STUDIU COMPARATIV LA COMPRESIUNE PE DIAGONALĂ ÎNTRE MATRICEA CIMENTOASĂ CU PLASĂ DE FIBRE (FRCM) ȘI MATRICEA POLIMERICĂ CU FIBRE (FRP) CARE CĂMĂȘUIESC PEREȚII DIN ZIDĂRIE

FABRIC-REINFORCED CEMENTITIOUS MATRIX (FRCM) VERSUS FIBRE-REINFORCED PLASTIC (FRP) AS STRENGTHENING MATERIAL OF UNREINFORCED MASONRY WALLS SUBJECTED TO DIAGONAL COMPRESSION

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Unreinforced masonry (URM) structures represent a large percentage of the current built stock all around the world. The newly developed textile-reinforced mortar (TRM) composites recently facilitated the improvement of their structural performance. The paper considers the external-bonded TRM as an alternative method for the application of fibre-reinforced polymers (FRP). The effectiveness of TRM overlays is assessed compared to that provided by FRPs. The experimental program consists of diagonal compression tests on a total of five clay brick walls. One wall serves as a reference, the Alkali Resistant-Glass FRCM externally strengthened two walls on one or both sides, and the carbon or glass FRP retrofitted another two walls on one side. The analyzed parameters included the matrix material (mortar versus resin), the type of fibre and the symmetrical or unsymmetrical layout of the reinforcements. The experimental results demonstrate the effectiveness of FRCM on improving the shear strength of the masonry wall.

Structurile din zidărie simplă/ nearmată (URM) reprezintă o componentă importantă a actualului fond construit din întreaga lume. În ultima vreme, îmbunătățirea performanțelor structurale ale acestora a fost facilitată de dezvoltarea mortarelor compozite armate cu fibre textile (TRM). Lucrarea consideră aplicarea TRM pe exteriorul panoului de zidărie ca o alternativă la folosirea polimerilor armați cu fibre (FRP). Eficacitatea cămășuirii cu TRM este evaluată în comparație cu cea dată de cămășuirea cu FRP. Programul experimental constă în încercări de compresiune pe diagonală pe un număr de cinci pereți de cărămidă plină din argilă arsă. Un perete a fost considerat referință, doi pereți au fost armați pe exterior cu plasă din fibră de sticlă rezistentă la mediul alcalin (FRCM) pe una sau ambele fețe, iar alți doi pereți au fost cămășuiți cu polimeri armați cu fibre de carbon sau sticlă pe o singură față. Parametrii analizați au inclus materialul matricei (mortar și rășină), tipul de fibră și dispunerea simetrică sau nesimetrică a armăturilor. Rezultatele experimentale demonstrează eficiența consolidării FRCM în ceea ce privește îmbunătățirea rezistenței la forfecare a peretelui din zidărie.

Keywords: *Unreinforced masonry wall; FRCM; TRM; diagonal compression*

1. Introduction

URM walls exhibit vulnerability when subjected to in-plane loading generally caused by earthquakes or wind [1]. Several factors could determine this weak behaviour: the use of poor-quality materials, their degradation over time, inappropriate construction regulations and, above all, the fact that often these buildings were only designed to withstand gravitational loads [2-4]. Therefore, there is an urgent need to retrofit such constructions [2].

FRP composite are among the most popular materials for strengthening methods, mainly due to their lightweight, significant mechanical strength and ease of application. However, externally-bonded FRPs have some drawbacks. The latter include damp vulnerability, poor adhesion on damp sublayers, unsatisfactory behaviour of the resin at elevated temperatures, lack of permeability, poor bond between rough masonry surfaces and high cost of structural epoxy adhesive products [5 - 7]. Because of these limitations, there has been noticeable research on alternative retrofitting methods. One solution is to replace the FRP with a reinforced cementitious matrix [8].

Accordingly, textile reinforced mortar (TRM) composites or fabric-reinforced cementitious matrix

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(FRCM) have emerged as an alternative external retrofit technique to address the shortcomings associated with FRP composite solutions. The use of TRM strengthening solutions are particularly suited for the retrofitting of heritage structures, where the limited invasiveness and compatibility sides are essential [9].

