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ORIGINAL ARTICLE

Diagonal compression tests on masonry wallets coated with mortars reinforced with glass fibers

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Abstract Low shear strength of historical masonry constructions is a matter of great concern, especially when these buildings are located in areas of high seismic risk. In recent years this issue has led to many investigations on the development of innovative reinforcement techniques. The application of cement mortar, commonly used in this type of reinforcements, involves a number of material incompatibility problems that could be overcome with the use of lime-based binder mortars. The present article presents the results of an experimental study on solid mock brick wallets reinforced with thin layers of mortar mixed with glass fibers; Diagonal compression tests have been carried out to determine the behaviour of the reinforced masonries, evaluated both in terms of shear strength and deformation capacity. Test results verify that the coating of mortar mixed with fibers is practically as effective as cement mortar regarding shear strength, while they improve deformation capacity.

Keywords Cement mortar · Mixed mortar · Coating · Glass fibers · Ductility · Historical masonry · Diagonal compression

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1 Introduction

Given the heterogeneity of their constituent materials, brick masonry structures hardly resist tensile stress. In general, their mechanical behaviour is very complex and depends on the mechanical characteristics of the bricks and mortar they are made of. In addition, the conditions under which these constructions were built have a great influence. Brick masonry structures are found worldwide; both in urban and rural areas, some of them belonging to the historical and artistic heritage, often presenting important structural problems because of static and dynamic actions alike.

The recent earthquakes recorded in Southern Europe and in the Middle East (Lorca, Spain 2011; Bam, Irán 2003; Emilia, Italy 2012; Amatrice, Italy 2016) have brought to light the high vulnerability of the existing masonry structures which were designed and built without taking into account a possible seismic action. Consequently, a growing interest has recently emerged towards the development of effective techniques for reinforcing masonry walls. El Gawady et al. [1] presented an exhaustive review of conventional wall reinforcement techniques studied by various authors. These include the application of FRP laminates—glass and carbon—on solid brick [2, 3] and hollow brick [4], external reinforcement with steel plates or tubes [5], use of post-tensile tendons [6], resin mortar injection [7] or wall confinement [8].

Kahn [9] and Hutchison et al. [10] proposed a reinforcement of 80–150 mm thick concrete layers in combination with a conventional steel wire mesh, but this solution brought a great disadvantage, as it modified the structural behaviour of the building due to the weight gain. As an alternative solution, they proposed the application of thinner and 10–50 mm thick lighter layers of cement mortars reinforced with fiberglass meshes [11], carbon fiber meshes [12] and textile meshes [13]. Recently, Messali et al. [14] conducted a series of cyclic tests on masonry walls made with triple hollow bricks and poor mortar cement, applied on both sides of the wall and reinforced with a high performance mortar made of calcium aluminate—25 mm thick—and with electrowelded wire meshes. The outcome supports the effectiveness of the proposed technique, resulting in an improvement of both shear resistance and post peak deformations.

Fiber-reinforced mortars (FRC) are a successful alternative to concrete coatings reinforced with mesh. Sevil et al. [15] reinforced hollow brick walls with a 20 mm thick cement mortar coating with an addition of steel fibers, which resulted in an improvement in terms of strength and deformation. Facconi et al. [16] analysed solid clay brick with poor cement walls reinforced with aluminate calcium mortar with nanosilica—25 mm thick on both sides—and steel fibers anchored with different types of fixings; the experimental results showed that the proposed technique was able to improve the strength and the stiffness of the walls. However, the application of cement mortar on historic masonries involves a series of incompatibilities: excessive strength and rigidity, low permeability and release of soluble salts [17]. The importance of using materials that are compatible with the old ones is well known [18] and aims to maintain as much as possible the properties—chemical composition, porosity, apparent specific gravity, mechanical characteristics and elastic behaviour—both before and after the intervention.

Lime-based mortars have increasingly been used for the purpose of achieving the required compatibility with the original materials. This is way several studies have been carried out in recent years to demonstrate the advantages of the use of lime-based mortars in restoration as an alternative to cement mortars [19–22]. However, these mortars show low strength at an early age as well as a long hardening time. In this context, both the hydraulic lime mortars and the mixed mortars (a combination of air lime and cement), can be an interesting alternative as they are able to combine the advantages of the two materials: air lime can contribute to the workability of mortars, water retention and permeability, guaranteeing compatibility with old mortars, whereas cement can contribute with a considerable strength at an early age and a faster setting time that facilitates its application.

Recent studies on mortars based on hydraulic lime have confirmed that it reduces the risk of incompatibilities with old materials [23, 24], though natural hydraulic lime has a reduced availability compared to Portland cement in many countries [25]. In this context, Silva et al. [26] concluded that mixed air lime and cement mortars have a high potential to replace hydraulic mortars in restoration works, all this considering that the content in cement must be higher than 25% in order to increase the strength at an early age, and less than 50% to minimize the incompatibility risks.

