Shear capacity of masonry walls externally strengthened using Flax-TRM composite systems: experimental tests and comparative assessment

Shear capacity of masonry walls externally strengthened using Flax-TRM composite systems: experimental tests and comparative assessment.

Giuseppe Ferrara

University of Salerno, Dept. of Civil Engineering, via Giovanni Paolo II n.132, 84084 Fisciano (SA), Italy.

e-mail: giferrara@unisa.it

University Claude Bernard Lyon 1, Laboratory of Composite Materials for Construction (LMC2), Site Bohr, 82 Boulevard Niels Bohr, Campus de la Doua, 69622 Villeurbanne Cedex, France.

Carmelo Caggegi

University Claude Bernard Lyon 1, Laboratory of Composite Materials for Construction (LMC2), Site Bohr, 82 Boulevard Niels Bohr, Campus de la Doua, 69622 Villeurbanne Cedex, France.

e-mail: carmelo.caggegi@univ-lyon1.fr

Enzo Martinelli

University of Salerno, Dept. of Civil Engineering, via Giovanni Paolo II n.132, 84084 Fisciano (SA), Italy.

e-mail: e.martinelli@unisa.it

Aron Gabor

University Claude Bernard Lyon 1, Laboratory of Composite Materials for Construction (LMC2), Site Bohr, 82 Boulevard Niels Bohr, Campus de la Doua, 69622 Villeurbanne Cedex, France.

e-mail: aron.gabor@univ-lyon1.fr

Corresponding author: Giuseppe Ferrara; mail: giferrara@unisa.it

ABSTRACT

A growing environmental awareness is gradually changing the entire economic system, and consequently, the building materials sector is increasingly interested in innovative sustainable solutions. The use of plant fibres as reinforcement in inorganic composite systems, generally referred to as Textile Reinforced Mortar (TRM), represents an attractive alternative to the use of most traditional high-strength inorganic fibres, which reduces the environmental impact of the composite. However, there are several unresolved issues regarding the correct mechanical behaviour of such innovative systems. Various studies have been *conducted to assess the fibre-to-mortar bond properties and to investigate the tensile behaviour of TRMs prepared using plant textiles such as flax, hemp, coir, sisal, and jute. Moreover, there is still a lack of experimental evidence concerning the efficiency of the composite material once applied to structural elements. Therefore, this paper reports on an experimental study on the shear capacity of walls strengthened by two TRMs characterised by a different amount of textile reinforcement. The experimental results are discussed and compared by using theoretical models derived from formulations proposed by the standards in this field. This study shows that Flax-TRM reinforcement enhances the strength and ductility of a masonry assemblage, confirming the potential utility of such materials. Furthermore, it points out some limitations of this reinforcement technique and paves the way for future studies to address such problems and improve the efficiency of the entire system.*

KEYWORDS:

TRM/FRCM

Strengthening

Masonry

Plant/natural fibres

Flax

Diagonal Compression Test

HIGHLIGHTS:

Flax textiles are an efficient reinforcement in lime-based composites

Flax TRMs enhance the shear capacity of masonry walls

Flax TRM reinforcement guarantees a post-failure integrity of the wall

1. INTRODUCTION

Recent seismic events occurred in the Mediterranean Area highlighted the need for reducing vulnerability of existing buildings, most of which are made of masonry, typically characterised by significant capacity under gravity loads, but generally unsuited for resisting horizontal loads. In fact, catastrophic seismic events led to both out-of-plain failures and in-plane failure of walls, often due to a lack of shear capacity [1].

Several retrofitting techniques were developed with the aim of increasing the capacity of individual structural elements, and in general, conferring to the entire building a global response per the safety performances proposed by standards. Among these techniques, the use of a class of inorganic composite systems, generally referred to as Textile Reinforced Mortar (TRM), as reinforcement for masonry elements experienced a significant increase in the last decade. Actually, different acronyms were used by the scientific community to define the same kind of inorganic-based composite system characterised by textile reinforcement, e.g., fibre reinforced cementitious matrix (FRCM), textile reinforced concrete (TRC), cementitious matrix grid (CMG), inorganic-matrix grid (IMG), composite reinforced mortar (CRM) [2]. Interest in using TRM composites composed of high-strength fibre textile embedded in a mortar matrix is due to several properties, which make this solution particularly suitable, such as good mechanical performance, discreet fire resistance, permeability, reversibility of the intervention, and compatibility with masonry substrates due to the affinity between the materials adopted [3].

The application of TRM systems has proven to be a versatile reinforcement technique adopted in confinement of masonry members, in-plane and out-of-plane strengthening of walls, reinforcement of arches and vaults, and combined seismic and energy retrofitting [4]. Several studies were carried out to define characterisation methods and to mechanically characterise the response of different TRM systems. The most common applications were characterised by the use of textiles made of high-strength fibres, such as Polybenzoxazole (PBO) [5], carbon [6], steel [7], glass [8], and basalt [9][10]. Particular attention was paid to choosing effective and easily repeatable testing methods capable of determining the relevant mechanical parameters needed to characterise the strength of the system [11][12][13]. Technical recommendations were provided on standardising the procedure of composite characterisation consisting of two main tests: tensile tests of the TRM composite coupons [15] and single-shear tests of the TRM-to-masonry system, also called shear bond tests, in which by transferring the stress from the textile to the substrate, passing through the TRM, it is possible to amplify the weakness of the system primarily due to fibre strength or adhesion issues at the fibre-to-matrix or TRM-to-substrate interface surfaces [16]. However, there are still several uncertainties concerning durability of TRM composite systems, hence several experimental studies were carried out to provide more information about the structural reliability in the long-term [17].

In the United States, guidelines have been formulated on designing retrofitting intervention using TRM and acceptance criteria for masonry and concrete strengthening [18]. Furthermore, in Italy, instructions for both qualifying the materials and designing interventions based on the use of TRM systems were released to regulate the activity of practitioners in the field [19][20].

Experimental investigations were also conducted on a larger scale by assessing the actual capacity of masonry elements strengthened externally by TRM systems. Several tests, often carried out by adopting the diagonal-compression layout, were carried out both in situ and in the laboratory by varying the masonry substrate, TRM composite, and reinforcement configuration, showing that this technique can significantly increase the mechanical behaviour of the masonry elements on which it is applied [21][22][23].

Furthermore, as recognised by the EU research and innovation programme, "Horizon 2020", the need for more sustainable solutions is one of the leading "societal challenges" of our day. Globally, several initiatives were proposed to find alternative materials and technologies, resulting in more sustainable and affordable constructions [24]. The careful selection of constituents has been recognised as the easiest way for designers to meet such sustainable principles when conceiving building projects.

In this context, the use of plant fibres as internal reinforcement in inorganic-matrix composites emerged as a valuable and promising solution [25][26]. Therefore, fibres produced from several plants, such as flax, jute, sisal, coir, hemp, and cotton, were employed as reinforcement in mortar-based composites tested in tension, which showed that the composite system has good potential [27], and is generally characterised by a good bond between fibres and mortar-based matrix [28][29]. Some issues were also highlighted, such as variable results due to the nature of the fibres, and low stiffness values.

The determination of a proper volumetric ratio and impregnation treatment of fibres seems to be a crucial aspect to respond to these issues and achieving mechanical properties comparable to those of synthetic fibre based TRM systems [30][31]. Furthermore, adhesion between plant-fibre-based TRM composites and clay-brick substrate was also investigated to understand whether and to what extent these composite systems can be employed in strengthening masonry walls [32][33]. On a smaller scale, pull-out tests were carried out to analyse the adherence behaviour between single yarns of fibre and organic mortars, cement, or lime-based [34][35], and it was shown that by adopting fibre treatments, such as polymer coating, hornification, and alkali treatments, the bond properties may be improved [36][37].

A few tests were conducted with the aim to assess the mechanical performance of masonry elements reinforcement, either in-plane or out-of-plane, by plant-fibre-based TRMs. The tests showed that these composite systems have significant potential for strengthening masonry structures, but further improvements and optimisations are required [38][39][40][41].

The aforementioned applications confirm that the use of plant fibres as reinforcement in mortar-based composites presents a promising solution for improving the sustainability of the material. However, due to the peculiar mechanical properties of plant textiles (e.g., lower strength and stiffness), some differences in the mechanical behaviour were observed with respect to masonry walls strengthened using conventional TRM systems.

Therefore, further studies are needed to better understand the actual influence of plant based TRMs on the overall mechanical behaviour of structural elements. Specifically, investigating the efficiency of TRM systems to enhance in-plane shear capacity of masonry elements is one of the most relevant objectives, as it plays a fundamental role in the response of masonry structures under seismic excitations. Based on the promising results of previous studies on the mechanical response of sustainable TRMs comprising plant fibres [34][42], the present paper reports an experimental analysis on clay-brick masonry walls externally strengthened using a sustainable TRM composite composed of flax textiles embedded in a hydraulic lime-based mortar. Specifically, these masonry walls were tested under diagonal compression to determine their shear strength without and with the external strengthening of a composite system hereafter referred as Flax-TRM. After describing materials and methods (Section 2), the study reports into details the experimental results (Section 3) and proposes a comparison of the obtained results with analytical models adopted by relevant codes and standards (Section 4).

2. MATERIALS AND METHODS

2.1 Characterisation of the Flax TRM-to-masonry system constituents

The plant textile adopted in this study was a bidirectional flax fabric (Figure 1). It was characterised by filaments ordered in threads, which can be considered as the elementary element of the flax fabric under consideration. The threads defined a mesh such that the interspaces within the grid were large enough (about 3 mm) to allow the mortar to easily penetrate through them. The main physical and mechanical properties of the flax textile are presented in Table 1 [42]. The filament geometry was assessed via SEM image analysis and the thread cross section was indirectly derived from the density estimation.

