EXPERIMENTAL CHARACTERIZATION OF OUT-OF-PLANE BEHAVIOUR OF INFILL MASONRY WALLS STRENGTHENED WITH COMPOSITE MATERIALS

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ABSTRACT

The experimental comparison among various types of composites materials applied to hollow blocks masonry panels is presented. Performance of Textile Reinforced Mortar (TRM), using basalt or glass mesh, and Steel Reinforced Grouts (SRG) is compared with Carbon FRP (Fiber Reinforced Polymer), Steel Reinforced Polymers (SRP), and flax and hemp FRP sheets. After a wide characterization of constituent materials and masonry, 27 specimens were subjected to four-point monotonic bending tests. As for inorganic matrix, cement-based mortars were considered; nevertheless, a comparison with a magnesia-based matrix was also proposed for SRGs. The tests were aimed at reproducing in laboratory, in a simplified way, the failure condition of infill masonry walls under out-of-plane actions.

Results showed a ultimate load increase ratio, compared to the unreinforced masonry, ranging from about 3 (Flax FRP) to more than 9 (SRP). TRMs showed a intermediate behavior between those two reinforcing systems. Failure modes included fiber rupture (mostly for natural fibres), slippage of reinforcements from the matrix (SRG), and hybrid failure (crushing/debonding or shear/debonding for SRP, FRP and TRM).

KEYWORDS: masonry, infill walls, TRM, natural fibres, bending tests.

INTRODUCTION

Composite materials provide effective performance on masonry components, both for strengthening and repair interventions. Nowadays, besides the use of the most common Fiber Reinforced Polymers (FRP), research is increasingly focused on the reliability of composites more compatible with the characteristics of the substrate, which can allow, at the same time, maximizing the exploitation of the reinforcement properties and the structural performances of the strengthened components. Particularly for masonry, inorganic mortars are preferred to epoxy resins to be applied as matrix to bond reinforcing materials in Externally bonded (EB) wet lay-up systems. Those matrixes can be selected or designed properly to improve workability, bond, strength, etc.

As reinforcing textiles, steel or natural/mineral fibers (like flax, hemp or basalt) can be considered in substitution to more common products as carbon or glass, used in the recent past basically with epoxy, and applied as sheets or textile meshes (Textile Reinforced Mortar - TRM) or Steel Reinforced Grouts (SRG). The consequent advantages are clear in terms of durability, removability, fire resistance, and air-permeability for the substrate, although mechanical performance remain lower (but still significant in the context of masonry) than in case of FRPs.

Moreover, inorganic mortars can be applied on moist substrates, which is a quite normal state for masonry, and at low-temperature environment.

Nevertheless, to avoid defects on bonding or problems in the application phase, the proper choice of materials (matrix and fiber strengthening system) to be combined is crucial. This requires the selection of the constituents, e.g., in terms of particle size distribution for the matrix, to allow the mortar to penetrate among the fibers, and at the same time the definition of the suitable density of the composite, i.e., the spacing between the fiber bundle (e.g, in a mesh) or the wires (e.g., for steel).

Being the use of TRM and SRG on masonry components quite recent, the experimental investigations of those systems is particularly in need. Studies available on the strengthening on vaults, panels and on bond of EB reinforcing systems [1] [2] [3] [4] pointed out the effectiveness of this solution to improve the behavior of masonry elements, measured not only by increase of strength but also by ultimate displacement capacity. Those promising aspects and the more affordable costs in comparison with FRPs increased the interest towards those products for real application on buildings. Nevertheless, standards on composites are still limited to FRPs [5] [6], therefore no specifications are available about qualification methods (e.g., material testing) or design of components for SRG or TRM systems. Moreover, failure modes and performance still need to be compared with the knowledge acquired on FRPs, to make clear the differences in the mechanical behavior and allow the identification of parameters suitable for assessment and design.