On the other hand, the weak resistance to earthquakes of these buildings is due to, as previously mentioned, several structural deficiencies related to the low tensile strength and fragility of the materials (mortar, brick or stone), which causes a critical shear behaviour [27, 28]. Therefore, the codes and standards of the countries contemplate different parameters that quantify the mechanical behaviour of the masonry under seismic loads, being one of the most important the shear strength under zero normal tension. Eurocode 6 [29], allows to determine the characteristic shear resistance f_{vk0}, either through an estimate using a previously calculated table of values, or through experimental tests on triplets with standard EN 1052-3 [30]. For existing masonry walls, Eurocode 8 [31] suggests the direct determination of this parameter by means of diagonal compression tests and according to specifications ASTM 509-2010 [32] and

RILEM LUMB6 [33]. Several authors have performed diagonal compression tests in the laboratory testing different types of wallets [34–37], but despite the fact that this particular test is widely used, the formulas used to calculate the shear strength according to the specifications of the ASTM and the RILEM have been questioned by several researchers. At present, different formulations can be found in related literature, that allow different interpretations of the results [38, 39].

Although the reinforcement of masonry has been extensively researched, there is still a need to develop a technique that may be appropriate and compatible with the reinforcement of historic masonry. This research aims at proposing an alternative and cost-effective reinforcement material to reinforce solid clay bricks masonries and low resistance mortars similar to those that could be found in old buildings. Following the researches carried out by Silva et al. [24, 26], the proposed alternative is a 15 mm thick coating on both sides of the wallet, made of mixed mortar (MMC) and mixed mortar with 0.5% glass fibers (MMCGF). Aerial lime and cement mixed mortars are adequate for their use in restoration works as they have a pore structure and water transport properties more compatible with aerial lime materials used in ancient times. However, in order to make these materials compatible, they have to present a predetermined dosage. The cement content should be higher that 25% so that there is strength increase, but lower than 50% in order to minimize incompatibility risks. Wallets were also reinforced with cement mortars with (CMCGF) and without fibers (CMC), as a comparison with the techniques of "shotcreting" used in recent years. The quantity of fibers added is based on previous tests carried out on different mortars.

In order to assess the structural results provided by this reinforcement technique, an experimental program based on diagonal compression tests of masonry wallets was carried out in the Vilnius Gediminas Technical University Laboratory. The tests have been performed on mock wallets, which have been manufactured as scale models in the laboratory trying to emulate historical masonries using materials as similar as possible to those used in the past. The effectiveness of the reinforcement was evaluated both in terms of shear strength—applying the three formulas available in the literature—and deformation capacity.

2 Experimental programme

2.1 Mechanical properties of the wallet's materials

The experimental process started with the selection of materials. As extracting wall specimens of old buildings is a very "damaging" process, we decided to build in a laboratory the most similar wallets possible to the ones manufactured in ancient times. This type of masonries is characterized for being manufactured with very porous bricks as the firing temperatures were low and the raw material was impure clay; and with aerial lime mortars with a low quantity of binder to decrease costs.

With this objective, a mixed cement and air lime mortar with a low binder dosage (1:1:6) was used. The compression strength and bending of the mortar was determined on 6 specimens according to standard EN 1015-11 [40]. The mean values of compression and flexural strength came out respectively as 5.2 (0.4) and 1.4 (0.1) MPa (coefficient of variation in brackets). Therefore, considering the value of the average compression strength, this mortar can be classified as M5 (according to EN 1996-1-1 [29]).

The used bricks were very porous. The absorption and suction of water from the bricks was measured following EN 772-11 [41]. The nominal dimensions of a solid brick are $250 \times 120 \times 65$ mm^3. The compression strength of the bricks was determined by tests on 6 bricks according to standard EN 772-1 [42]. The results gave an average compression strength of 45 MPa. Due to the high suction of the bricks, before the construction of the wallet, the bricks were submerged and then drained until they presented a saturation appearance with a dry surface, in order to avoid altering the qualities of the mortar because of the excessive suction of the bricks.

2.2 Mechanical properties of coating mortars and application method

Two types of mortar were used in the making of the reinforcement coatings: cement and mixed, with addition in both cases of glass fibers. Additionally, the same mortars but without fibers were studied in order to evaluate the influence of the latter. The materials used were the following:

- Cement CEM II/A-LL 42.5 N according to the specifications of standard EN 197-1 [43], supplied by Akmenes Cementas.
- CL 90-S calcium lime, according to standard EN 459-1 [44], supplied by Lhoist.
- As an aggregate, siliceous river sand, with a size comprised within the 0–2 mm granulometric fraction.
- Added fibers: composed of AR glass (Fibre Eagle).

The different dosages of the mortars are shown in Table 1.

The compression and flexural strength were determined following the above indicated standard, and the resistance to bonding between the mortars and the wallet was determined according to EN 1015-12 [45]. The good adhesion properties of the mortar on the wallets represent an additional benefit when the material is used as an external coating. The mechanical properties of the different reinforcing mortars are summarized in Table 2.