FRCM represents a composite material that consists of one or more layers of a cement-based matrix reinforced with dry fibres in the form of open mesh fabric. The reinforcement may consist of glass, carbon, basalt or steel fibres [10-12]. The most common matrix is the cement-based, but using hydraulic lime mortar is equally appropriate [13, 14].

Prota et al. [15] conducted experimental studies on tuff masonry externally retrofitted using Carbon and coated AR-Glass FRCM on one or two sides. Walls were tested under diagonal compression to evaluate their in-plane deformation and strength properties.

The experimental results showed that retrofitted walls reached higher shear strength and pseudo-ductility. Papanicolaou et al. [8, 16] presented FRCM as an alternative solution for the strengthening of masonry structures subjected to in-plane and out-of-plane loadings. The experimental results validated the significant improvements in terms of strength capability and overall pseudo-ductility.

During an experimental program on ten URM walls made of clay bricks, the possibility of retrofitting the masonry wall using Glass FRCM was explored [5] considering the influence of various parameters as thickness and number of reinforcement layers. Results confirmed that the TRM layers improve the shear strength and pseudo-ductility, especially for the walls strengthened on both sides. The authors, also studied the effectiveness of using mechanical anchors to prevent the end debonding for various types of TRM systems applied to masonry walls. According to their results, the symmetry in the reinforcing schemes has a positive influence on the ultimate load.

Although previous studies provided valuable research on the strengthening of URM walls using FRCM, more experimental data are needed to assess the effectiveness of the solution. Furthermore, in comparison to the large number of studies on FRP retrofitted structures, investigations on TRM are still in the very early stages.

This paper presents an experimental program performed in the Laboratory of composite structures at the Faculty of Civil Engineering and Building Services, Iași, Romania. URM walls were externally strengthened using two different reinforcing meshes (glass and carbon), and subjected to diagonal compression tests. The results were analyzed in material properties [17] and panels characteristics.

2.Experimental program

The investigation was carried on five 1200 x 1200 x 115 mm URM walls (Table 1). The specimens were manufactured using clay masonry units [18] assembled with a mortar [19] composed of Portland cement and sand, in common proportion and quality for existing traditional URM buildings in Romania.

A professional mason prepared the URM walls to ensure the quality and consistency of construction. The thickness of the mortar joint was about 10 mm. Bricks were saturated with water in advance to prevent further absorption from mortar. The curing process lasted 28 days in laboratory conditions. Specimens were marked down XYRWM where ‘‘X” denotes the number of strengthened faces (1 – single face, 2 – two faces), ‘‘Y” is for the type of textile fabrics (G for Glass fabric and C for Carbon fabric. The subscript ‘‘M” denotes the type of mortar used, while ‘‘RW” stands for reinforced wall.

2.1. Glass FRCM System

The system identification and material testing allowed to find out the mechanical properties of bricks, mortar and masonry units. The dimensions of the clay brick were 240 x 115 x 63 mm [18]. An M5 mortar type [19] was used to construct all the panels. According to EN1015-11 [17], mortar flexural and compression tests were performed at 28 days on mortar prisms and cubes. The average flexural strength was 2 MPa.

Each of the two fractured parts of the prisms that resulted from the flexural tests were subjected to compression at a loading rate of 200 N/s. The experimentally determined compressive strength of the mortar was approximately 4 MPa.

Clay bricks were tested in compression using the Universal Testing Machine PR-500 no.15 based on ASTM C67 provisions [20]. The average compressive strength of the bricks was 12.13 MPa. Also, masonry prisms made of three clay bricks were manufactured and tested in compression according to the provisions of ASTM C1314 [21]. The average compressive strength of the masonry prisms of 8.5 MPa.