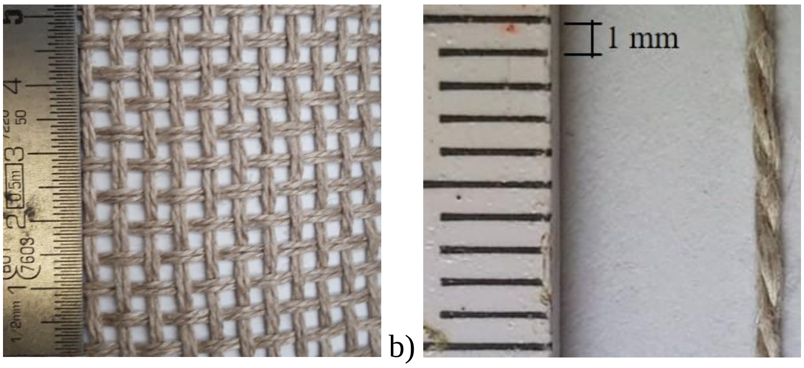
a) b)


Figure 1: a) Bidirectional flax textile; b) Flax thread.

The matrix of the TRM system consisted of a pre-mixed mortar with a natural hydraulic lime binder and selected inert materials with a maximum effective diameter of 1.19 mm (99% of the aggregates < 1.19 mm). It was cast by mixing an amount of water equal to 19% (in weight) of the pre-mixed formula, as recommended by the manufacturer. The mortar grain size distribution curve and its properties in the fresh state were presented in a previous study [34]. The main engineering properties of the mortar are presented in Table 1 and were assessed according to the relevant standards [43] through three-point bending tests on 40 x 40 x 160 mm^3 prisms and compression tests on the two half parts derived from each specimen tested under bending.

Clay bricks 55 mm thick, 120 mm wide, and 250 mm long were employed for preparing the masonry substrate. The bricks were arranged in a monolayer configuration characterised by a single row of bricks in the thickness of one head. The main mechanical properties of the type of brick adopted in this study are presented in Table 1 [44].

The bed and head joints of the masonry, characterised by a thickness of 10 mm, consisted of a low strength hydraulic lime-based mortar specifically designed to be representative of the mortar typically found in existing masonry buildings. It was characterised by the volumetric composition recommended in the Italian Guidelines [45] to reproduce a low strength hydraulic mortar consisting of 2 parts of binder, 4 parts of sand (maximum grain size of 2 mm) and 1.3 parts of water. Table 1 also summarises the mechanical properties of the mortar joints.

Table 1: Main physical and mechanical properties of the Flax TRM-to-masonry system components.

	Unit of measurement	Mean	Co.V. (%)	number of tests
Flax textile				
filament diameter	[mm]	16.78	30	28
density	[g/cm^3]	1.19	3	5
linear density	[Tex]	302	15	5
n° threads/cm	[threads/cm]	4.3	-	-
Thread cross section	[mm^2]	0.25	17	5
Thread Young's Modulus	[GPa]	9.36	11	26
Thread strain to failure	[%]	3.85	13	26
Thread tensile strength	[MPa]	353.72	12	26
Hydraulic lime mortar (matrix)				
flexural strength	[MPa]	3.13	13	18
compression strength	[MPa]	11.13	8	36
Clay bricks				
splitting strength	[MPa]	2.46	11	7
compression strength	[MPa]	17.89	5	12
Hydraulic lime mortar (masonry)				
flexural strength	[MPa]	0.94	20	27
compression strength	[MPa]	4.11	21	54

2.2 Characterisation of the Flax-TRM composite and Flax TRM-to-masonry system.

Two TRM systems were considered in this study. The first one, labelled *Flax-TRM-1L*, consisted of a TRM characterised by a thickness of 5 mm and one layer of reinforcing flax textile, with a fibre volumetric ratio of 2.04%. The second one, labelled as *Flax-TRM-2L*, was characterised by a thickness of 8 mm and two plies of flax fabric overlapping each other via a thin layer of mortar, with a resulting fibre volumetric ratio of 2.55%. Based on RILEM recommendations [15][16], in previous related studies [46][47], the characterisation of the Flax-TRM composite system was conducted via tensile (Figure 2a) and single-shear tests (Figure 3a), for both *Flax-TRM-1L* and *Flax-TRM-2L*. Specimens tested in tension (width of 60 mm, gauge length of 300 mm) exhibited a response characterised by the development of several cracks through the free length. The specimens failed with a rupture of the textile in proximity to a cracked section (Figure 2b). Single-shear tests highlighted that the system comprising Flax-TRM strip (width of 60 mm, bonded length of 260 mm) applied on masonry substrate was characterised by good adhesion at the fibre-to-mortar interface with respect to the tensile strength of the flax textile itself. The failure mode was characterised by a tensile failure of the textile in the free length out of the composite (Figure 3b). The main values of the maximum strength, in terms of load P_{max}, stress with respect to the fibre area, σ_f, and stress with respect to the matrix section, σ_m, are presented in Table 2 [46][47].

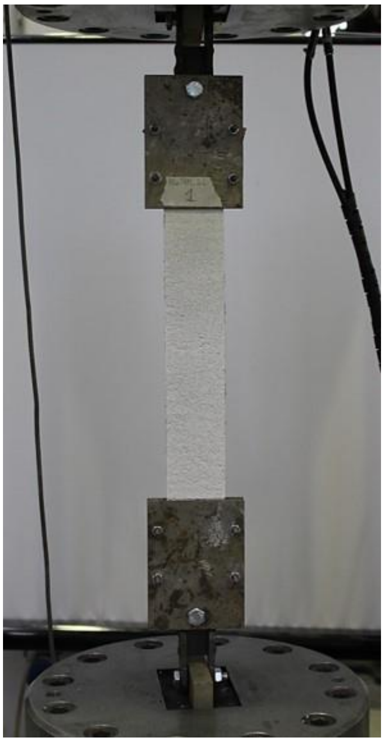
a)  b) 

Figure 2: a) Flax TRM tensile test set-up; b) Tensile test failure mode of Flax TRM system.

a)  b) 

Figure 3: a) Flax TRM-to-masonry single-shear test set-up; b) Single-shear test failure mode of Flax TRM-to-masonry system.

Table 2: Strength of the Flax-TRM system in tensile and single-shear tests.

type of test	type of reinforcement	n° of specimens	P_{max} (kN)	σ_f (MPa)	σ_m (MPa)	Co.V. (%)	Failure mode
tensile	*Flax-TRM-1L*	4	1.25	204.34	4.18	10	textile rupture
tensile	*Flax-TRM-2L*	5	2.43	198.62	5.06	8	textile rupture
single-shear	*Flax-TRM-1L*	3	1.35	220.69	4.50	2	textile rupture
single-shear	*Flax-TRM-2L*	5	2.57	210.06	5.35	1	textile rupture

2.3 Methods

Masonry assemblages externally strengthened by using Flax-TRM systems were subjected to diagonal compression tests with the aim to assess their shear (tensile) strength, achieved as the wall specimen split apart in the direction perpendicular to the direction of load. The tests were conducted at the Laboratory of Composite Materials for Construction (LMC²) of the University Claude Bernard Lyon, 1 France.

Three different series of specimens were considered (Figure 4):

- the first series, labelled *USW*, were characterised by unstrengthened walls and was configured to demonstrate the reference mechanical behaviour;
- the second series, labelled *SW-1L*, were characterised by walls externally strengthened via the *Flax-TRM-1L* system;
- the third series, labelled *SW-2L*, were characterised by walls externally strengthened via the *Flax-TRM-2L* system.

The substrate consisted in a single leaf panels with bricks arranged in the running bond pattern. In both the strengthened series, the reinforcing system was applied uniformly throughout the wall surfaces and symmetrically to both sides of the masonry elements, in line with similar studies in literature where this reinforcement configuration appeared as a valuable solution to enhance the shear capacity of the panels [2].

The installation of the Flax-TRM reinforcing system involved the application of the first layer of mortar on the masonry surface (Figure 5a), the application of the textile by ensuring that it was properly tight and impregnated within the matrix (Figure 5b), the application of the next layer of mortar and possible application of further flax textile layers, and then the application and smoothing of an external layer of mortar (Figure 5c). Table 3 lists the main properties of the three series of specimens considered, including the TRM unit tensile strength, ρ, defined as the maximum capacity in tension of the textile (assessed via tensile tests on 60 mm large flax strips) included in a one-meter wide composite portion.

Figure 6 illustrates the apparatus adopted for conducting the diagonal compression tests. The testing machine, with a maximum compressive load capacity of 500 kN, was equipped with a load cell placed along the loading axis to record load values during the test.

The test was conducted in displacement control at a rate of 1 mm/min. The load was transmitted to the specimen via two loading shoes placed at the two edges of the vertical axis. The loading shoe consisted of a steel device characterised by high stiffness (30 mm of thickness) and a bearing of length 150 mm specifically designed to avoid excessive local stress in the bearing zone and to correspond with the mortar bed joints in the loaded corner of the wall. The loading shoe was connected to the masonry assemblage via a high-strength fast setting cement-based mortar. The walls were instrumented via two linear displacement transducers, with a gage length of 1000 mm, to measure the shortening of the vertical diagonal and the lengthening of the horizontal diagonal under load.

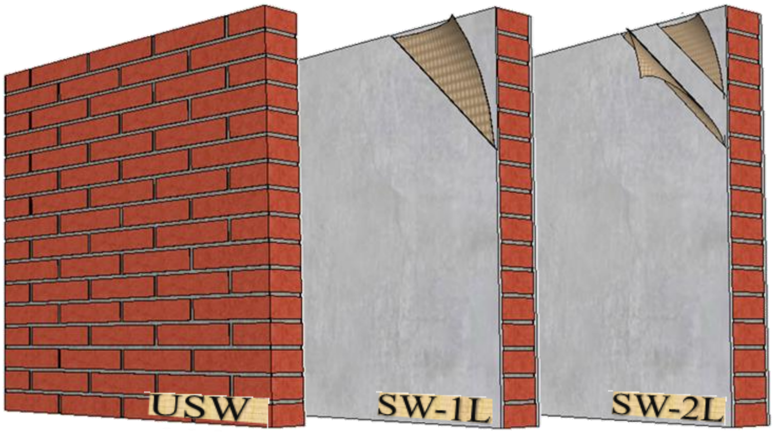


Figure 4: Specimens subjected to diagonal compression test: UnStrengthened (USW), Flax-TRM-1L-Strengthened (SW-1L), and Flax-TRM-2L-Strengthened (SW-2L) walls.