For the characterization of the post-cracking mechanical response of the GFRM material—which depends notably on its tenacity—the fracture energy was determined by adapting the experimental process arranged in the RILEM 50-FMC [46]. Three point bending tests were carried out on $40 \times 40 \times 160\ mm^3$ specimens. The test specimens were loaded at a constant speed of 0.5 mm/min until the end of the test. The load–displacement curve was used to obtain the fracture energy parameter [47]. Results of typical curves are presented in Fig. 1. Graph show brittle behaviour of CMC and CMM mortars while with glass fibre reinforced mortars post-peak behave is ductile. Highest influence of fibres can be seen right after the peak load is reached (for low values of crack width).

To ensure shear strength of interface between masonry and coating additional provisions were taken into account. The coating application procedure was similar in all cases, regardless of the composition of the coating:

- The joints of the wallets were scraped so that they all had a similar thickness of 1 cm that allowed the mortar to penetrate the wallet, thus achieving a better interaction of masonry with mortar coating.
- The surface of the wallets was brushed to remove loose particles of mortar and dust and to improve the adhesion of the coating.
- A layer of mortar ($\sim$ 15 mm) was applied on each side of the wallet, while the surface was kept wet by spraying water. The material was applied in consecutive layers of about 5 or 6 mm each to avoid the detachment of the mortar.
- Finally, in order to mitigate shrinkage cracks, the surface of the coating was kept wet the first 3 days after the test was carried out. The rest of the days, until the test date, the wallets were moistened once a day.

2.3 Mechanical properties of masonry

The uniaxial compression strength of the masonry was determined by tests on $560 \times 520 \times 120\ mm^3$ dimension wallets. They were tested following the standard EN 1052-1 [48], a test that also allows us to calculate Young's modulus. The loading speed was set at 700 N/s. In order to determine the deformations, two linear variable displacement transducers (LVDT) were placed on each side of the wallet parallel to the direction of the load.

The uniaxial shear strength was evaluated following the B procedure indicated in the regulation EN 1052-3 [49]. The test procedure consists of applying

Table 1 Dosages of the mixtures used in the study

Mortar mixtures	Cement (kg/m^3)	Lime (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Fiber volume	
					(kg/m^3)	(%)
CM	400		1800	342	0	0
GFRCM	400		1800	342	13.4	0.5
MM	200	250	1800	393	0	0
GFRMM	200	250	1800	393	13.4	0.5

Table 2 Summary of the results of the characterization tests carried out on the materials used

	Property		Unit	No. test	Mean value	
Brick	Compressive strength	$f_{c,b}$	MPa	6	45	(2.1)
	Water absorption	C	%	6	20	(0.1)
	Suction	$C_{w,i}$	Kg/(m^2 min)	6	1.7	(0.3)
Joint mortar	Compressive strength	$f_{c,jm}$	MPa	12	5.2	(0.4)
	Flexural strength	$f_{t,jm}$	MPa	6	1.4	(0.1)
Masonry	Compressive strength uniaxial	$f_{c,m}$	MPa	3	10.7	(1.04)
	Young's modulus	$E_{m,m}$	MPa	3	6700	(230)
	Initial shear strength	f_{vko}	MPa	3	0.23	(0.03)
Mortar coating	Compressive strength CM (7/21 days)	$f_{c,cm}$	MPa	12	8.5/13.4	(0.9)(1.3)
	Flexural strength CM	$f_{t,cm}$	MPa	6	2.2/2.6	(0.1)(0.3)
	Fracture energy CM	$G_{f,cm}$	N/m	6	41.5	(13.2)
	Adhesion strength CM	$f_{u,cm}$	MPa	5	1.09	(0.20)
	Compressive strength GFRCM	$f_{c,gfrcm}$	MPa	12	8.5/14.4	(0.7)(1.5)
	Flexural strength GFRCM	$f_{t,gfrcm}$	MPa	6	2.4/3.2	(0.3)(0.2)
	Fracture energy GFRCM	$G_{f,gfrcm}$	N/m	6	195.9	(31.6)
	Adhesion strength GFRCM	$f_{u,gfrcm}$	MPa	5	1.51	(0.32)
	Compressive strength MM	$f_{c,mm}$	MPa	12	2.6/3.1	(0.1)(0.2)
	Flexural strength MM	$f_{t,mm}$	MPa	6	0.8/1.1	(0.1)(0.1)
	Fracture energy MM	$G_{f,mm}$	N/m	6	13.3	(3.2)
	Adhesion strength MM	$f_{u,mm}$	MPa	5	0.39	(0.04)
	Compressive strength GFRMM	$f_{c,gfrmm}$	MPa	12	2.7/3.3	(0.1)(0.2)
	Flexural strength GFRMM	$f_{t,gfrmm}$	MPa	6	0.8/1.2	(0.1)(0.1)
	Fracture energy GFRMM	$G_{f,gfrmm}$	N/m	6	17.2	(2.9)
	Adhesion strength GFRMM	$f_{u,gfrmm}$	MPa	5	0.54	(0.03)
Glass fiber	Length		mm		12	
	Density		g/cm^3		2.68	
	Elastic modulus		GPa		72	
	Tensile strength		GPa		1 a 1.7	
	Elongation at break		%		4.3	