A high strength cement-based mortar Sika MonoTop-722Mur was utilized as overlay. The ingredients amount and proportion are compatible with the fibre strand spacing, to enable mortar penetration through the GFRCM mesh openings. The 28-day mortar compressive strength determined by testing 50-mm mortar cube samples under ASTM C109 [22, 23] led to an average of 17.56 MPa. Table 2 summarizes the mechanical properties of the masonry constitutive elements. Similar approach was identified in previous experimental works [24]

Table 1

Strengthening systems / *Sisteme de consolidare [23, 25-31]*

Specimen number	Sample Code	Fiber type	Mortar type	Layout	Chemical anchors
	UW	None	-	-	
W1	$2G_1RW_{M1}$	Sikawrap 350G	SikaMonotop 722	symmetrical	Yes (Connectors)
W2	$1G_1RW_{M1}$	Sikawrap 350G	SikaMonotop 722	Unsymmetrical	No
W3	$1CRW_{M2}$	Sikawrap 230 C	Sika Monotop 910N & Sika Monotop 612	Unsymmetrical	Yes
W4	$1G_2RW_{M2}$	Sikawrap 430 G	Sika Monotop 910N & Sika Monotop 612	Unsymmetrical	Yes

Table 2

The mechanical properties of the constituents of the masonry panels / *Proprietățile mecanice ale constituenților panourilor de zidărie*

Test specimen	standard	No of specimens	Test type	Strength (Mpa)
Mortar for masonry joint	EN 1015-11	3	Flexural test	2
		6	Compression test	4
Mortar for reinforcemen t matrix	ASTM C109	3	Compression test	17.56
	EN 1015-11	6	Flexural test	5.64
Brick	ASTM C-67	2	Compression test	12.13
Masonry Prism	ASTM C1314	2	Compression test	8.5

2.2. Application procedure of the strengthening system

2.2.1. Glass FRCM System

The GFRCM system was applied on two masonry panels. The configurations consist in different types of reinforcement layouts (symmetrical/unsymmetrical) and chemical anchorages.

The FRCM consists of a balanced bidirectional Glass fibre grid with an alkali-resistant coating SikaWrap 350G Grid (Fig.1), embedded between two layers of a high ductility mortar matrix Sika MonoTop-722 Mur.

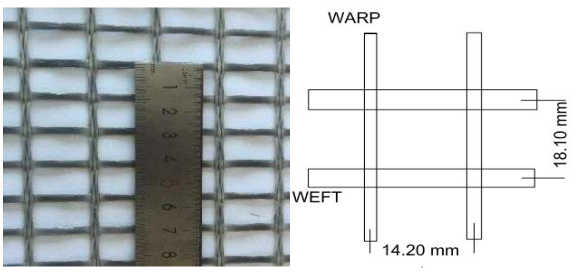


Fig.1 - Geometry of the glass fabric/ *Geometria plasei din fibre de sticlă.*

The overall thickness of the TRM layer is approximately 1cm. The first layer (thickness 5mm) of Sika MonoTop-722 Mur was applied (Fig.2a) to the substrate. Prior to this, the substrate was prepared by sand blast cleaning and wetting. The SikaWrap-350 G Grid was carefully embedded in the first layer of mortar (Fig.2b).