Table 3:Properties of the three series of specimens tested in diagonal compression.

Series	# spec.	masonry type	Wall size t x w x h [mm^3]	Reinf. type	type of mortar	type of textile	TRM thick. [mm]	ρ [kN/m]
USW	3	clay bricks	120 x 1030 x 1030	—	—	—	—	—
SW-1L	3	clay bricks	130 x 1030 x 1030	Flax-TRM-1L	hydraulic lime	Flax	5	31
SW-2L	3	clay bricks	136 x 1030 x 1030	Flax-TRM-2L	hydraulic lime	Flax	8	62

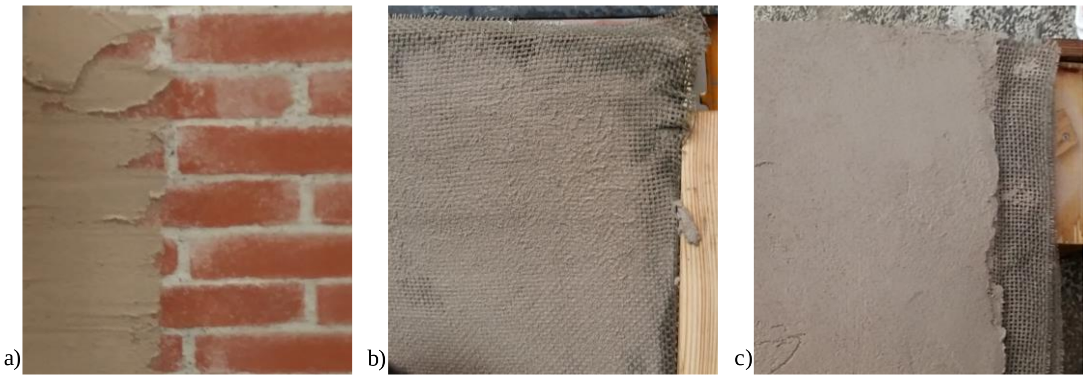


Figure 5: Application of the Flax-TRM system: a) application of the first layer of mortar; b) application of the flax textile and impregnation of the matrix; c) application of the last layer of mortar and smoothing of the surface.

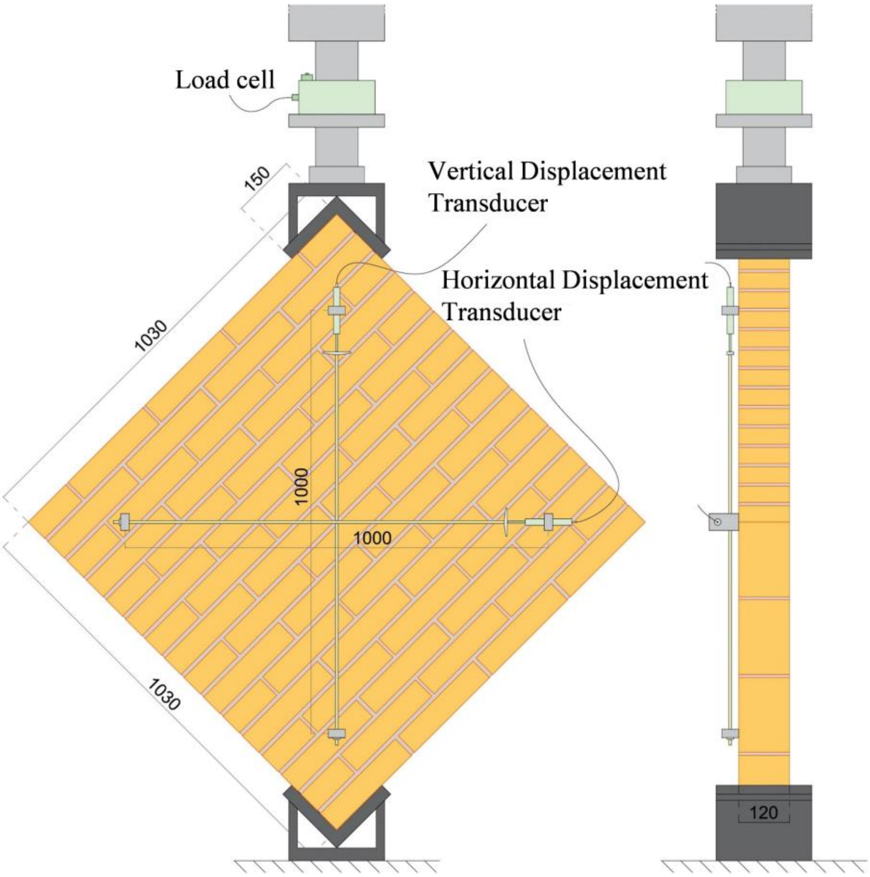


Figure 6: Test set-up of Diagonal Compression Tests.

3. RESULTS AND DISCUSSION

3.1 Shear stress vs shear strain response

The results of diagonal compression tests conducted on the three series of specimens *USW*, *SW-1L*, *SW-2L*, are shown in terms of applied load versus vertical and horizontal displacements (*ΔV* and *ΔH*), respectively. Specifically, the shortening of the vertical diagonal and the lengthening of the horizontal diagonal are represented in Figure 7, 8 and 9.

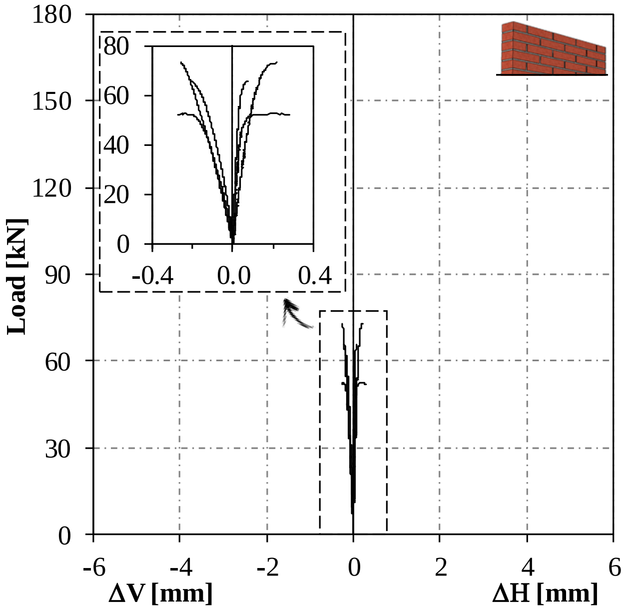


Figure 7: Load-Vertical/Horizontal displacements curves of diagonal compression tests of series USW.

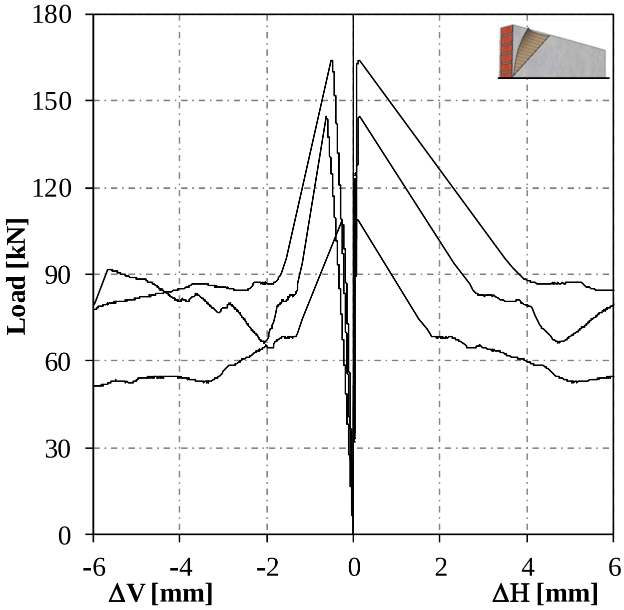


Figure 8: Load-Vertical/Horizontal displacements curves of diagonal compression tests of series SW-1L.

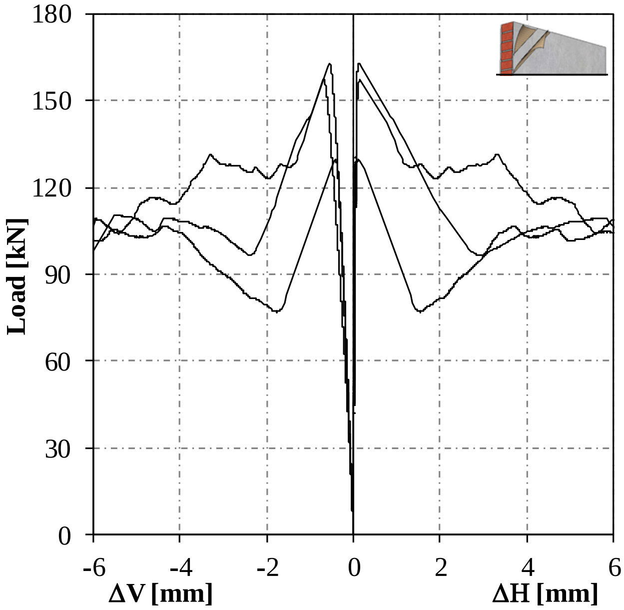


Figure 9: Load-Vertical/Horizontal displacements curves of diagonal compression tests of series SW-2L.