Note: Coefficient of variation in brackets

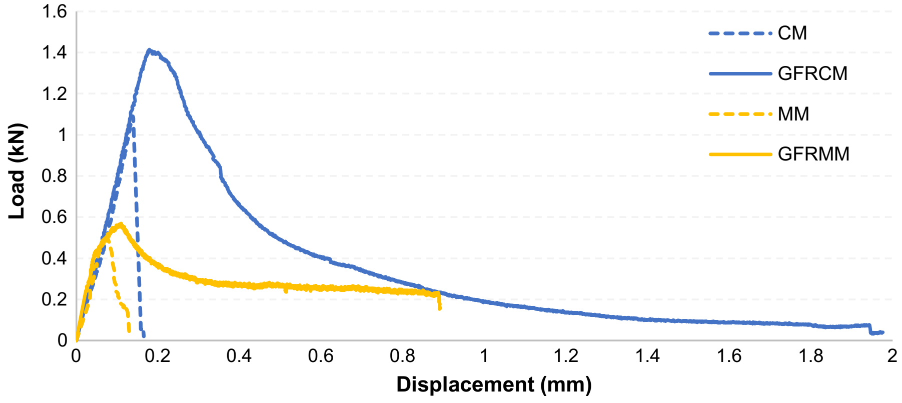

Fig. 1 Load–displacement curves for different kind of mortars

load (50 N/s) on a triplet whose support points are the small sides, without applying lateral pre-compression. By using this procedure, the tests get rather unstable close to the peak strength of the triplets, so the obtained result must be considered an indicative value. The shear failure occurred along the unit-mortar interfaces, with the mortar getting separated from the interior or the exterior brick without damage to the brick surfaces. Consequently, the shear strength depended almost exclusively on the friction behaviour and, in addition, the mortar showed no obvious damage.

2.4 Manufactured wallets

In order to run a wider experiment, a series of walls were built on a small scale. Literature review reviled that similar dimension samples were used by other authors [39, 50] in purpose to investigate the influence of various factors. The test program was built in order to characterise the influence of different type coatings to masonry shear strength and deformations. The dimensions of these wallets were 560 × 520 mm^2, they were made up of 7 rows of two bricks each and had a thickness of 120 mm. Both the horizontal and the vertical joints had a thickness of 15 mm.

In total, 20 single brick wallets were tested, divided into five groups as described in Table 3. Out of each group of four, one specimen (W1) was tested at 7 days, while the remaining three (W2, W3 and W4) were tested at 28 days after the coating was applied.

2.5 Test conditions

A Walter + bai ag model PAC-V-10 machine was used to perform the diagonal compression tests. The wallets were placed between the load cells of the machine, ensuring that the panel was centred and plumb by using two metallic footings manufactured for that purpose and arranged in the two corners of the diagonal coinciding with the direction of the load. One of the metallic footings was placed on the metal frame, and the other, interposed between the upper corner of the panel and the load cell. The purpose of the metal devices was to distribute the load over a larger surface, avoiding the concentration of compression forces and, consequently, local failures in the corners. The application of the load was uniform and was carried out by displacement control to describe the entire loading process. The displacement speed was fixed at 0.005 mm/s until break.

With the purpose of determining the deformation of the wallets, the values of the applied load and of the diagonal displacements were recorded. In order to do so, two variable displacement linear transducers (LVDT) were placed, with $a \pm 25$ mm length, on both lateral sides along the directions of the two diagonals (Fig. 2), calibrating them each time their installation was modified.

2.6 Interpretation of the diagonal compression test

The test specifications are provided in standard ASTM E519-2010 [32] and RILEM LUMB6 [33]. The RILEM code provides information only on the diagonal tensile strength, while the ASTM standard also gives indications on the evaluation of the shear tension section. The main difference is the definition of the voltage field inside the panel, when the latter is subjected to diagonal loading.

According to the ASTM standard, it is assumed that the tension state in the centre of the panel is pure shear tension, and the main directions coincide with the two diagonals of the panels. This state of stress is

Table 3 Summary of the experimental program (specimen, no. of wallets, type, short description)

Specimen	No. of wallets	Type	Description
W-REF	4	Unreinforced	URM wallet without strengthening coating
W-CMC	4	Strengthened	URM wallet strengthened with 15 mm cement mortar- coating
W-CMCGF	4	Strengthened	URM wallet strengthened with 15 mm cement mortar with 0,5% glass fiber (GFRCM) coating
W-MMC	4	Strengthened	URM wallet strengthened with 15 mm mixed mortar coating
W-MMCGF	4	Strengthened	URM wallet strengthened with 15 mm mixed mortar with 0,5% glass fiber (GFRMM) coating

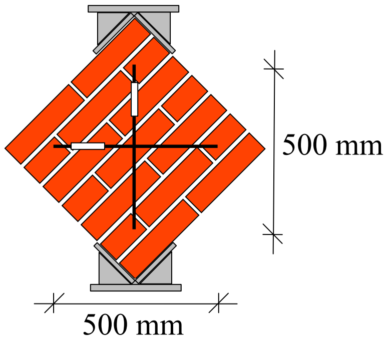

Fig. 2 Position of the displacement linear transducers (LVDT)

adequately represented by the Mohr circle shown in Fig. 3a.