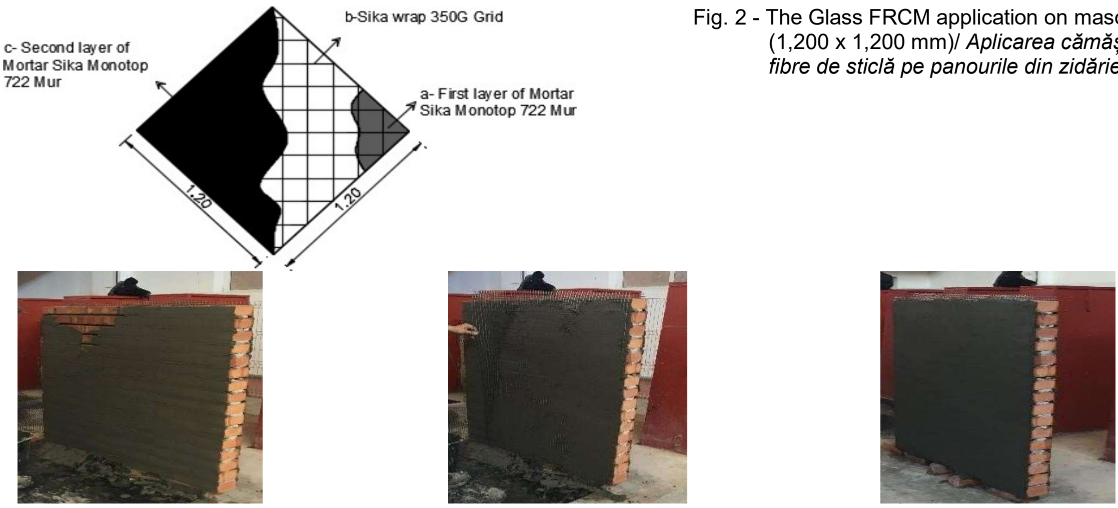


Fig. 2 - The Glass FRCM application on masonry pannels (1,200 x 1,200 mm)/ *Aplicarea cămășuirii armate cu fibre de sticlă pe panourile din zidărie.*

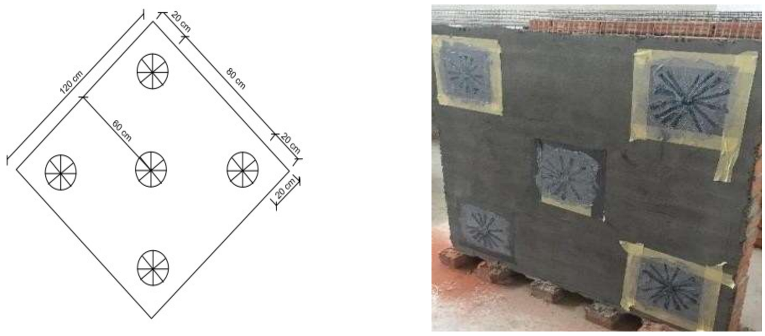


Fig. 3 - GFRCM strengthening system with transversal connectors / *Cămășuire armată, cu ancoraje transversal.*

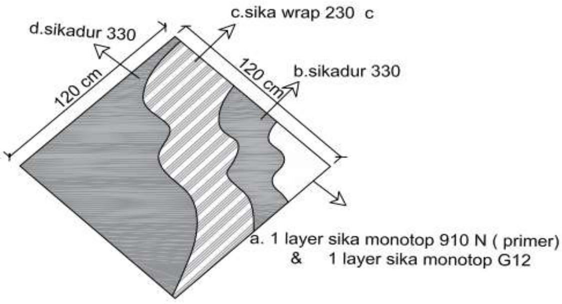
Table 3

Properties of glass fabric reinforcing meshes [24]
Proprietățile plaselor de armare din fibre de sticlă

Characteristics	Unit	Dry Fiber Properties
Fiber orientation	-	Bi-directional
Tensile strength	MPa	2600
Tensile Modulus of Elasticity	GPa	80
Fiber Density	g/cm^3	2.6
Weight per Area	g/cm^3	295

In the last stage, the second layer of Sika MonoTop-722 Mur (layer thickness is 5 mm) was applied (Fig.2c) to completely cover the reinforcement grid.

Fig. 2 presents the geometrical configuration of the GFRCM reinforced URM walls. The AR-Glass fibre grid (Table 3) was extended with 20 mm starting from the panel's edges, to prevent the premature debonding of the exterior layers.



The maximum fabric width is 1m, thus a minimum overlap of 15 cm [24] of Sikawrap 350G Grid was needed to cover the surface of the wall.

Chemical connectors were applied after 7 days from the application of the system (Sika wrap 350G Grid+ Sika Monotop 722 Mur). The connectors consisted of 5 rolled fibres cords (100mm width) inserted into passing-through holes (20mm diameter) purposely drilled in the corners and center of panels (Fig.3), and finally filled with Sikadur 330 [23].

2.2.2.Glass and Carbon TRM systems

Two walls were strengthened on one face using glass and carbon meshes embedded in an epoxy adhesive layer. First 1-layer of Sika Monotop 910N [25] was applied as primer and then, the second layer of Sika Monotop 612 [26] was added (Fig.4a). These products are used to prepare an adequate substrate for SikaWrap- 430G and SikaWrap 230 applications [27, 28].