On the basis of the recorded data, load and displacements, the values of the shear stress and the shear strain in the centre of the masonry assemblage can be determined, per the standards governing diagonal compression tests [48]. Shear stress, τ_o, and shear strain, γ, under the hypothesis of pure shear conditions in the middle of the panel, can be respectively determined via Equation 1 and Equation 2:

$$\tau_{o,ASTM} = \frac{P}{\sqrt{2} \cdot A_n} \qquad \textit{Equation 1}$$

$$\gamma = \frac{\Delta V + \Delta H}{L_g} \qquad \textit{Equation 2}$$

where P represents the applied load, A_n, the net transversal area of the specimen (i.e. $An=0.5(w+h)t$ with w the panel width, h the panel height and t the panel thickness [48]), ΔV the vertical shortening, ΔH the horizontal lengthening, and L_g is the gauge length, equal to 1000 mm.

The curves in terms of shear stress, τ_0, and shear strain, γ, for all the series of specimens are plotted in Figure 10, 11 and 12. The behaviour of the unstrengthened specimens, *USW*, was characterised by a pseudo-elastic branch followed by a short plastic branch and a brittle failure of the wall due to the opening of a crack along the vertical direction (Figure 10). The externally strengthened walls, *SW-1L* and *SW-2L*, exhibited an elasto-plastic behaviour as well, up to the achievement of the maximum capacity. Furthermore, in these cases, the end of the elastic phase is due to the development of cracks within the wall and the mortar of the Flax-TRM system in correspondence to the loaded diagonal. The unavoidable geometric inaccuracies deriving from the installation process of the strengthening composite over the wall surfaces, resulted in more scattered results in series *SW-1L* and *SW-2L*. Unlike the *USW* specimens, the reinforced ones exhibited a post-peak phase in which the textile was properly tight and conferred to the system the capacity of bearing significant loads at high values of the displacement. Although a considerable strength loss after the attainment of the maximum load occurred, the implementation of the Flax TRM systems over the masonry assemblages insured the post-failure integrity of wall, as shown by the residual load which is sustained for large values of shear deformation. This aspect, as known, represents a fundamental aspect, especially in view of solutions aimed at improving the structures performance toward horizontal actions. The significant drop of load following the peak is due to the crack opening in the TRM along the vertical diagonal. The crack, starting from the middle of the panel, progressively spread to the edges of the wall. That caused the involvement of larger number of fibre yarns through the entire diagonal cross section, resulting in a hardening residual branch. The next progressive decrease of the load observed corresponds to the gradual failure of the textile bundles in correspondence of the cracks developed along the loaded diagonal.

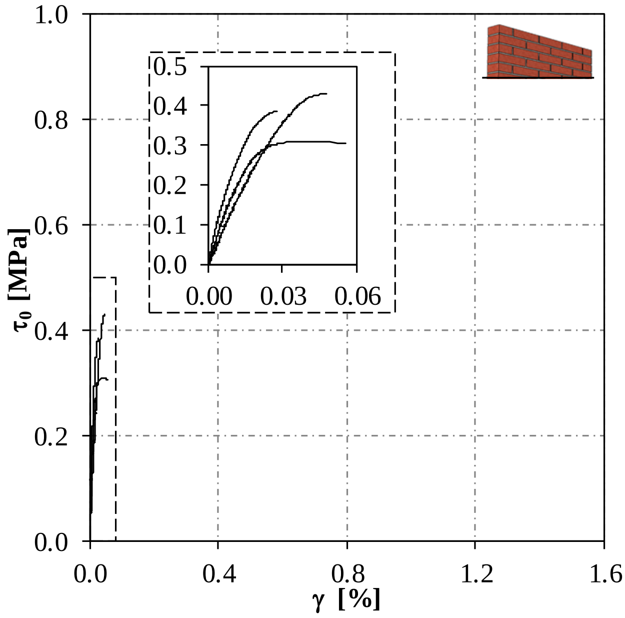


Figure 10: Shear stress – shear strain curves concerning diagonal compression tests of series USW.

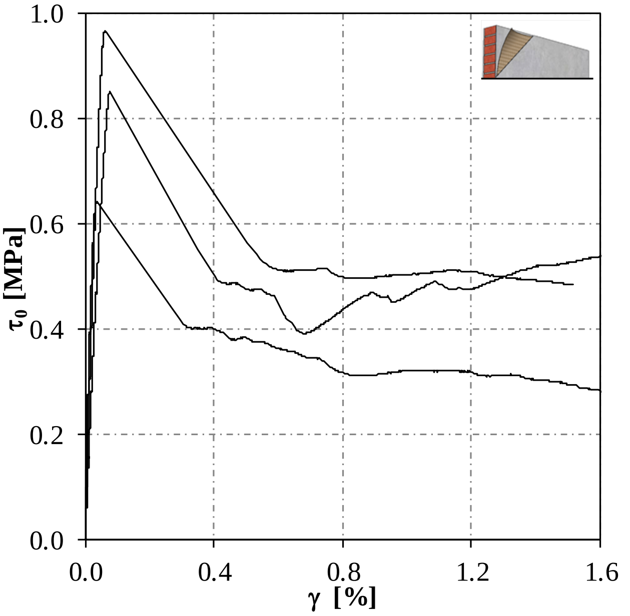


Figure 11: Shear stress – shear strain curves concerning diagonal compression tests of series SW-1L.

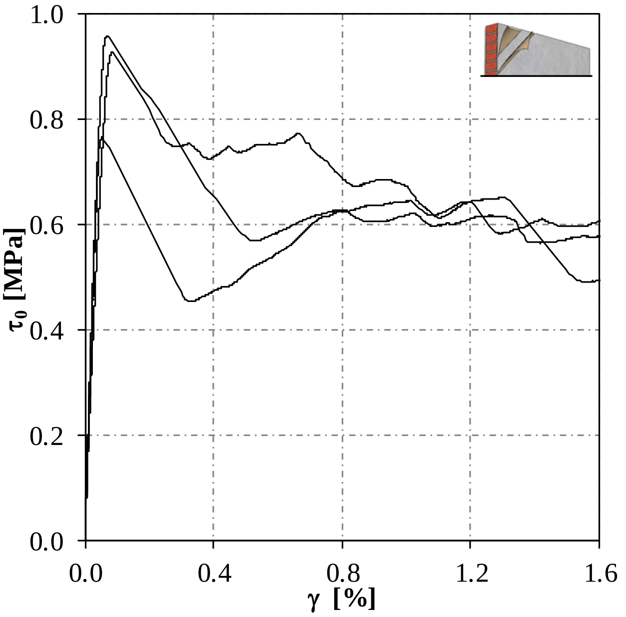


Figure 12: Shear stress – shear strain curves concerning diagonal compression tests of series SW-2L.

The main parameters concerning the diagonal compression tests conducted on the three series of specimens, are listed in Table 4 with respect to the single walls and in terms of mean values for each series together with the corresponding coefficient of variation.

Table 4: Parameters concerning diagonal compression tests conducted on the three series of specimens: USW, SW-1L and SW-2L.

specimen	P_{peak} [kN]	$\tau_{o,peak}$ [MPa]	γ_{peak} [%]	G [MPa]	μ	Γ_1 [J]	Γ_2 [J]
USW-1	66	0.39	0.03	2987	-	9	-

USW-2	73	0.43	0.05	1473	-	11	-
USW-3	53	0.31	0.05	2104	-	11	-
mean	64	0.38	0.04	2188	-	10	-
Co.V.	16	16	27	35	-	11	-
SW-1L-1	164	0.97	0.03	2412	4.25	48	881
SW-1L-2	145	0.85	0.05	1460	3.01	51	1552
SW-1L-3	109	0.64	0.05	3560	4.88	19	1019
mean	139	0.82	0.04	2478	4.05	39	1151
Co.V.	20	20	27	42	23	45	31
SW-2L-1	163	0.96	0.07	2335	3.72	54	1730
SW-2L-2	130	0.77	0.05	1945	3.42	31	2964
SW-2L-3	158	0.93	0.08	2002	4.14	65	3222
mean	150	0.88	0.07	2094	3.76	50	2639
Co.V.	12	12	22	10	10	35	30

In terms of maximum load, P_{peak}, the externally strengthened walls, *SW-1L* and *SW-2L*, gained an average value more than two times higher than the one attained by the unstrengthened walls, *USW*. However, in comparing the two reinforced series, no significant differences are observed, even if the amount of textile reinforcement was doubled in the *SW-2L* series with respect to the *SW-1L* series. As might be expected, the textile did not significantly impact the elastic phase, which was primarily governed by the contribution of the matrix, while the impact of the textile was significant when higher values of the strains were obtained in the post-peak phase with the mortar matrix already cracked.

Similar considerations can be made for the shear modulus *G*, determined as the slope of the shear stress-shear strain curve in the elastic phase (slope of the secant line intersecting the curve at 10% of the maximum shear stress), which did not show any significant change between the three series of specimens.

In all strengthened walls, a significant load loss was observed immediately after the achievement of the peak load. However, this load loss, that was of about the 30% of the maximum load in the case of *SW-1L* specimens, halved in the case of *SW-2L* (about 15% of the maximum load). This aspect emphasised that in the post-peak phase, at higher values of the strain, the contribution of the fibres became significant, and better performance was attained by increasing its amount within the reinforcement system.

The μ coefficient, defined as the ratio of the shear strain value after the peak (corresponding to a loss of the charge of the 20% of the peak load in the post-peak phase) to the value of the elastic shear strain (corresponding to the maximum load), was assumed as a parameter representative of the loss of charge corresponding to the peak load. Unless *USW* specimens, in which an abrupt failure followed the peak load, the strengthened series, *SW-1L* and *SW-2L*, exhibited a mean value of the parameter μ indicating that in correspondence of a loss of charge of 20% the system was capable to show a shear strain about four times the value of the elastic strain corresponding to the peak load (Table 4).