Among various application on bearing walls, composites materials can be very helpful to prevent out-of-plane brittle failure of infill walls in modern buildings, particularly in seismic region. The last earthquakes (Italy, 2009 and 2012; Turkey, 2012), still pointed out the high vulnerability of infill panels in reinforced concrete framed structures under horizontal actions (Figure 1). In fact, due to their dead loads and position, the collapse of infill loads can induce high hazard for human lives, also in case of not significant damage in the main structure [7].


a) b)

Figure 1: Out-of-plane collapse of infill walls in r.c. framed structures registered in the regions struck by recent earthquakes in Italy [7]

Interventions are therefore aimed at avoiding brittle failures and possibly improve the global behavior of the buildings. The strengthening of the infill walls and the connection to the reinforced concrete frame is essential to prevent out-of-plane collapse, improve the collaboration with the r.c. structure and reduce or eliminate unfavorable local effects. Moreover, out-of-plane collapses can be activated by low level of loads in comparison with in-plane ones, and occur without any warning. Therefore, their inhibition by strengthening intervention is crucial, to allow infill panels to resist to higher seismic loads and shift their behavior into shear.

Experimental studies on out-of-plane strengthening of masonry walls, since late 90s, were focused on the use of FRPs, applied as EB or NSM (Near Surface Mounted) [8] [9] [10] [11] [12] [13], ferrocement or shotcrete overlays [14] [15]. Still few works are available on the use of TRMs [16] [17]; they emphasize the improvement provided by textile meshes in comparison with FRP strengthening, particularly when the failure mechanism does not involve the fiber tensile strength.

The results of an experimental campaign aimed at comparing the effectiveness of various composite materials and reinforcing systems applied to hollow brick masonry panels, using EB Carbon FRP, SRP/G, Basalt, Glass, Hemp and Flax TRM sheets and meshes are presented. The four-point monotonic bending tests was adopted on a total of 27 specimens to simulate the out-of-plane capacity of the walls. Two kind of mortars were selected as matrix for SRG and TRM specimens, cementious and magnesiac ones, the last one applied only to SRG specimens.

In the paper, the results obtained are compared in terms of failure load, ultimate strength and displacement capacity, and increase of performance respect to unreinforced masonry.

EXPERIMENTAL PROGRAM

The experimental program consisted in a wide preliminary phase of characterization of the constituent materials (hollow clay blocks, embedding mortar, fibres and inorganic matrix) and the masonry; subsequently, masonry panels in the various strengthened conditions were subjected to bending tests.

Masonry characterization

Masonry blocks having dimensions 250x250x120mm were characterized by compression (8 specimens) according to EN 772-1, and splitting (6 specimens); also single sects were tested, under flexure (12 specimens, according to UNI 1015-11) and compression (8 specimens). The mortar used in bed joints (10mm wide, cement-based, classified M5 following UNI EN 998-2) was fully characterized on bending (3 specimens) and compression (6 specimens), and elastic modulus (3 specimens), according to UNI 1015-11 and UNI 6556, respectively.

The unreinforced (URM) masonry was characterized by considering various assemblages: (i) two-blocks wallettes (250x515x120mm) for bending tests on the mortar joint (6 specimens); (ii) wallettes 390x780x120mm for compression tests (strength and elastic modulus, 6 specimens each, tested according to UNI 1052). Those tests provided the reference maximum load of URM: (i) 1.18 kN, with a coefficient of variation (CoV) of 0.29 for bending; (ii) 81.3 kN for compression (CoV of 0.26). Both bending and compression failure were brittle.

Figure 2, Figure 3 and Figure 4 show some phases of the tests. The results of the mechanical characterization phase are summarized in Table 1.

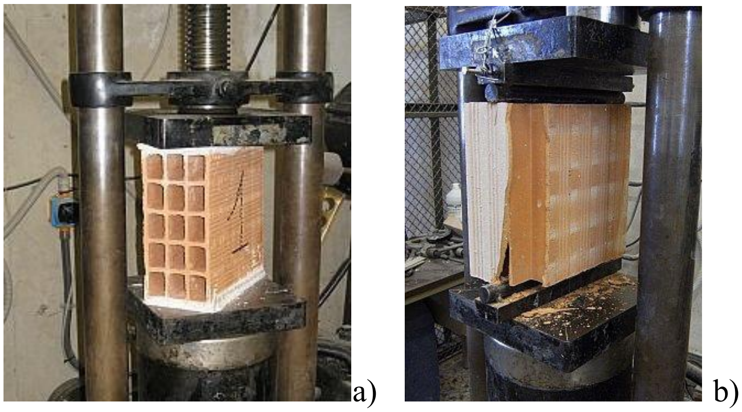
a) b)

Figure 2: Mechanical characterization of blocks: compression (a) and splitting (b) tests.