Fig. 4 - The Carbon TRM system./ *Sistemul de consolidare prin cămășuire armată cu fibre de carbon.*

2.2.3. Diagonal compression test setup

The diagonal compression tests were performed on the PR-500 universal testing machine. The experimental tests were force-controlled at a 5 kN/min loading speed. The loading was transmitted to the wall by means of two steel shoes placed on the diagonally opposite corners. A load cell (Fig.5) installed on the upper loading plate was utilized to record the applied loads. Two linear variable displacement transducers (LVDT's) were set on each face of the walls, one oriented along the compression line and the other in the perpendicular direction along the tension line, to record the wall shortening and elongation in both orthogonal directions.

3.Test results and discussions

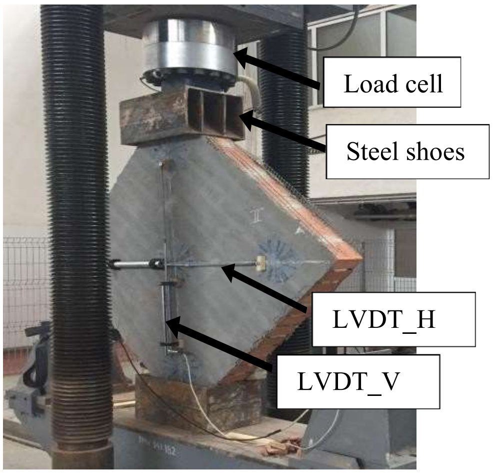


Fig. 5 - The in-plane test setup configuration/ *Schema încercării.*

3.1. Ultimate load

Table 4 presents the test results in terms of ultimate load and shear strength. The results (Fig.6) show a peak load of 21 kN for the control wall, while the peak load for 1G1RWM1 (masonry wall strengthened with GFRCM on one face) was 30 kN. That was about 1.4 times higher than that of the unstrengthen wall. The ultimate loads of the wall reinforced with Glass TRM (1G2RWM2) on one face and those of the wall reinforced with carbon (1CRWM2) were 34KN and 31KN, respectively. The ultimate load for 1CRWM2 and 1G2RWM2 was about 1.42 and 1.48 times higher than that of the unstrengthen wall. The wall reinforced with GFRCM (2G1RWM1) on both faces experienced the highest ultimate load (40 kN), about 2 times higher, compared to that developed for the unreinforced wall.

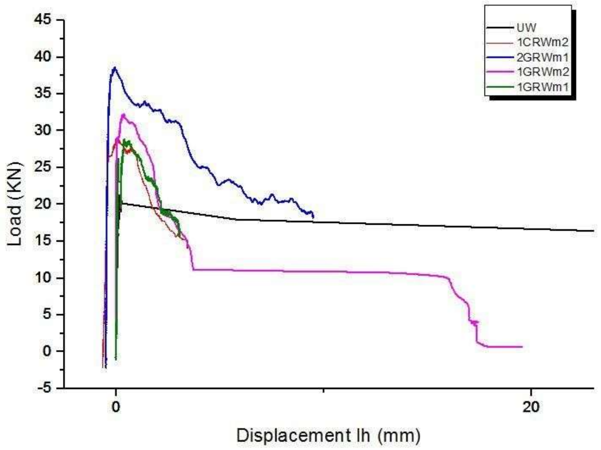


Fig. 6 - Load-displacement diagram, elongation/ *Diagrama încărcare-alungire, elongație.*

Fig. 7 - Failure mode of unreinforced wall / *Modul de cedare al peretelui necămășuit.*

Table 4

Experimental results/ *Rezultate experimentale*

Specimen ID	Maximum Applied load Pu (KN)	Δv (mm)	Δh (mm)	Shear stress (MPa)	Shear strain(mm/mm)	Modulus of rigidity (MPa)
UW	21	0.74	0.16	0.10888	0.00186	58.53
W1	40	0.186	0.143	0.20492	0.0068	30.14
W2	30	1.4784	0.392	0.15369	0.00386	39.81
W3	31	0.006	0.019	0.15881	0.0052	30.54
W4	34	1.1033	0.435	0.17418	0.00517	33.69

3.2. Crack pattern and failure modes

The unstrengthen masonry wall developed a complex failure mechanism consisting in the rupture of both masonry unit (bricks) along the vertical direction and mortar joint.