Under these conditions, the shear stress (τ_0) is equal to the main traction (σ_t), and was determined using the following equation:

$$\tau_0 = \sigma_t = \frac{0.707P_{ult}}{A_n} \quad (1)$$

where P_{ult} is the maximum load that it supports in a wallet, and A_n is the net cross section of the wallet, determined as the average of the width and height of the sample multiplied by its thickness.

In the experimental analysis the angular deformation γ was also evaluated:

$$\gamma = \frac{\Delta V + \Delta H}{g} \quad (2)$$

where ΔV = diagonal shortening, ΔH = diagonal extension, and g = gage length. The RILEM standard interprets the results in a different way, considering the masonry wallet as if it were an isotropic and homogeneous material and executing a linear elastic analysis: the state of tension in the centre of the wallet

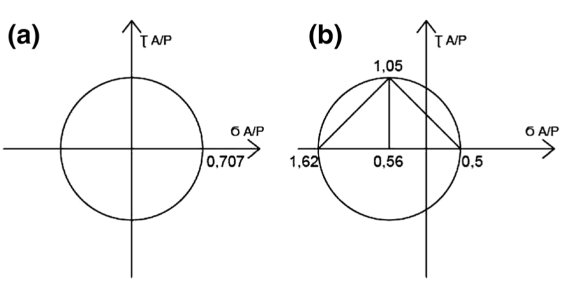

Fig. 3 Interpretation of the diagonal compression test according to the ASTM standard and the RILEM code, for the representation of the Mohr circle

is not a pure shear tension state, however, the main directions still coincide with the two diagonals of the panels. The Mohr circle related to this tensional state is represented in Fig. 3b.

This interpretation gives the values of the main stress state located in the centre of the panel as:

$$\sigma_I = 0.5\frac{P}{A_n} \quad (3)$$

$$\sigma_{II} = -1.62\frac{P}{A_n} \quad (4)$$

According to this interpretation, it is possible to evaluate the tensile strength (σ_t) of the masonry by:

$$\tau_0 = \sigma_t = \frac{0.5P_{ult}}{A_n} \quad (5)$$

Whereas using the formulation of Turnšek and Čačovič [51], the shear strength (τ_0) of a diagonal compression test is given by:

$$\tau_0 = \frac{\sigma_t}{1.5} = \frac{P_{ult}}{3A_n} \quad (6)$$

3 Results

The results obtained after the tests were analysed using the different interpretations provided in the literature (Sect. 2.5), showing substantial differences among the obtained values, as can be seen in Table 4 below.

It should be noted that for the uncoated wallets that were tested, the shear strength value determined by the diagonal compression test using formula (5), is the closest to that calculated by the triplet test and to those tabulated in Eurocode 6, where the values of the term f_{vko} are estimated according to the type of mortar and masonry. Similar results appear in [34].

The masonry wallets tested showed two different types of breakage: cracks developed along the direction of the load (denoted by "D") (Fig. 4), and cracks developed along a non-diagonal direction—named with "ND"—(Fig. 5). In the latter case, the failure occurs because the load exceeds the tensile strength—adhesion—of the joint mortar. However, it cannot be excluded that the tension distribution before failure corresponds to the model described in Sect. 2.5.

It can be observed that the failure mode "ND" has only occurred in the uncoated wallets (W–R). The

Table 4 Results of the diagonal compression tests

Break date	Specimen code	Maximum load (N)	Relative deformation		Angular deformation	Shear strength (MPa)			Failure mode
			Horizontal	Vertical		Equation (1)	Equation (5)	Equation (6)	
7 days	W1-REF	48,950	0.0008	− 0.0020	0.0029	0.534	0.378	0.249	ND
	W1-CMC	101550	0.0011	− 0.0023	0.0034	0.871	0.616	0.406	D
	W1-CMCGF	114,280	0.0016	− 0.0038	0.0054	0.993	0.702	0.463	D
	W1-MMC	71,550	0.0011	− 0.0030	0.0040	0.625	0.442	0.292	D
	W1-MMCGF	76,800	0.0023	− 0.0032	0.0055	0.664	0.470	0.310	D
28 days	W2-REF	50,970	0.0011	− 0.0022	0.0033	0.556	0.393	0.260	ND
	W3-REF	57,870	0.0011	− 0.0029	0.0040	0.631	0.447	0.295	ND
	W4-REF	52,240	0.0004	− 0.0016	0.0020	0.561	0.396	0.262	ND
	Average	53,690	0.0009	− 0.0022	0.0031	0.583	0.412	0.272	
	W2-CMC	144,970	0.0034	− 0.0055	0.0089	1.254	0.887	0.585	D
	W3-CMC	160,920	0.0006	− 0.0029	0.0035	1.394	0.986	0.651	D
	W4-CMC	163,940	0.0017	− 0.0046	0.0063	1.427	1.009	0.666	D
	Average	156,610	0.0019	− 0.0043	0.0062	1.358	0.961	0.634	
	W2-CMCGF	177,740	0.0020	− 0.0064	0.0084	1.537	1.087	0.717	D
	W3-CMCGF	186,230	0.0028	− 0.0050	0.0078	1.611	1.139	0.752	D
	W4-CMCGF	166,500	0.0015	− 0.0043	0.0058	1.447	1.023	0.675	D
	Average	176,820	0.0021	− 0.0052	0.0073	1.531	1.083	0.715	
	W2-MMC	142,380	0.0012	− 0.0032	0.0043	1.243	0.879	0.580	D
	W3-MMC	143,360	0.0016	− 0.0043	0.0059	1.246	0.881	0.581	D
	W4-MMC	138,000	0.0021	− 0.0128	0.0149	1.193	0.844	0.557	D
	Average	141,250	0.0016	− 0.0068	0.0084	1.227	0.868	0.573	
	W2-MMCGF	171,300	0.0014	− 0.0045	0.0059	1.481	1.048	0.691	D
	W3-MMCGF	165,320	0.0029	− 0.0049	0.0078	1.436	1.016	0.670	D
	W4-MMCGF	186,200	0.0026	− 0.0133	0.0159	1.610	1.139	0.752	D
	Average	174,270	0.0023	− 0.0075	0.0098	1.509	1.067	0.705	