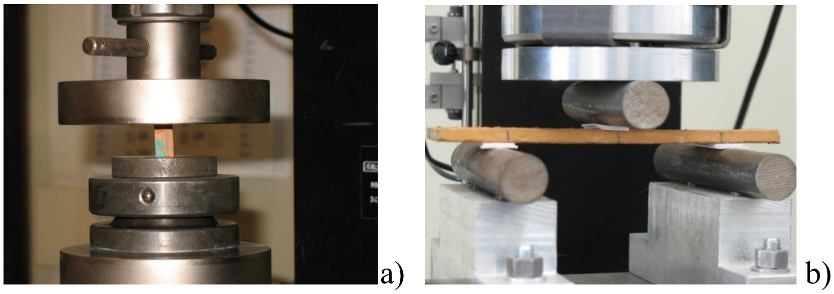
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Figure 3: Mechanical characterization of single sects: compression (a) and flexure (b).

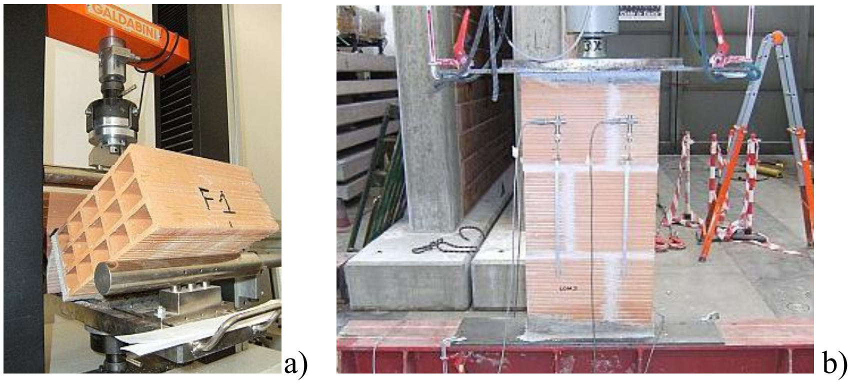
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Figure 4: Mechanical characterization of masonry assemblages: a) flexure on the mortar joint; b) compression.

Table 1: Mean mechanical properties of masonry materials and assemblages (CoV in %).

Material/specimen	Compression strength [MPa]	Tensile load (from splitting) [kN]	Flexural strength [MPa]	Elastic modulus [MPa]
Block	3.53 (16)	10.91 (30)	-	-
Sects	35.65 (16)	16.12 (10)	-	-
Mortar	4.11 (8)	-	1.10 (9)	6138 (8)
Masonry	1.80 (20)	-	0.21 (28)	2827 (26)

Composite materials and specimens preparation

Specimens for the characterization of reinforced masonry had dimensions 385x1300x120mm; reinforcement was applied in one central sheet 50mm wide, except for the basalt and glass mesh, which covered the whole surface (385mm wide) (Figure 5). The glass fibre net (10x10mm mesh) considered in the experimental campaign derives from the common use as support for plasters. The properties of the composites given by the providers are listed in Table 2. Steel wires are composed by strands having section of 0.481mm^2 (distributed as 7.8 strands/cm) and 0.538 mm^2 (distributed as 1.57 strands/cm), for HD and LD, respectively.