In order to analyse the influence of the textile amount in the post-peak phase, the value of the energy dissipated was determined as the area underlying the load-vertical displacement curve. Specifically, Γ_1 is the energy dissipated to achieve the peak load, Γ_2 represented the energy dissipated during the post-peak phase corresponding to the range between the peak load and a load equal to 30% the peak load. This threshold, although considering the response of the panel at strain values significantly larger than those corresponding to the wall failure, was chosen to get a parameter of comparison between the series of specimens analysed to describe the influence of the textile amount in the post-peak phase. Due to the preservation of experimental tools (LVDT, technical setup), it was not possible to continue the test until a post peak load equal to "0". It was observed that by doubling the amount of flax textile, the mean value of the dissipated energy more than doubled (Figure 13). The analysis of this parameter, in line with the others, confirmed the significant contribution of the textile during the post-peak phase.

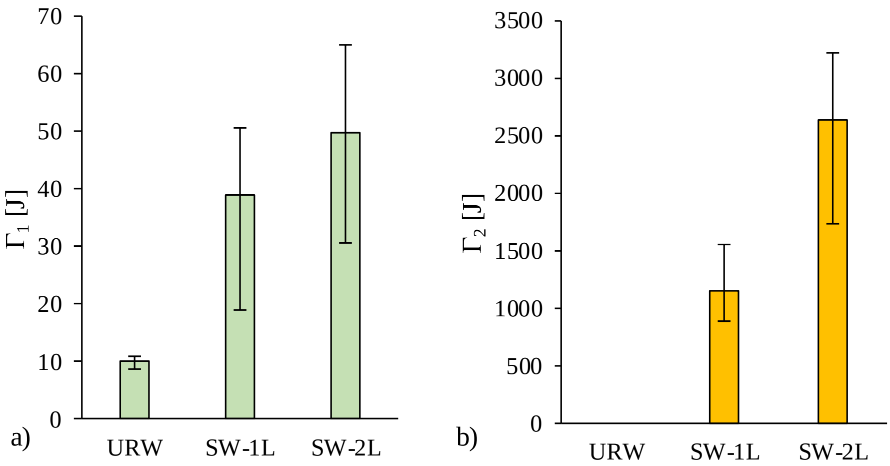


Figure 13: Mean values of the energy dissipated during diagonal compression tests for all series of specimens a) energy dissipated to achieve the peak load, b) energy dissipated during the post-peak phase.

The increase in shear capacity provided by the Flax TRM system investigated, is in line with similar few studies from literature in which plant textiles, i.e. hemp and flax based, were adopted as reinforcement in TRMs for strengthening of masonry panels [41][42]. The cited studies, comprising 9 different series of walls characterised by a unit tensile strength, ρ, varying between 13 kN/m and 54 kN/m, showed a mean value of the maximum shear stress $\tau_{0,peakx}$, varying in the range between 0.50 MPa and 2.13 MPa. The increase of strength in the reinforced panels with respect to the unreinforced walls varied between the values 1.2 and 5.4. In the present study, the two series of strengthened specimens, *SW-1L* and *SW-2L*, respectively comprising a composite system with a unit tensile strength ρ of 31 kN/m and 62 kN/m, showed a maximum shear stress of 0.82 MPa and 0.82 MPa, and an increase of shear capacity of 2.2 and 2.3. It can be asserted that in terms of maximum shear capacity, the results obtained are consistent with similar literature studies.

3.2 Failure mode

As expected, the failure mode was characterised by the development of cracks along the loaded vertical diagonal, due to a stress concentration in correspondence to the tensile principal direction. A brittle failure mode characterised the unreinforced walls, with the splitting of the two parts of the wall via quasi-vertical cracks that primarily followed the mortar bed joints and in some parts broke the clay bricks (Figure 14a). The same crack development trend was observed on the externally strengthened walls in which the cracks spread to the mortar matrix of the Flax-TRM system adopted (Figure 14b). During the post-peak phase, the rupture of the flax threads was observed in correspondence of such transversal cracked surfaces in both the reinforced series of specimens, *SW-1L* and *SW-2L* (Figure 15). This aspect is consistent with what was observed in the characterisation tests on a local scale, tensile and single-shear lap tests, in which in both the cases, the ultimate failure was mainly governed by the tensile capacity of the flax textile (Table 2) [47]. This behaviour, although being due to the relatively low tensile capacity of flax fabric (for instance compared to the more common high-strength fibre textiles), emphasised that the system was characterised by an effective bond between its components, i.e., good properties at both TRM-to-masonry and fibres-to-mortar interface surfaces. Furthermore, this behaviour did not change with an increase in the amount of textile, leaving room for the possibility of further research aimed at improving the global shear capacity of the system by further increasing the amount of textile reinforcement.

In one case (specimen *SW-1L-1*) a local buckling of the reinforcing layer was observed, with a detachment of the Flax-TRM system from the masonry substrate at one of the edges of the wall (Figure 14c). This behaviour, due to its isolated nature, may be attributed to possible inaccuracy of the installation of the TRM composite to the wall.

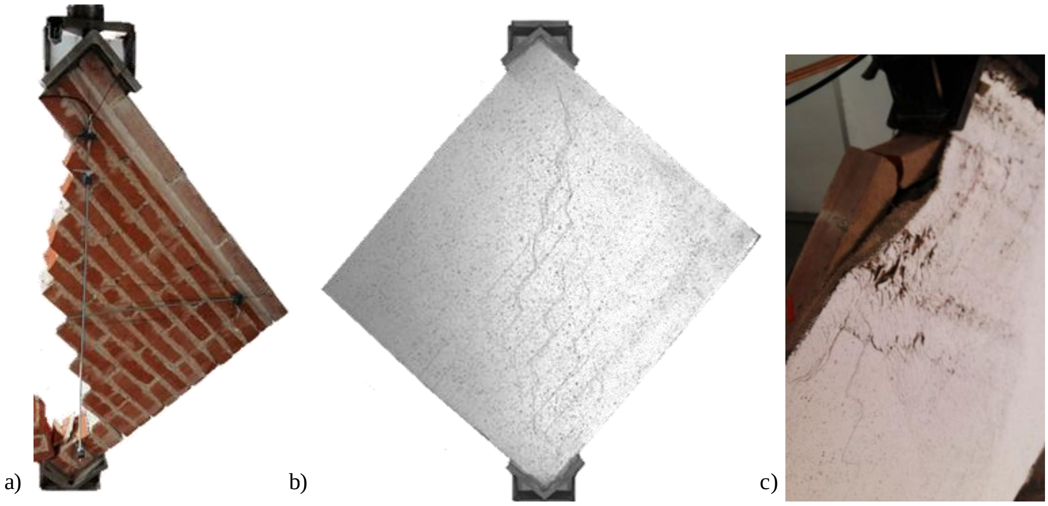


Figure 14: Failure modes: a) USW representative specimen; b) SW representative specimen; c) failure for local debonding (specimen SW-1L-1).

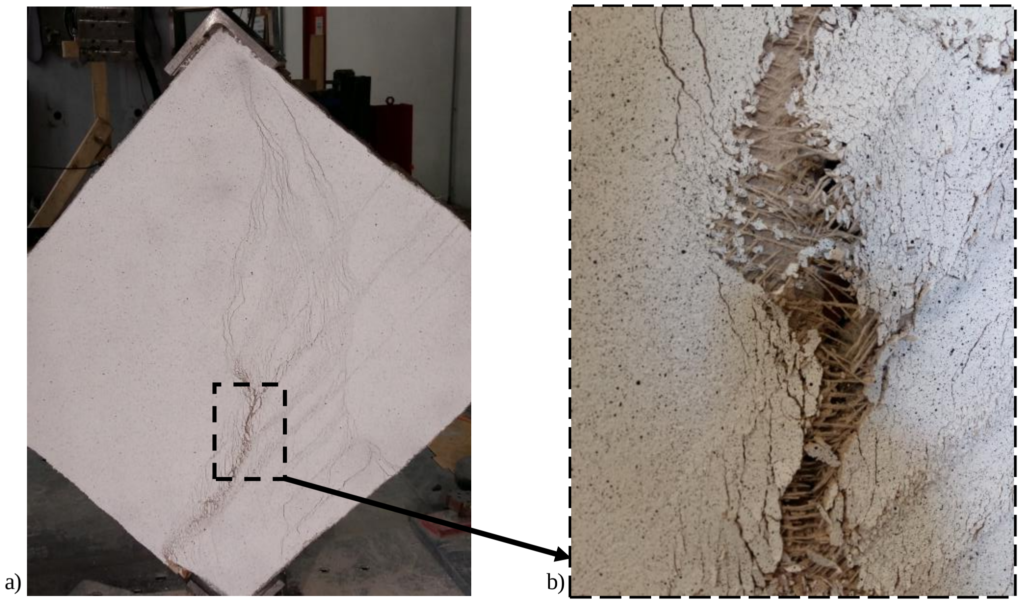


Figure 15: Tensile failure of the flax textile: a) specimen SW-2L-3; b) close-up of the textile rupture.

4. COMPARISON WITH ANALYTICAL MODELS

The aim of this section is to compare the experimental evidence with the strength value obtained theoretically by adopting the formulations proposed by the standards on the assessment of the shear capacity of masonry elements and walls externally strengthened by TRM systems. First, the experimental strength of unstrengthened walls was compared with the strength assessed with respect to the Italian standard NTC 2018 [45], and specifically referring to the section concerning the assessment of the capacity of existing buildings. Secondly, the increase in shear capacity conferred by the TRM composite experimentally observed was compared with the increase evaluated according to the instructions provided by the CNR-DT 215/18 [20] conceived to design such retrofitting interventions.

The models adopted by the standards provided the shear strength of masonry elements in direct shear loading conditions while in this experimental study the capacity of the wall was assessed via diagonal compression tests. Because it was not possible to directly compare the shear capacities, the comparison was done in terms of shear stress attained in the centre of the masonry element, for unstrengthened walls, and in terms of the increment of strength provided by the reinforcement, for strengthened walls.

4.1 Unstrengthened walls

The capacity of unstrengthened walls was expressed in terms of the parameter, labelled τ_0, defined as the maximum shear stress attained in the centre of the panel in pure shear conditions, in the absence of compression stress.