maximum load values registered for this group of wallets are significantly lower than those registered in coated wallets, while the shear strength values are also lower.

Figure 6 shows a diagram with the average values of the shear strength using the Turnšek and Čačovič formulation and of the angular deformation, of each of the studied wallets, in order to facilitate the comparison between the effectiveness of the different techniques. The experimental results obtained prove that the brick wallet shear strength values depend on the type of coating. The value of the shear strength of the wallet covered with cement mortar is superior to that of the covered with mixed mortar, while the values obtained in the wallets coated with fiber-reinforced mortars are superior to their non-fiber counterparts.

The shear strength of the coated wallets at 7 days (Fig. 7), is higher than that of the uncoated wallets by 63% when the coating is cement mortars without fibers, and by 86% if it has fibers, whereas if the wallets are covered with mixed mortar, the increase in shear strength is 17% higher when it has no fibers and 24% when it has them. The wallets covered with mortars with fibers have higher strengths than their reference counterparts by 14% when it comes to cement mortars, and by 6% when they are mixed.

For the wallets tested at 28 days (Fig. 8), in comparison with the wallets without coating, the shear strength is 133% and 163% higher when the coatings are made of cement mortar without and with fibers respectively, while in the case of mixed mortars, they are superior by 111% and 159%. The wallets covered with fiber-reinforced mortars have higher

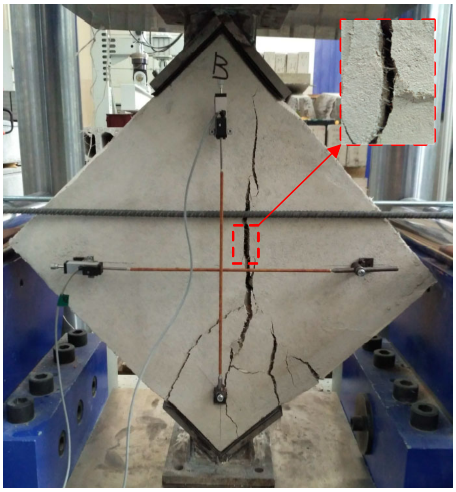

Fig. 4 Diagonal compression test: failure mode D

Fig. 5 Diagonal compression test: failure mode ND

strengths than their reference counterparts by 13% when it comes to cement mortars and 23% when they are mixed.

The maximum angular deformation values show a similar behaviour, with the coated wallets having greater deformation capacity than the uncoated wallets. However, mixed mortars present a deformation capacity superior to that of cement mortars.

The angular deformation of the coated wallets at 7 days (Fig. 7), is higher than that of the uncoated wallets by 18% when the coating is made of cement mortars without fibers, and 87% when it has fibers, whereas if the wallets are covered with mixed mortar, the increase in angular deformation is 41% higher when it does not include fibers, and 92% when it has them. The wallets covered with fiber-reinforced mortars have higher angular deformations than their reference counterparts by 59% when it comes to cement mortars, and 36% when they are mixed.

For the wallets tested at 28 days (Fig. 8), the angular deformation is 101% and 137% higher when the coatings are composed of cement mortar without and with fibers respectively, while in the case of mixed mortars they are higher by 171% and 218%. The wallets covered with fiber-reinforced mortars have higher angular deformations than their reference counterparts by 18% when it comes to cement mortars, and 17% when they are mixed.

Comparing the results obtained at 7 and at 28 days, we observe a higher evolution of the values of the shear strength, together with a maximum angular deformation, in the mixed mortars in comparison with the cement mortars. The reason behind this is that the aerial lime used in the mixed mortar (55% of the binder's total) shows low strengths at early stages. Over the course of the days, the mixed mortar improves its features showing more homogeneous and consistent results. It is also observed, that the evolution of these values in the uncoated wallets is considerably lower than that suffered by the coated wallets: below 10%.