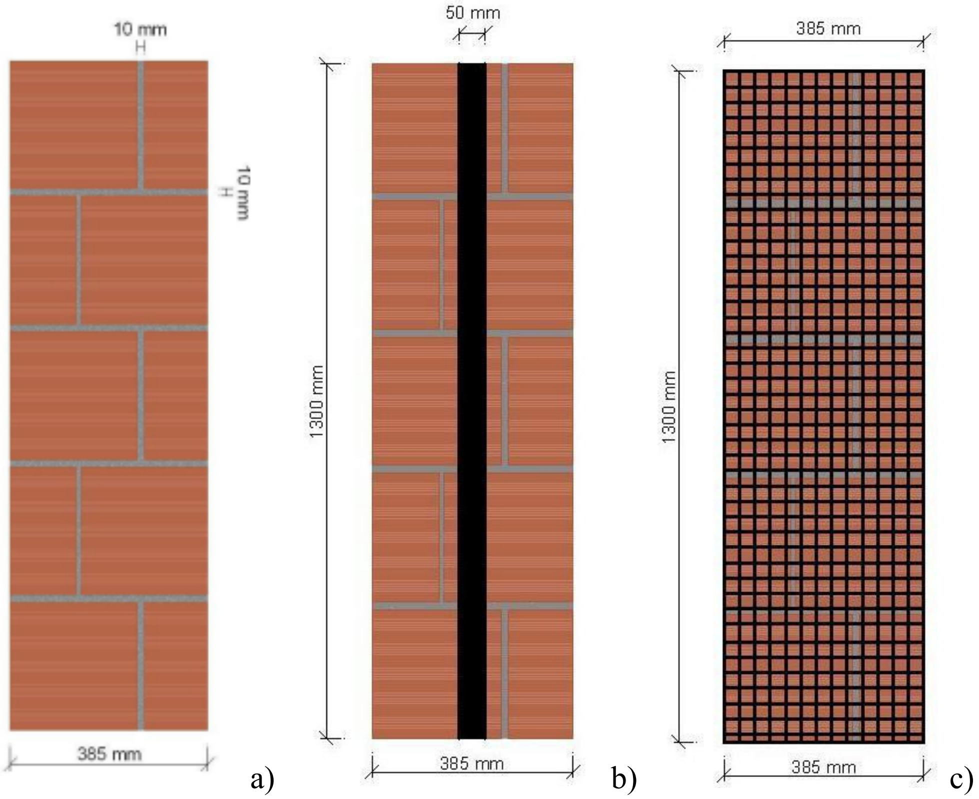


Figure 5: Strengthening configuration for bending tests: pilot URM (a), single sheet (b), textile mesh (c).

Table 2: Properties of composites (from data-sheets).

Fiber	Density (g/m^2)	Equivalent thickness (mm)	Characteristic tensile strength (MPa)	Young's modulus (GPa)	Strain at failure (%)
CARBON UNIDIR 320 HS240	300	0.165	3700	230	1.75
BASALT UNIDIR 400 C95	396	0.140	1900	90	2.11
FLAX UNIDIR 300 HS45	292	0.194	710	45	2.74
HEMP UNIDIR 240 HS22	234	0.155	496	22	3.10
STEEL 3X2-B 20-12-500 (HD)	3010	0.380	3070	190	1.60
STEEL 3X2-G 4-12-500 (LD)	670	0.084	2820	190	1.50
BASALT GRID 300 C95	300	0.053	1735	90	1.93

The single wires of the glass fibre plaster net were characterized in laboratory under tensile tests, resulting in a mean tensile strength of 231 MPa (each wire having section of 1.22mm^2), and elastic modulus around 14 GPa. Just to compare those properties with the same type of reinforcement adopted in the tests, the basalt used as sheet or mesh has a characteristic tensile strength of 3080 MPa an elastic modulus of 95 MPa.

Carbon, Basalt, Flax, Hemp and High Density (HD) Steel sheets were applied as FRP, i.e., with epoxy resin. Low Density (LD) Steel, Basalt and Glass net were applied with inorganic matrix (SRG and TRM), using a cementitious mortar; for LD SRG, also a magnesiac mortar was used.

Table 3 provides the experimental program on the strengthened panels. Three specimens for each conditions were prepared.

Table 3: Qualification of strengthened specimens.

Reinforcing system	Fiber	Matrix	Fiber product	Matrix product	Specimen label
FRP	Carbon	epoxy	CARBON UNIDIR 320 HS240	FIDSATURANT HM	Carbon FRP
	Basalt	epoxy	BASALT UNIDIR 400 C95	FIDSATURANT HM	Basalt FRP
	Flax	epoxy	FLAX UNIDIR 300 HS45	FIDSATURANT HM	Flax FRP
	Hemp	epoxy	HEMP UNIDIR 240 HS22	FIDSATURANT HM	Hemp FRP
SRP	HD Steel	epoxy	STEEL 3X2-B 20-12-500	FIDSATURANT HM-T	HD SRP
SRG	LD Steel	cementitious	STEEL 3X2-G 4-12-500	EMACO NANOCRETE FC	LD SRG cem
		magnesiac	STEEL 3X2-G 4-12-500	ORSAN PL57	LD SRG mag
TRM	Basalt	cementitious	BASALT GRID 300 C95	EMACO NANOCRETE FC	Basalt TRM
	Glass	cementitious	RET01-D1020F	EMACO NANOCRETE FC	Plaster net

The application of strengthening on panels consisted in the following phases. For FRP and SRP: a) application of primer, b) regularization of the surface by application of putty, c) application of a first layer of epoxy resin, d) positioning of the fibres, e) use of small paint roller (FRP) to press the strip or of a palette-knife (SRP), to allow the proper impregnation of the fibres. For SRG and TRM: a) application of a first layer of matrix (4-5mm), b) positioning of the mesh, c) use of a palette-knife to spread the matrix and allow the proper impregnation of the fibres.