Considering diagonal compression test loading conditions, several approaches are available to determine the shear stress, τ_0. According to the approach followed by the standard ASTM 519-2 [48] considering the element in the middle of the panel, with the axis oriented parallel to the two diagonals with the origin at their intersection, the two principal stresses, oriented along these axes, attain the same value, and the shear stress in the absence of normal stress, $\tau_{0,ASTM}$, can be defined according to Equation 3, where A_n represents the net area of the wall. According to the approach described by RILEM TC-76-LUM recommendations [49], the state of stress in the middle of the panel is the result of an elastic solution considering the wall a homogeneous and isotropic material. Based on that hypothesis, the principal stress in compression and tension assume different values and the shear stress in the absence of normal stress, $\tau_{0,RILEM}$, is determined using Equation 4.

$$\tau_{0,ASTM} = \frac{P_{peak}}{\sqrt{2} \cdot A_n} \qquad \textit{Equation 3}$$

$$\tau_{0,RILEM} = \frac{0.90 \cdot P_{peak}}{A_n} \qquad \textit{Equation 4}$$

It can be assumed that the experimental maximum value of the shear stress in the middle of the panel, with respect to the series of specimens *URW*, is included in range between $\tau_{0,ASTM}$ and $\tau_{0,RILEM}$.

The theoretical value of the shear stress, τ_0, was assessed by taking into account the mean values proposed by the Italian standard code, according to which the strength of the masonry assemblage is assessed based on the mechanical properties of the components of the wall. Specifically, with the mechanical strength of the bricks and the mortar of the bed joints being known, an estimation of the characteristic compression strength of the masonry was done by interpolating values proposed by the standard (Table 11.10.VI of the [45]). A mean compression strength of the masonry equal to 6.3 MPa was computed. As a function of this strength, and considering a masonry typology of solid bricks with hydraulic lime-based mortar, a range of values, $\tau_{0,1} \div \tau_{0,2}$, in which the shear stress is included, was assessed (Table C8.5.I and Table C8.5.II of the [45]).

The range of values in which the shear stress is contained, deriving from both the experimental and theoretical evaluation, are listed in Table 5.

Table 5: Comparison of the shear strength between experimental and theoretical results of unstrengthened walls.

Experimental results			Standard model
$\tau_{0,ASTM}$	0.38	MPa	0.10 MPa < τ_0 < 0.25 MPa
$\tau_{0,RILEM}$	0.48	MPa	

The values of shear stress τ_0 derived from the tests were about 2.5 times the average value assessed via the formulation proposed by the standard code, highlighting that the strength values conventionally used in the design phase guarantee a wide safety margin. This aspect also emphasises that the diagonal compression test does not perfectly guarantee pure shear conditions.

The theoretical shear capacity of the unreinforced wall, under direct shear conditions, was assessed based on the modified formulation of the Turnsek-Cacovic criterion reported in the Italian standard NTC 2018 [45], which in the absence of normal stress takes the following form (Equation 5):

$$V_t = \frac{A_n \cdot 1.5 \cdot \tau_0}{b} \qquad \textit{Equation 5}$$

where A_n represents the net area of the wall defined as the product of the length and the thickness, τ_0 is the shear stress in the absence of normal stress defined as the mean value of the range $\tau_{0,1} \div \tau_{0,2}$ previously assessed, b is a corrective coefficient that takes into account the distribution of the shear stress over the section (in this case assumed equal to 1). The theoretical value of the shear capacity of the unreinforced wall in direct shear conditions, V_t, is equal to 31 kN.

4.2 TRM externally strengthened walls

The increase of strength experimentally observed by applying the TRM system on the masonry elements was compared with the increase in strength that can be theoretically assessed using models proposed by the standards. According to the Italian instructions on designing TRM interventions [19], the shear capacity of masonry elements loaded in their plane, $V_{t,R}$, externally strengthened by TRM systems symmetrically applied to both sides of the wall, uniformly over the entire surface, and preferably with the fibres oriented in both vertical and horizontal directions, is calculated as the sum of the contribution of the unstrengthened wall, V_t, and the contribution brought by the application of the TRM composite system, $V_{t,f}$. The latter can be evaluated via Equation 6.

$$V_{t,f} = 0.5 \cdot n_f \cdot t_{v,f} \cdot b_f \cdot \alpha_t \cdot \varepsilon_{lim,conv} \cdot E_f \qquad \textit{Equation 6}$$

where the product $n_f t_{v,f} b_f$ represents the area of the textile comprised in the cross section of the wall in the direction parallel to its sides (assuming the values of 219 mm^2 for *SW-1L*, 438 mm^2 for *SW-2L*); α_t is a coefficient that takes into account the decrease of tensile test of the fibres when subjected to shear and it is equal to 0.8; $\varepsilon_{lim,conv}$ represents the maximum deformation of the textile superiorly limited by the maximum value attained during the single-lap shear test; E_f represents the dry textile stiffness. In Figure 16, a representative shear bond test response of Flax-TRM-to-masonry substrate system and a representative tensile response of the dry flax textile are compared. These responses, deriving from previous studies ([42], [47]), refer to the Flax TRM systems adopted in the present study (Table 2). According to the procedure proposed by the instructions on designing TRM interventions [19], the strain ε_2, derived from the graphical construction shown, would represent the conventional strain to be used for designing purposes. However, in the instructions, it is assumed the tensile textile response to be linear. In the case of plant fibres, a less stiff branch is typically exhibited at low strain levels, due to the morphology of the fibres at a microscale, and of the textile on a macro scale. Being the stiffness, E_f, determined in the linear branch, it is necessary to define the limit value of the strain, $\varepsilon_{lim,conv}$, as the difference between the strains values ε_1 and ε_2, such that the product between the conventional limit strain and the mean stiffness results to be equal to the conventional limit stress, $\sigma_{conv,lim}$ (Figure 16). The resulting mean values: conventional limit stress, $\sigma_{conv,lim}$, 215 MPa [47]; mean dry stiffness of the textile, E_f, 9.03 GPa [42]; conventional limit strain, $\varepsilon_{lim,conv}$, 2.4%.

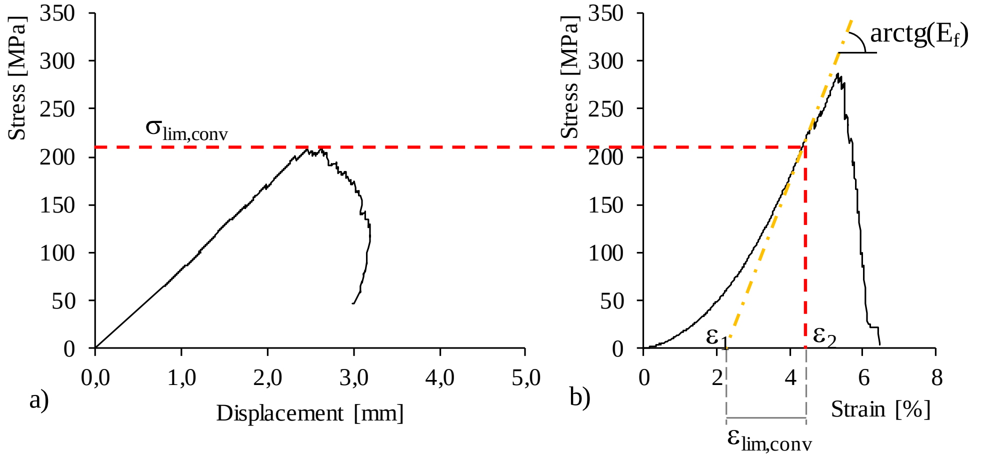


Figure 16: Assessment of the conventional limit stress and strain from the comparison between a representative curve of Flax-TRM-to-masonry single-lap shear test (a) [47], and a representative curve of Flax strip tensile test (b) [42].

Applying Equation 6 to the case of the reinforcement *Flax-TRM-1L* and *Flax-TRM-2L*, considered uniformly applied to both the sides of the wall, it was obtained an increase in strength, $V_{t,f}$, of 19 kN and 38 kN, respectively. It is clear that the theoretical approach proposed by the standards was conceived such that the TRM strength contribution linearly increases with increase in the amount of reinforcing fibre.

The values of the resulting global shear capacities of the TRM externally strengthened walls, $V_{t,R}$, (obtained by summing the contribution of the unstrengthened wall strength, V_t, and the increase in strength provided by the TRM system, $V_{t,f}$) were 50 kN, for the *SW-1L* walls, and 69 kN, for the *SW-2L* walls, respectively. Figure 15 presents the ratio of the strength of the strengthened wall over the strength of the unstrengthened wall.

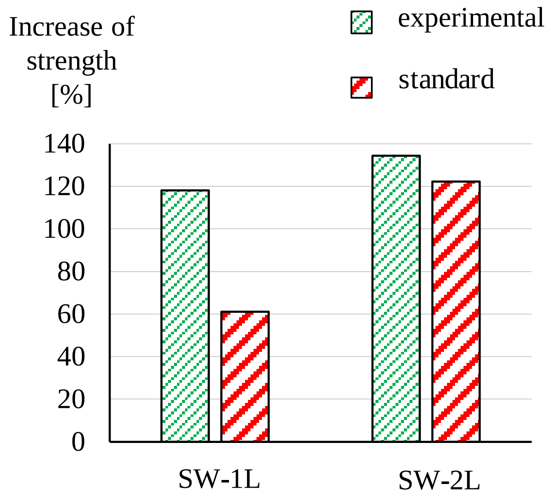


Figure 17: Comparison of the increase in strength derived from standard models and from the experimental campaign for series SW-1L and SW-2L.

