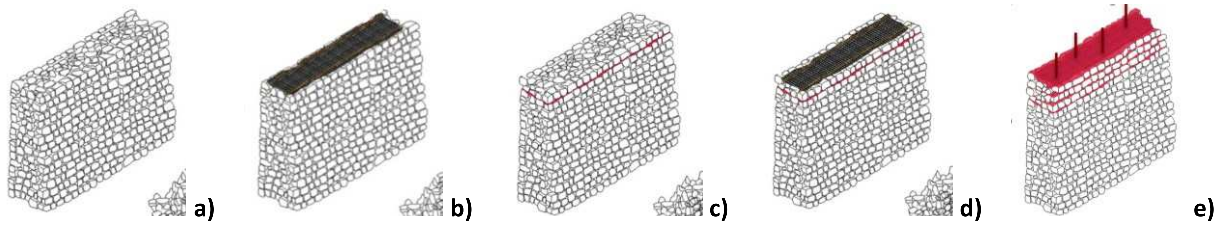

Figure 19 – Construction methods of a reinforced masonry ring beam: a) removing the upper part of the existing wall; b) applying the first mortar layer reinforced with the GFRP grid; c) applying the stones; d) applying a second GFRP reinforced mortar layer; e) repeating the phases described in c) and d) until reaching the necessary height

Both mortars have been tested in compression according with UNI EN 12390-3 standard. Type CM and type MI mortars exhibited a compressive strength of 5.99 and 10.61 MPa, respectively. Also stones and bricks have been tested: the compressive strength values evaluated were 46.33 and 24.42 MPa. With regard to the reinforcement, two different mesh sizes were used, having a rigid square grid size of 33 x 33 and 66 x 66 mm.

In order to evaluate the effectiveness of the strengthening technique, reinforced ring beams have been tested in bending by applying the load perpendicularly or parallel to the mortar bed joints. This latter has been done in order to simulate the behaviour of a masonry ring beam in earthquake. However the testing apparatus was not designed to simulate precisely the loading condition which may be produced by a seismic event, but to create a set of internal forces in the ring beam similar to those which would be generated by the vertical and horizontal out-of-plane component of earthquake loading.

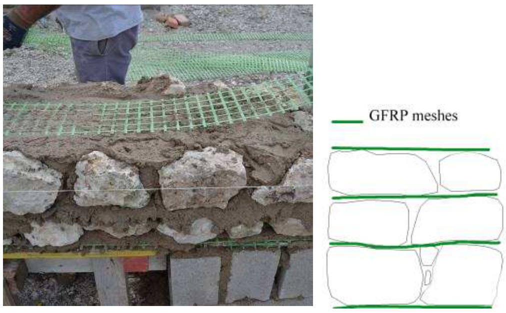

Figure 20 – Stone FRCM ring beam

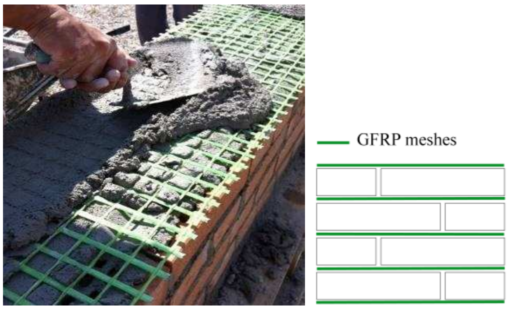

Figure 21 – Clay brick FRCM ring beam

Ring beams were simply supported at the ends and test were carried out over a span of 4 m. Load was applied by using concrete blocks and/or cement bags distributed along a load-span of 2 m. LVDTs were used to record vertical deflections at 1/4, 1/2 and 3/4 of the test span on both sides of the beam (Figure 22). Figure 23 shows the test arrangement.

Because masonry is a material having little tensile strength (known as no-tension material), it was not possible to test unreinforced beams as a control to compare results. Unreinforced beams cannot support the stresses produced due by self-weight.