Figure 6 shows some phases of the application.

a) b) c)

Figure 6: Composites application on panels: epoxy impregnation for hemp FRP (a), cement mortar applied to Basalt TRM (b), magnesiac mortar applied to LD SRG (c).

Test setup

The setup consisted in a universal testing machine able to apply monotonic vertical loads (hydraulic jack of 500t, load cell of 10t). Six transducers (LVDT) were applied to the two transverse faces of the specimen to measure vertical displacements: five were distributed on the front and one was positioned in the middle of the back; the LVDTs were fixed on two metallic bars (one per side), connected to the specimens by two hinges each, while the movable rod is fixed at the base of the panel. Moreover, the supports of the panels were properly enlarged, to allow the specimen to follow the rotation during loading.

Figure 7 shows the setup adopted for the tests.

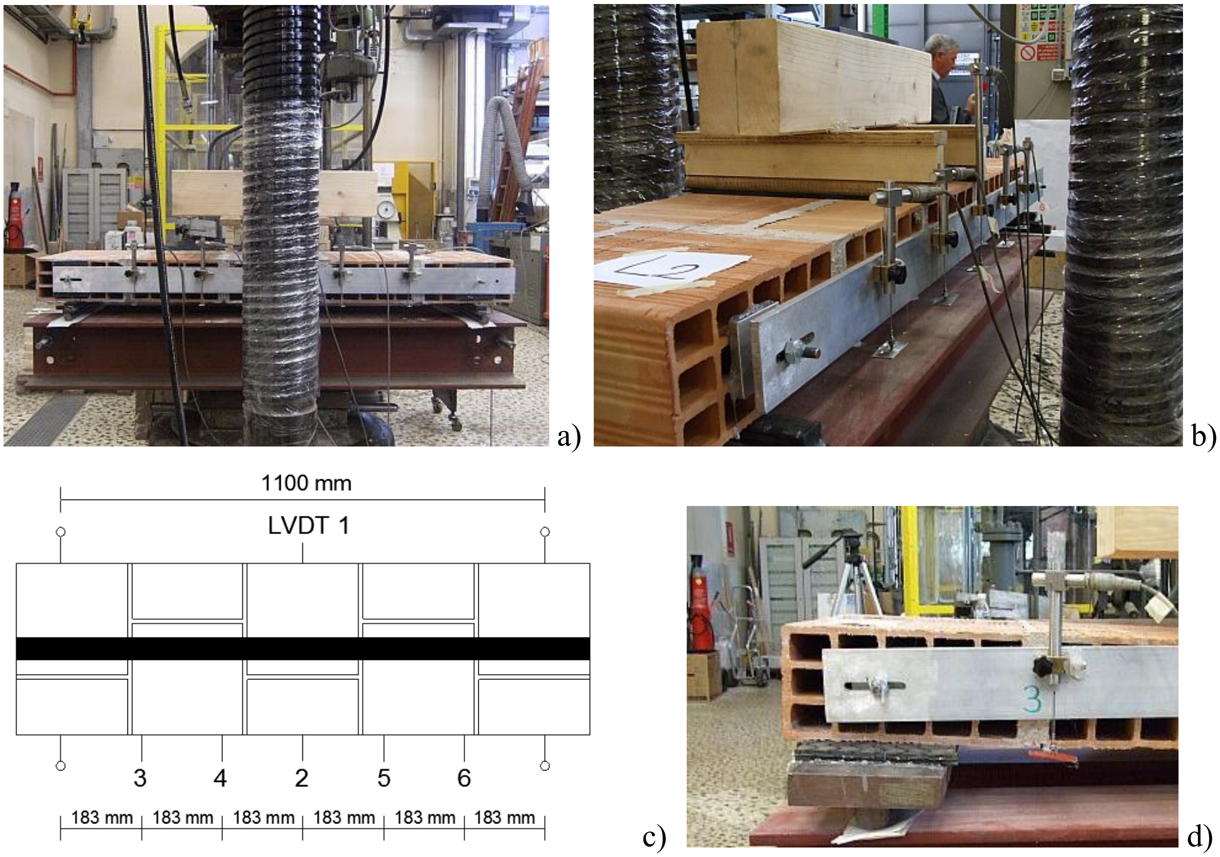


Figure 7: Test set-up: frontal (a) and lateral (b) view; lay-out of transducers (c) and detail of supports and LVDT positioning (d).