Furthermore, due to the poor adhesion between bricks and mortar layers, the sample experienced a brittle and sudden failure (Fig.7). This behaviour is illustrated in Fig. 8, where the two linear branches of the curve are very closed.

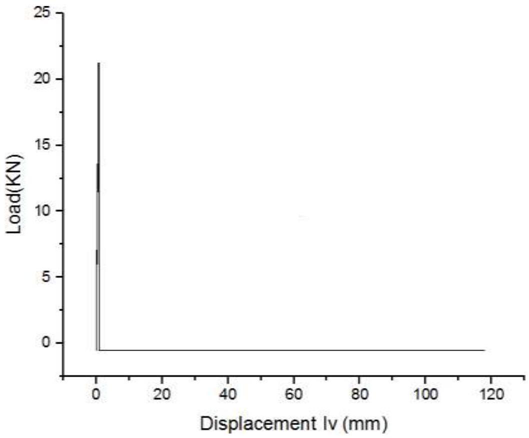


Fig. 8 - UW, Unreinforced wall: Load-displacement diagram / *Perete necămășuit: Diagrama încărcare-descărcare.*

The panel strengthened on one face with Glass FRCM developed multiple cracks along the compressed diagonal. Fig.9 illustrates the characteristic failure mechanism. In this case, the reinforcement came up with a significant increase in the wall shear load capacity and a less brittle failure.

A disruption of the strengthening system appeared in the stress-strain curve (Fig 13.b). The masonry wall worked alone for a while. A relative movement of bricks occurred once the disruption triggered. It means that a relative pushing in the strengthening system produced, and the whole system works together. It develops loading increase because of the higher stiffness of the system that happens again after the disruption.

Also, the horizontal displacement increased faster than expected at higher loading stages for the unstrengthen face compared with the reinforced one.

In case of the wall reinforced with 1-ply of GFRCM on both faces, a fibre tear mechanism was developed, followed by various horizontal hairline cracks along the bed joints (Fig.10). The panel failed when the FRCM system achieved its ultimate strength (Fig.13a). Also, partial delamination was observed on both sides, in the vicinity of the central anchorage.

The results in terms of force and displacements are similar for both faces. After the ultimate load was reached (Fig. 6), a stabilization plateau was developed, and afterwards, the load-bearing capacity decreased progressively.

For the masonry wall reinforced on one face with Glass fibre meshes embedded in an epoxy adhesive layer, multiple diagonal cracks developed on the unstrengthen face. When the ultimate load was reached, suddenly a large vertical crack developed on the reinforced side (Fig.11). Thus, even if this type composite strengthening system can increase the shear capability of the unreinforced masonry, the failure mode remains a fragile one.

For the last configuration, the wall reinforced with Carbon fibre meshes embedded in an epoxy adhesive layer on one face, the failure mode (Fig. 12) consists in a single and continuous diagonal crack on the unstrengthen side. Moreover, consistent delamination of the reinforcement was observed near the edges of the panel and along the compression line.

Fig. 9 - Failure mode of the panel strengthened on one face with GFRCM/ *Modul de cedare a peretelui cămășuit pe o față cu GFRCM.*