Figure 22 – Bending test set-up

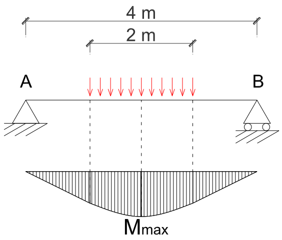

Figure 23 – Test arrangement and bending moment diagram

Table 6 presents the results of the bending tests carried out on reinforced ring beam. Each specimen is identified with an index composed by three parts: the first designates the masonry type (P for stone masonry and L for brick masonry) and the beam's identification number, the second the type of grid used (G33 in case of GFRP mesh with a grid size of 33 x 33 mm while G66 for gird size of 66 x 66 mm) and the third the direction of the bending loads (V for loads parallel to the mortar joints and H for loads perpendicular to the bed joints). The cross section area of the reinforced material used on each specimen is reported in the table. In the same are also listed the mid-span bending moments produced by both self-weight (M_w) and by applied load (M_{max}). For specimen P7_G66_V the maximum mid-span bending moment was 54.73 kNm and the maximum load was 62.9 kN. Failure initiated at mid-span with the opening of vertical cracks, which increased with the load while horizontal cracks at the mortar joints opened near the beam's ends. For the brick-masonry beams, specimen L9-G33-V the maximum bending moment was 39.73 kNm and the maximum load was 51.2 kN. The bending test for the L10_G33_H specimen was stopped with an applied load of 38.3 kN without reaching the failure. Figure 24 shows the failure mode of a stonemasonry ring beam and in Figure 25 it can be seen a detail of a failed brick masonry ring beam with the GFRP grid detached from the mortar.

Table 6 – Tests results on ring beams

Beam designation	Dry fibre cross sectional area (mm^2)	Maximum Load (kN)	Bending moment M_w (kNm)	Bending moment M_{Max} (kNm)	Total bending moment (kNm)
P5_G33_V	171.1	56.8	10.7	39.75	50.45
P6_G33_H	171.1	56.6	10.7	39.62	50.32
P7_G66_V	342.2	62.9	10.7	44.03	54.73
P8_G66_H	342.2	43.1	10.7	30.14	40.84
L9_G33_V	213.9	51.2	3.86	35.87	39.73
L10_G33_H	213.9	38.3	3.86	26.80	30.66

Figure 24 – Failure of a stone masonry ring beam

Figure 25 – Detail of a brick masonry ring beam after failure

4. Conclusions

It is possible to conclude that some common damage typically found in historic adobe constructions can be easily prevented through the use of composite materials bonded using inorganic mortars and the load capacity of these masonry structural elements can be also efficiently increased. This paper set out to review the advantages of this retrofitting technique and has summarized the test results of previous research investigations conducted by the authors on masonry wall panels, tiled brickwork vaults and stonemasonry ring-beams. The differences in the performance of unreinforced and FRCM-retrofitted masonry structures of different forms of construction has been studied, enabling a better understanding of the structural behaviour of masonry elements reinforced with FRCMs.

As a result of this study, it is possible to conclude that:

1. Test results demonstrate how GFRP grids bonded using thermal insulating mortars can produce a double positive effect of increasing the lateral capacity and substantially enlarging the thermal insulation of external walls. The results of the investigation highlighted the need to find a compromise between the mortar's thermal resistance (mainly governed by its lightweight characteristics) and its mechanical strength (conversely increasing with higher weight density of the aggregates and quantity of cement). Test results demonstrated that it is possible to increase the wall's lateral capacity using thermal insulating mortars with shear increments up to 115 %.
2. For tiled vaults, GFRP grids were applied to the extrados of the vaults alternating layers of tiled bricks and GFRP grids, and vaults were again tested to determine their strengthened response. Measurements were taken of both the global vault response using displacement transducers and of a local behaviour to obtain a detailed understanding of the FRCM strengthened vault. Significant increases in terms of load capacity have been measured and test results demonstrated that tile brickwork vaults may be effectively retrofitted using GFRG grids embedded into the mortar joints.
3. The construction of a ring-beam at eaves level is an effective method to prevent out-of-plane collapse mechanisms of masonry wall panels. In this paper the use of GFRP grids coupled with inorganic mortars has been investigated by testing several brick- and stone-work masonry ring beams. It was concluded that it is possible to construct FRCM strengthened ring beams and test results showed a high bending capacity of strengthened beams. It is also possible to keep the fair-faced aspect of the masonry by inserting the grid reinforcement into the horizontal mortar joints. The bending capacity of the reinforced ring beams was governed by the behaviour of the bond between the masonry and the GFRP grid.

The present work is not exhaustive and further development work is needed, but a clear trend has been identified: FRCM reinforcement can enhance the mechanical characteristics of masonry structural elements. This enhancement is usually smaller compared to the one achievable using more traditional composite reinforcements applied with organic resins. However the use FRCMs may overcome several drawbacks typical of traditional composite reinforcements and meet the requirements of conservation bodies having more sustainable features and a better long-term behaviour.

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