Panels were tested after suitable curing, according to the various materials used as matrix (at least 7 days for epoxy and 28 days for inorganic mortars).

RESULTS AND DISCUSSION

Panels exhibited various failure modes: a) fibres rupture, in case of the low strength composites (Plaster net, Flax and Hemp FRP), regardless the type of matrix; b) fibres sliding into the matrix for SRG, regardless the type of mortar used as matrix; c) shear in the masonry section, for Basalt TRM and Carbon FRP; d) combined ruptures: crushing and intermediate debonding for Basalt

FRP, and shear and end debonding for HD SRP. Nevertheless, those failure modes occurred at different levels of maximum load, resulting the highest ones in case of shear rupture (even in combination with debonding).

Table 4 and Figure 8 show the comparison of mechanical results and behaviour at failure.

Table 4: Results of strengthened panels subjected to monotonic bending tests.

Specimen	Failure mode	Peak load (N)	Max displacement at midspan (mm)
Carbon FRP	Shear	6355	10,91
Basalt FRP	Crushing + debonding	4089	11,88
Flax FRP	Fibre tensile rupture	2096	12,86
Hemp FRP	Fibre tensile rupture	2562	13,29
HD SRP	Shear + end debonding	6847	6,08
LD SRG cem	Fibre sliding into matrix	3381	8,79
LD SRG mag	Fibre sliding into matrix	5944	20,00
Basalt TRM	Shear	6050	3,86
Plaster net	Fibre tensile rupture	5057	7,83