It can be observed that in the case of the reinforcement *Flax-TRM-1L* the experimental increase in strength observed is much higher than what was observed by applying the theoretical model of the standard. In the case of SW-2L series, such a difference between experimental and theoretical results decreases. In both cases, the results of the standard model tend to be conservative, providing smaller values of increase in strength. By looking at the increase in strength concerning the reinforcement system *Flax-TRM-2L*, it can be observed that, contrary to what proposed by the standard, the experimental evidence show that the increase in strength was not directly proportional to the increment in terms of fibre textile reinforcement. This discrepancy in the results emphasises that the increase in the fibre mechanical ratio by overlapping different textile plies does not necessarily result in the same increase in strength obtainable with the use of a denser textile grid. Furthermore, it confirms that the textile arrangement plays a fundamental role in the global behaviour of the system, especially in the case of the use of plant fibres, already characterised by issues related to a uniform distribution of the stress between the several fibre bundles due to the unavoidable imperfections of the natural fabric itself.

The approach of the standard seems to consider the maximum capacity of the system coinciding with the tensile failure of the reinforcing grid. However, while a tensile crisis of the fibres characterised the ultimate state, the maximum capacity coincided with the end of the phase when the masonry and the mortar matrix of the TRM system began to crack, but the textile remained unbroken. Although this indicates a discrepancy between the experimental and theoretical results, it also highlights a limit in the standard model that does not consider different failure modes, like the one that occurred in this study. For example, it did not take into account the nature and contribution of the mortar used in the TRM system.

Further analysis aimed at obtaining a more elaborate formulation that would better consider the contribution of all the components of the TRM-to-masonry system may provide a more efficient model capable of better predicting the mechanical behaviour of the entire system. Textile amount, and fibres mechanical properties (stiffness and adherence with the mortar) play a fundamental role in the response of the overall system: massive walls strengthened with TRMs with poor fibre amounts, tend to fail after the achievement of the elastic peak load; slender walls, strengthened by TRM with large fibre amounts, tend to show a hardening post-elastic phase. In order to better predict the shear response, critical values of the fibre amount have to be defined, and in the case of “poor strengthened walls”, the model proposed by the standard need to be enriched with formulations taking into account the failure of the wall in correspondence of the mortar matrix crack.

5. CONCLUSIONS

This study proposes an experimental investigation of the shear strength of masonry walls externally strengthened using Flax-TRM composite systems. Experimental evidences are discussed and compared with the strength values derived using the formulations proposed by standards in the field. The main findings of the research are summarised as follow:

- application of the Flax-TRM system significantly enhances the mechanical response of clay-brick masonry walls tested under diagonal compression, by giving them an increase in shear capacity of 118% in the case of the system characterised by one ply of flax textile (*SW-1L)*, and 136% in the case of the system characterised by two overlapping flax textile plies (*SW-2L)*;
- the failure mode of the walls is characterised by the development of cracks along the loaded vertical diagonal, followed by a gradual rupture of the fibres with the opening of the cracks; no significant debonding phenomena are observed at the interface surface between the TRM and the masonry substrate;
- furthermore, the externally strengthened walls exhibit a post-peak phase, completely absent in the brittle behaviour of the unreinforced walls, underlying the significance of the TRM reinforcement that confers a "pseudo-ductility" to the entire system consisting in a post-failure integrity of the wall;
- no significant differences are recorded in terms of maximum shear stress, $\tau_{o,max}$, between the two series of specimens, *SW-1L* and *SW-2L*. However, in the post-peak phase, the walls externally strengthened using the *Flax-TRM-2L* system exhibit a value of dissipated energy, Γ_2, which is more than two times higher than that exhibited by the walls strengthened by the system *Flax-TRM-1L*;
- in terms of increase of shear capacity, the results provided by the study are in line with similar studies from literature in which plant fibres are adopted in TRM systems for strengthening of masonry elements;
- from the comparison of the experimental results with the models derived from the formulations proposed by standards in the field, as concerning the unstrengthened walls, the shear stress in the absence of normal stress, τ_0, derived from the experimental tests, is much higher than that derived by

applying the formulation of the standards, confirming that the latter provides a substantial safety margin;

- regarding the systems externally strengthened by TRMs it is observed that the increase of strength theoretically defined is conservative compared with the values derived experimentally. Furthermore, unlike the formulation proposed by the standards, in the experimental analysis, the increase in strength is not directly proportional to the increase in the amount of reinforcing fibres.

The study highlights the potential of using plant (e.g. flax) fibres and textiles, as reinforcement in TRM systems to enhance the shear capacity of masonry assemblages. Conversely, it also points out some possible limitations of this technique primarily related to significant loss of charge observed in the post-elastic phase. However, there is still room for improvement, and further studies are needed aiming at providing possible solutions to these issues. In this sense, fibre impregnation processes that allow the grid respond in a more uniform way can be investigated, and parametric studies that vary the amount of textile to achieve higher capacities in the post-peak phase can be conducted.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the company, Innovations srl. for providing the materials tested in the experimental research presented in this paper. The first author's PhD scholarship is awarded by the Italian Ministry for Education, University and Research (MIUR) as part of the programme "Dottorati Innovativi a caratterizzazione industriale" funded by the European Union (Structural Funding ERDF-ESF for Research and Innovation 2014-2020), whose financial support is gratefully acknowledged.

REFERENCES

[1] H. Kaplan, H. Bilgin, S. Yilmaz, H. Binici, and A. Öztas, 'Structural damages of L'Aquila (Italy) earthquake', *Nat. Hazards Earth Syst. Sci.*, vol. 10, n. 3, pp. 499–507, Mar. 2010.

[2] M. Del Zoppo, M. Di Ludovico, and A. Prota, 'Analysis of FRCM and CRM parameters for the in-plane shear strengthening of different URM types', *Compos. Part B Eng.*, vol. 171, pagg. 20–33, Aug. 2019.

[3] C. Papanicolaou, T. Triantafillou, and M. Lekka, 'Externally bonded grids as strengthening and seismic retrofitting materials of masonry panels', *Constr. Build. Mater.*, vol. 25, n. 2, pp. 504–514, feb. 2011.

[4] L. A. S. Kouris and T. C. Triantafillou, 'State-of-the-art on strengthening of masonry structures with textile reinforced mortar (TRM)', *Constr. Build. Mater.*, vol. 188, pp. 1221–1233, Nov. 2018.

[5] C. Caggegi, F. G. Carozzi, S. De Santis, F. Fabbrocino, F. Focacci, Ł. Hojdys, E. Lanoye, and L. Zuccarino, 'Experimental analysis on tensile and bond properties of PBO and aramid fabric reinforced cementitious matrix for strengthening masonry structures', *Compos. Part B Eng.*, vol. 127, pp. 175–195, Oct. 2017.

[6] F. G. Carozzi, A. Bellini, T. D'Antino, G. de Felice, F. Focacci, Ł. Hojdys, L. Laghi, E. Lanoye, F. Micelli, M. Panizza, and C. Poggi, 'Experimental investigation of tensile and bond properties of Carbon-FRCM composites for strengthening masonry elements', *Compos. Part B Eng.*, vol. 128, pp. 100–119, Nov. 2017.

[7] S. De Santis, F. Ceroni, G. de Felice, M. Fagone, B. Ghiassi, A. Kwiecień, G. P. Lignola, M. Morganti, M. Santandrea, M. R. Valluzzi, and A. Viskovic, 'Round Robin Test on tensile and bond behaviour of Steel Reinforced Grout systems', *Compos. Part B Eng.*, vol. 127, pp. 100–120, Oct. 2017.

[8] M. Saidi and A. Gabor, 'Experimental analysis of the tensile behaviour of textile reinforced cementitious matrix composites using distributed fibre optic sensing (DFOS) technology', *Constr. Build. Mater.*, vol. 230, p. 117027, Jan. 2020.

[9] G. P. Lignola, C. Caggegi, F. Ceroni, S. De Santis, P. Krajewski, P. B. Lourenço, M. Morganti, C. (Corina) Papanicolaou, C. Pellegrino, A. Prota, and L. Zuccarino, 'Performance assessment of basalt FRCM for retrofit applications on masonry', *Compos. Part B Eng.*, vol. 128, pp. 1–18, Nov. 2017.

[10] G. Ferrara, C. Caggegi, A. Gabor, and E. Martinelli, 'Experimental Study on the Adhesion of Basalt Textile Reinforced Mortars (TRM) to Clay Brick Masonry: The Influence of Textile Density', *Fibers*, vol. 7, no. 12, p. 103, Dec. 2019, doi: 10.3390/fib7120103.

[11] B. Ghiassi, 'Mechanics and durability of lime-based textile reinforced mortars', *RILEM Tech. Lett.*, vol. 4, pp. 130–137, 2019, doi: 10.21809/rilemtechlett.2019.99.

[12] A. Dalalbashi, B. Ghiassi, and D. V. Oliveira, ‘Textile-to-mortar bond behaviour in lime-based textile reinforced mortars’, *Constr. Build. Mater.*, vol. 227, p. 116682, Dec. 2019, doi: 10.1016/j.conbuildmat.2019.116682.

[13] M. Saidi and A. Gabor, ‘Experimental analysis and analytical modelling of the textile/matrix interface shear stress in textile reinforced cementitious matrix composites’, *Compos. Part Appl. Sci. Manuf.*, vol. 135, p. 105961, Aug. 2020, doi: 10.1016/j.compositesa.2020.105961.

[14] A. Dalalbashi, B. Ghiassi, D. V. Oliveira, and A. Freitas, ‘Fiber-to-mortar bond behavior in TRM composites: Effect of embedded length and fiber configuration’, *Compos. Part B Eng.*, vol. 152, pp. 43–57, Nov. 2018, doi: 10.1016/j.compositesb.2018.06.014.

[15] RILEM Technical Committee 232-TDT (Wolfgang Brameshuber), ‘Recommendation of RILEM TC 232-TDT: test methods and design of textile reinforced concrete’, *Mater. Struct.*, vol. 49, n. 12, pp. 4923–4927, Dec. 2016.