The shear strength-relative deformation diagrams (Figs. 9, 10) show the post-cracking behaviour of the different wallets tested at 7 and 28 days. Wallets reinforced with mortar coating present a sharp reduction of the strengths after reaching the maximum load, showing a quasi-brittle break. However, compared to uncoated wallets, they show a better post-cracking behaviour. In additions, the wallets with fiber-reinforced mortar coatings resist loads for longer periods of time, supporting large deformations (when deformation control test is performed) without detachments in the coating.

Analyzing the results obtained, it can be observed how the reinforcement of masonry wallets using glass fiber-reinforced mortar coatings is effective, as they improve the shear strength, increase the deformation

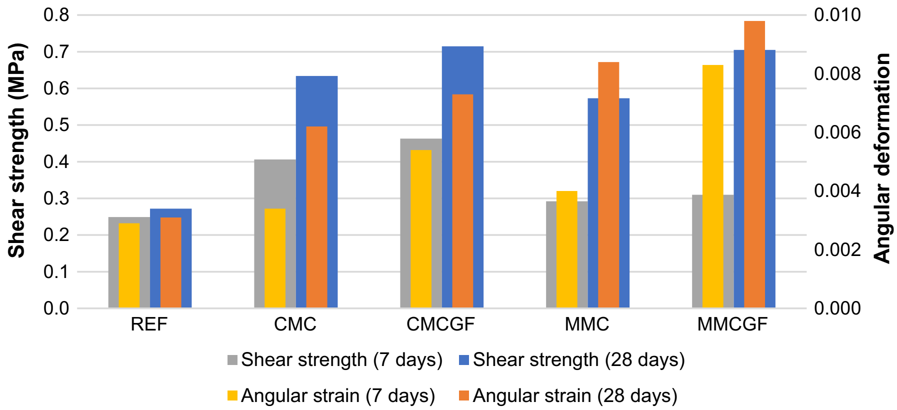

Fig. 6 Average values of the shear strength using the Turnšek and Čačovič formulation and of the angular deformation

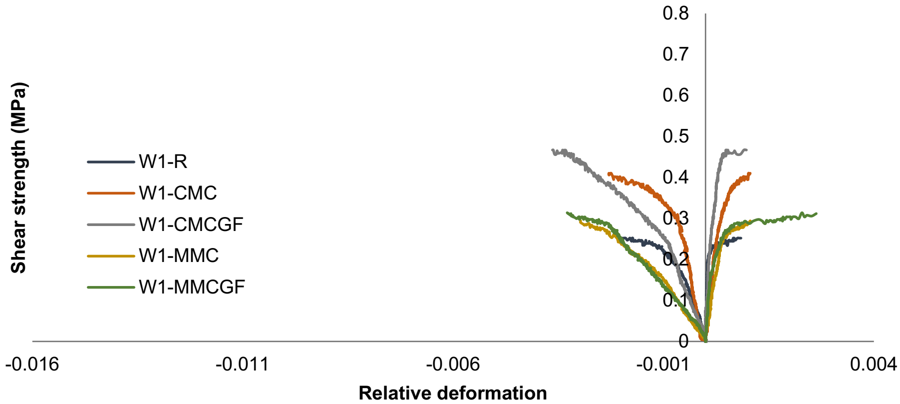

Fig. 7 Shear strength-relative deformation diagram to break (using the Turnšek and Čačovič formulation). Wallets tested at 7 days

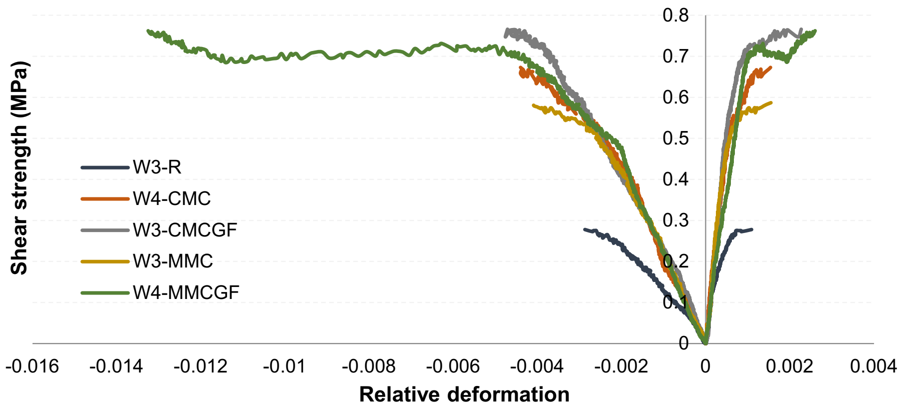

Fig. 8 Shear strength-relative deformation diagram to break (using the Turnšek and Čačovič formulation). Wallets tested at 28 days. *Note*: only the best results for each type of wallet tested are shown in order to facilitate the understanding of the results

capacity until the break and slightly improve the post-cracking behavior, although they do not avoid the brittle failure of the wallet. The results obtained of the wallets with mixed fiber-reinforced mortar coating are specially promising, showing a higher evolution of the values of the shear strength, together with a maximum angular deformation, in comparison with the cement mortars. The use of this type of mortars can be an alternative to reinforce historic masonries, since they have similar results to the cement fiber-reinforced mortars and are more adequate for their use in restoration works as they have a pore structure and water transport properties more compatible with aerial lime materials used in ancient times.