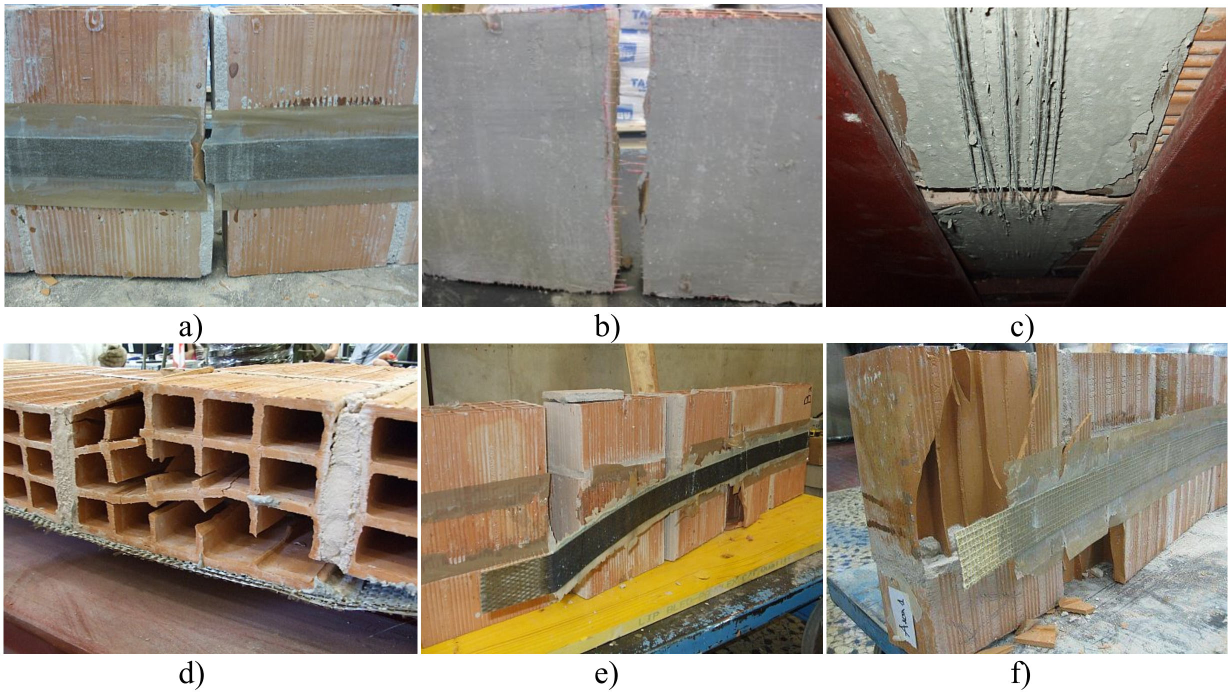
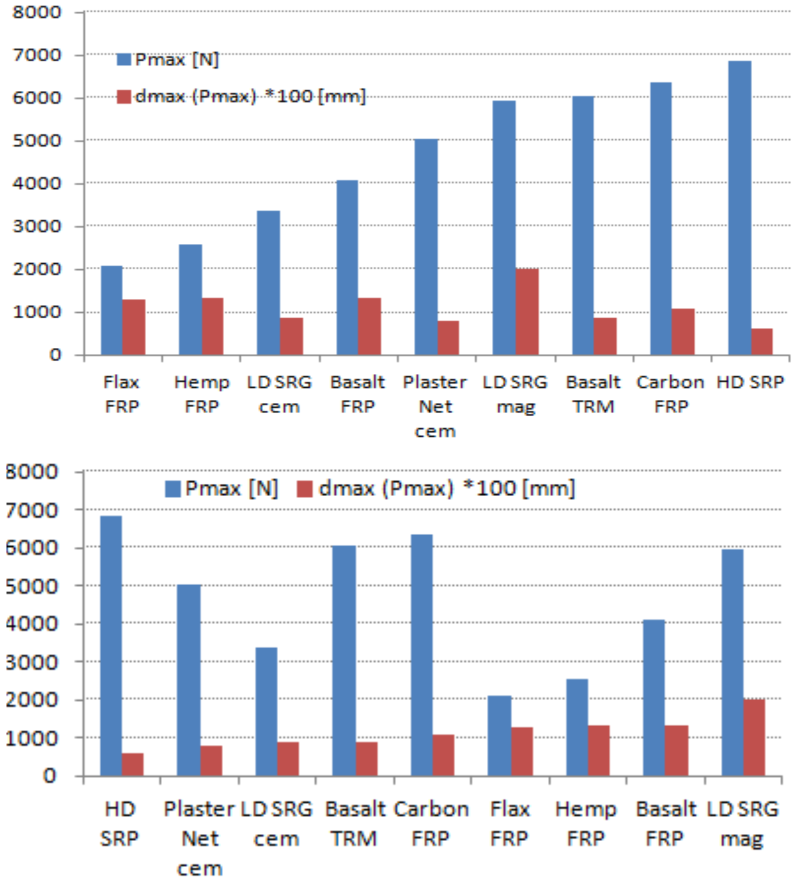

a) b) c)
d) e) f)

Figure 8: Fibre rupture for Flax FRP (a) and Plaster net (b); c) fibre sliding for SRG cem; d) shear rupture for Basalt TRM; detail of debonding for Basalt FRP (e) and HD SRP (f).

Figure 9 presents the results ordered following the crescent values for the maximum load (P_{max}) and the maximum displacement (d_{max}), respectively. Figure 10 shows the mean curves obtained by the three specimens tested for each strengthening condition. Moreover, by computing an estimated value of 720 N for the bending strength of the URM panel, it is possible to compare the effectiveness of the various strengthening proposals in terms of ultimate load or bending moment (Figure 11).



a)

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Figure 9: Results ordered for crescent values of strength (a) or displacements (b).