[16] G. de Felice, M. A. Aiello, C. Caggegi, F. Ceroni, S. De Santis, E. Garbin, N. Gattesco, Ł. Hojdys, P. Krajewski, A. Kwiecień, M. Leone, G. P. Lignola, C. Mazzotti, D. Oliveira, C. Papanicolaou, C. Poggi, T. Triantafillou, M. R. Valluzzi, and A. Viskovic, ‘Recommendation of RILEM Technical Committee 250-CSM: Test method for Textile Reinforced Mortar to substrate bond characterization’, *Mater. Struct.*, vol. 51, n. 4, pp. 95, Jul. 2018.

[17] K. Al-Lami, T. D’Antino, and P. Colombi, ‘Durability of Fabric-Reinforced Cementitious Matrix (FRCM) Composites: A Review’, *Appl. Sci.*, vol. 10, no. 5, p. 1714, Jan. 2020, doi: 10.3390/app10051714.

[18] A. C. I. Committee 549, *ACI 549.4R-13: Guide to Design and Construction of Externally Bonded Fabric-Reinforced Cementitious Matrix (FRCM) Systems for Repair and Strengthening Concrete and Masonry Structures*. American Concrete Institute, 2013.

[19] *Linea Guida per la identificazione, la qualificazione ed il controllo di accettazione di compositi fibrorinforzati a matrice inorganica (FRCM) da utilizzarsi per il consolidamento strutturale di costruzioni esistenti*. Consiglio Superiore Lavori Pubblici (Italy), 2018.

[20] CNR-DT 215/2018: *Istruzioni per la Progettazione, l’Esecuzione ed il Controllo di Interventi di Consolidamento Statico mediante l’utilizzo di Compositi Fibrorinforzati a matrice inorganica*. Consiglio Nazionale delle Ricerche – Commissione per lo studio per la predisposizione e l’analisi di norme tecniche relative alle costruzioni (Italy), 2018.

[21] M. Shabdin, M. Zargaran, and N. K. A. Attari, ‘Experimental diagonal tension (shear) test of Un-Reinforced Masonry (URM) walls strengthened with textile reinforced mortar (TRM)’, *Constr. Build. Mater.*, vol. 164, pp. 704–715, Mar. 2018.

[22] Y. Yardim and O. Lalaj, ‘Shear strengthening of unreinforced masonry wall with different fiber reinforced mortar jacketing’, *Constr. Build. Mater.*, vol. 102, pp. 149–154, Jan. 2016.

[23] A. V. Oskouei, A. Jafari, M. Bazli, and R. Ghahri, ‘Effect of different retrofitting techniques on in-plane behavior of masonry wallettes’, *Constr. Build. Mater.*, vol. 169, pp. 578–590, Apr. 2018.

[24] M. Bassani, L. Tefa, B. Coppola, and P. Palmero, ‘Alkali-activation of aggregate fines from construction and demolition waste: Valorisation in view of road pavement subbase applications’, *J. Clean. Prod.*, vol. 234, pp. 71–84, Oct. 2019, doi: 10.1016/j.jclepro.2019.06.207.

[25] F. Pacheco-Torgal and S. Jalali, ‘Cementitious building materials reinforced with vegetable fibres: A review’, *Constr. Build. Mater.*, vol. 25, n. 2, pp. 575–581, Feb. 2011.

[26] C.B. de Carvalho Bello, I. Boem, A. Cecchi, N. Gattesco and D.V. Oliveira, ‘Experimental tests for the characterization of sisal fiber reinforced cementitious matrix for strengthening masonry structures’, *Constr. Build. Mater., vol. 219, pp. 44–45, June 2019*.

[27] B. Ghiassi, A. Razavizadeh, D. V. Oliveira, V. Marques and P. B. Lourenco, ‘Tensile and bond characterisation of natural fibers embedded in inorganic matrices’ 2nd International Conference on Natural Fibers. Conference: Management in Construction Research Association (MiCRA) Postgraduate Conference. Azores, Portougal, 27-29 Apr. 2015.

[28] R. Codispoti, D. V. Oliveira, R. S. Olivito, P. B. Lourenço, and R. Fangueiro, ‘Mechanical performance of natural fiber-reinforced composites for the strengthening of masonry’, *Compos. Part B Eng.*, vol. 77, pp. 74–83, Aug. 2015.

[29] O. A. Cevallos and R. S. Olivito, ‘Effects of fabric parameters on the tensile behaviour of sustainable cementitious composites’, *Compos. Part B Eng.*, vol. 69, pp. 256–266, Feb. 2015.

[30] L. Mercedes, L. Gil, and E. Bernat-Maso, ‘Mechanical performance of vegetal fabric reinforced cementitious matrix (FRCM) composites’, *Constr. Build. Mater.*, vol. 175, pp. 161–173, Jun. 2018.

[31] R. S. Olivito, O. A. Cevallos, and A. Carrozzini, ‘Development of durable cementitious composites using sisal and flax fabrics for reinforcement of masonry structures’, *Mater. Des.*, vol. 57, pp. 258–268, May 2014.

[32] D R. S. Olivito, R. Codispoti, and O. A. Cevallos, ‘Bond behavior of Flax-FRCM and PBO-FRCM composites applied on clay bricks: Experimental and theoretical study’, *Compos. Struct.*, vol. 146, pp. 221–231, Jun. 2016.

[33] R. Codispoti, D. V. Oliveira, R. Fangueiro, P. B. Lourenço, and R. S. Olivito, ‘Experimental Behavior of Natural Fiber-Based Composites Used for Strengthening Masonry Structures’, *Conference Papers in Science*, 2013.

[34] G. Ferrara, M. Pepe, E. Martinelli, and R. Dias Tolêdo Filho, ‘Influence of an Impregnation Treatment on the Morphology and Mechanical Behaviour of Flax Yarns Embedded in Hydraulic Lime Mortar’, *Fibers*, vol. 7, n. 4, pp. 30, Apr. 2019.

[35] S. R. Ferreira, E. Martinelli, M. Pepe, F. de Andrade Silva, and R. D. Toledo Filho, ‘Inverse identification of the bond behavior for jute fibers in cementitious matrix’, *Compos. Part B Eng.*, vol. 95, pagg. 440–452, Jun. 2016.

[36] M. E. A. Fidelis, R. D. Toledo Filho, F. de Andrade Silva, B. Mobasher, S. Müller, and V. Mechtcherine, ‘Interface characteristics of jute fiber systems in a cementitious matrix’, *Cem. Concr. Res.*, vol. 116, pp. 252–265, Feb. 2019.

[37] S. R. Ferreira, F. de A. Silva, P. R. L. Lima, and R. D. Toledo Filho, ‘Effect of fiber treatments on the sisal fiber properties and fiber–matrix bond in cement based systems’, *Constr. Build. Mater.*, vol. 101, pp. 730–740, Dec. 2015.

[38] O. A. Cevallos, R. S. Olivito, R. Codispoti, and L. Ombres, ‘Flax and polyparaphenylene benzobisoxazole cementitious composites for the strengthening of masonry elements subjected to eccentric loading’, *Compos. Part B Eng.*, vol. 71, pp. 82–95, Mar. 2015.

[39] M. R. Valluzzi, F. da Porto, E. Garbin, and M. Panizza, ‘Out-of-plane behaviour of infill masonry panels strengthened with composite materials’, *Mater. Struct.*, vol. 47, n. 12, pp. 2131–2145, Dec. 2014.

[40] C. Menna, D. Asprone, M. Durante, A. Zinno, A. Balsamo, and A. Prota, ‘Structural behaviour of masonry panels strengthened with an innovative hemp fibre composite grid’, *Constr. Build. Mater.*, vol. 100, pp. 111–121, Dec. 2015.

[41] R.S. Olivito, F. Dubois, A. Venneri and F.A. Zuccarello, ‘Experimental and numerical analysis of masonry macroelements reinforced by natural-fibre-composite materials’, *Proc. of the 6th International conference on FRP composites in civil engineering, CICE2012, Jun. 13 to 15*, 2012, Rome, Italy.

[42] G. Ferrara, B. Coppola, L. Di Maio, L. Incarnato, and E. Martinelli, ‘Tensile strength of flax fabrics to be used as reinforcement in cement-based composites: experimental tests under different environmental exposures’, *Compos. Part B Eng.*, vol. 168, pp. 511–523, Jul. 2019.

[43] EN 196-1:1994. ‘Methods of Testing Cement-Part 1: Determination of strength’, *European Committee of Standardization*, Brussels, Belgium, 1994.

[44] G. de Felice, M. A. Aiello, A. Bellini, F. Ceroni, S. De Santis, E. Garbin, M. Leone, G. P. Lignola, M. Malena, C. Mazzotti, M. Panizza, and M. R. Valluzzi, ‘Experimental characterization of composite-to-brick masonry shear bond’, *Mater. Struct.*, vol. 49, n. 7, pp. 2581–2596, Jul. 2016.

[45] NTC 2018. ‘Norme Tecniche per le Costruzioni’, *Ministery of the Infrastractures and Transports of the Italian Republic*, decree 17 Jan. 2018.

[46] G. Ferrara and E. Martinelli, ‘Tensile behaviour of Textile Reinforced Mortar composite systems with flax fibres’, *Proc. of the 12th fib International PhD Symposium in Civil Engineering Aug 29 to 31*, 2018, Czech Technical University in Prague, Prague, Czech Republic.

[47] G. Ferrara, C. Caggegi, A. Gabor, and E. Martinelli, ‘Mechanical Behaviour of Masonry Panels Strengthened by Flax TRM Systems’, *Key Engineering Materials*, vol. 817, pp. 427-434, 2019.

[48] ASTM E519-2: 2003. ‘Standard test method for diagonal tension (shear) in masonry assemblages’, *ASTM Committee C15 on Manufactured Masonry Units,* West Conshohocken, PA, United States, 2003.

[49] RILEM TC-76-LUM. ‘Diagonal tensile strength tests of small wall specimens, RILEM recommendations for the testing and use of constructions materials, pp. 488-9, 1994.