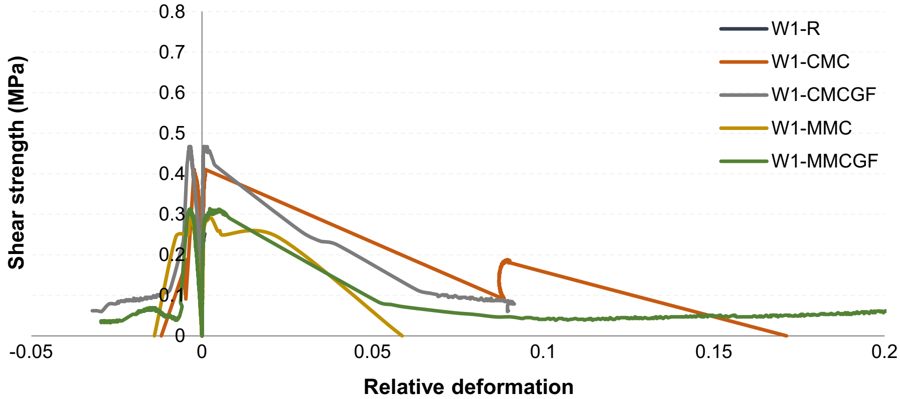

Fig. 9 Post-cracking shear strength-relative deformation diagram (using the Turnšek and Čačovič formulation). Wallets tested at 7 days

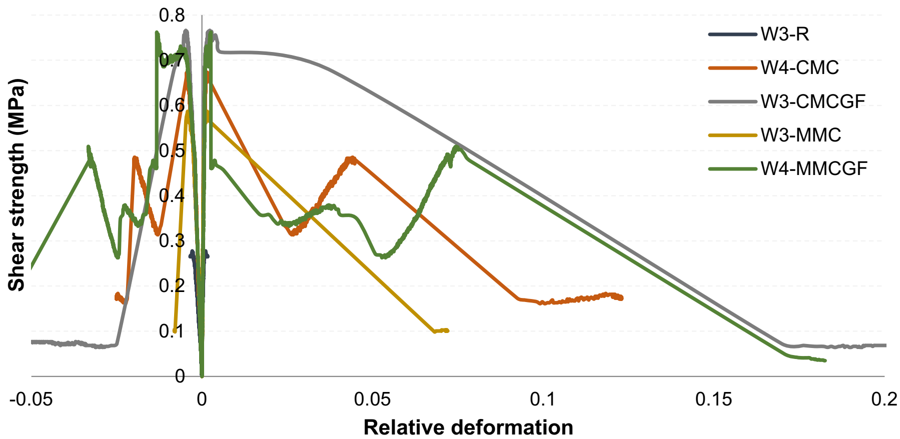

Fig. 10 Post-cracking shear strength-relative deformation diagram (using the Turnšek and Čačovič formulation). Wallets tested at 28 days. *Note*: only the best results for each type of wallet tested are shown in order to facilitate the understanding of the results

4 Conclusions

The present work shows the results of an experimental investigation that aims at evaluating the reinforcement of wallets of solid clay bricks and mortar of low strength using low thickness coatings made of fiber-reinforced mortars. The performance of the reinforced masonry was evaluated in terms of shear strength and deformation capacity. Once the results have been obtained and examined, the following conclusions can be drawn:

- The value of the shear resistance calculated by applying the Turnšek and Čačovič criterion (6) is the closest to that calculated by the triplet test and to the Eurocode 6 tabulations for uncoated wallets.
- The coated brickwork wallets showed a break along the direction of the load, while in the uncoated wallets the break did not follow the diagonal direction.
- The values of maximum load, shear strength and deformation capacity of the uncoated wallets, are significantly lower than those registered in coated wallets.
- The shear strength of wallets reinforced with cement mortars is superior to the one obtained by wallets reinforced with mixed mortars. However, the deformation capacity until the break is superior in wallets reinforced with mixed mortars, compared with its cement counterparts.
- Wallets reinforced with mortars with fibers show better results than their non-fiber counterparts. The shear strength is superior in a 13% when the coating is of cement mortar with fibers and in a 23% when the coating is of mixed mortar with fibers. On the other hand, the maximum deformations until the break are a 18% and 15% superior for the aforementioned mortars.
- Wallets reinforced with mortar coatings present a sharp reduction of the strengths after reaching the

maximum load, showing a quasi-brittle break. However, compared to uncoated wallets, they show a better post-cracking behavior.

- The coating of mixed fiber-reinforced mortar proved to be more effective than the cement mortars, and almost as effective as cement mortar with fibers in terms of shear strength, presenting better results than both in terms of deformation capacity.

In summary, the experimental results discussed in this article show that the reinforcement of masonry wallets using glass fiber-reinforced mortar coatings is effective, as they improve the shear strength, increase the deformation capacity until the break and slightly improve the post-cracking behavior, although they do not avoid the brittle failure of the wallet. The results obtained by the glass fiber-reinforced mixed mortar coatings are specially promising, as they can be an alternative to reinforced old masonries.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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