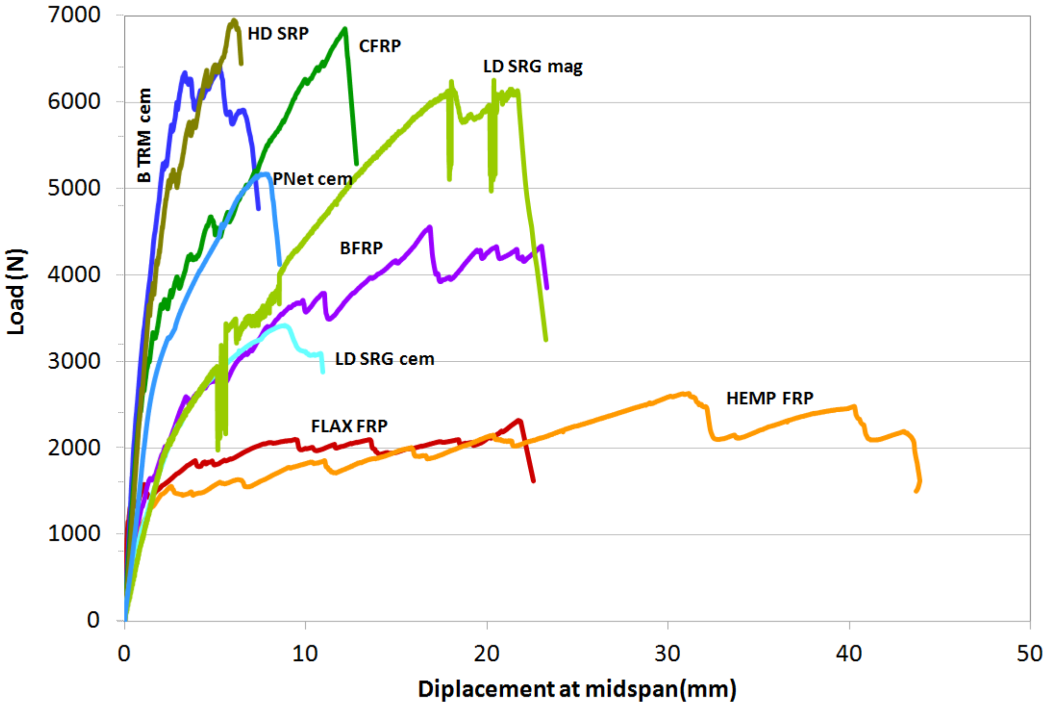

Figure 10: Representative (mean) curves for different types of specimens.

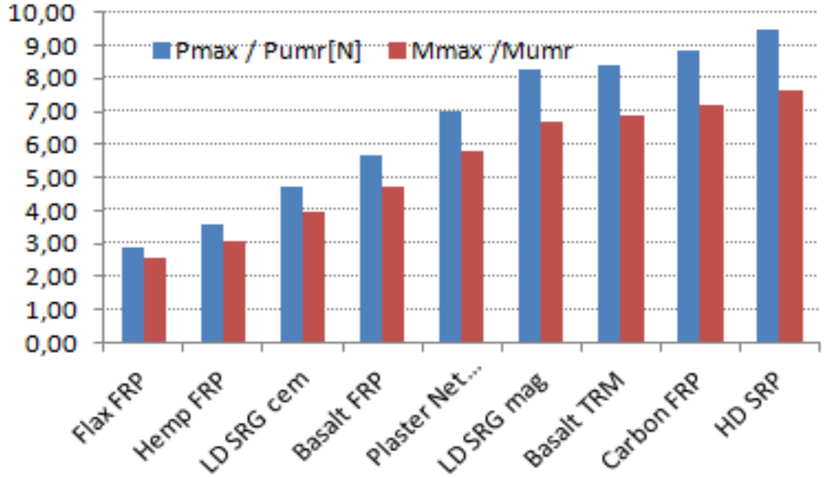

Figure 11: Increase ratio between strengthened and unstrengthened conditions.

CONCLUSIONS

The application of composite materials can be very effective to increase the bending strength of hollow block masonry panels. Increase in maximum load can vary between about 3 and 10 times respect to plain masonry, considering various EB systems as FRP, SRG/P or TRM. The highest load capacity are kept by the highest performing materials (CFRP and HD SRP), which corresponds, however, to very low displacements. The use of natural fibres combined with epoxy provided the lowest values in term of load (although significant respect to the URM), but they are related to high displacement capacity. Nevertheless, inorganic matrixes used for SRG and TRM provided intermediate values for load capacity, and good levels of corresponding displacements. Particularly for Basalt TRM, a good balance between load and displacement capacity was found.

These results can be useful to understand the contribution of strengthening to prevent out-of-plane brittle failure of infill walls in framed structures, when subjected to horizontal loads (e.g., in seismic regions). Nevertheless, several aspects still need to be clarified and investigated, as the role of anchorages, the influence of various lay-out of strengthening, the role of cyclic loads, etc.

Results will be used to calibrate simplified FE models and predictive analytical formulations available in literature, to contribute to the identification of design and assessment criteria for real structures.

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