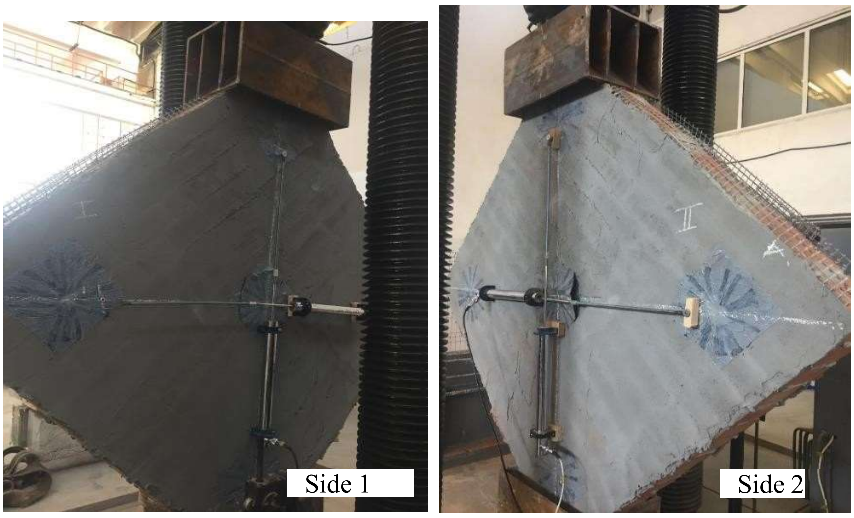


Fig. 10 - Failure mode of the panel strengthened on both faces with GFRCM/ *Modul de cedare a panoului cămășuit pe ambele fețe cu GFRCM.*

Fig. 11 - Failure mode of the panel strengthened on one face with GFRP*/ Modul de cedare a panoului cămășuit pe o față cu GFRP*

Fig. 12 - Failure mode of the panel strengthened on one face with CFRP; (a) reinforced side, (b) Unreinforced side/*Modul de cedare a panoului cămășuit pe o față cu CFRP; (a) partea cămășuită, (b) partea necămășuită.*

3.3. Shear stress-Shear strain diagram

According to ASTM E519/ E519M [29], the shear strength is computed as:

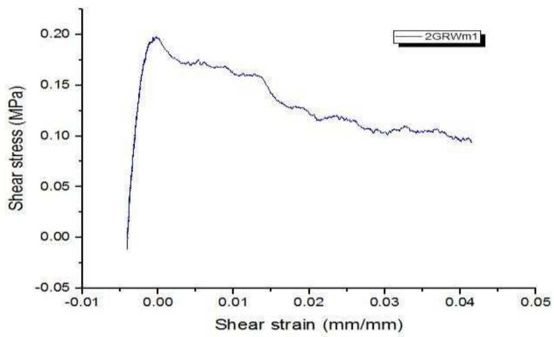
$$\tau_u = 0{,}707\frac{Pu}{An}$$

Where:
Pu = the applied load and
An = the net cross-sectional area of the wall,
$A_n = \frac{w+h}{2}tn;$
w = width of specimen, mm,
h = height of specimen, mm,
t = total thickness of specimen, mm, and
n = percent of the gross area of the unit that is solid.
For this study: An = 138000 mm²

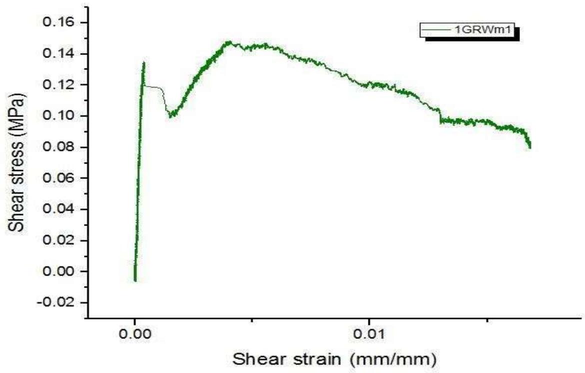
The shear strain is defined as: $\gamma = \frac{\Delta v+\Delta h}{g}$ where ***Δ***v and ***Δ***h [mm] are the vertical and horizontal displacement, measured by the LVDTs installed onto the panel and g is the monitoring length in mm.

The shear modulus of rigidity, "G", equals to τ_u/γ (MPa). Fig.13 illustrates the stress-strain diagrams of the tested panels.

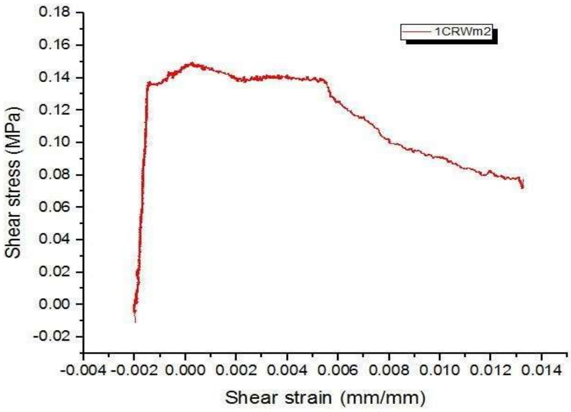
a)



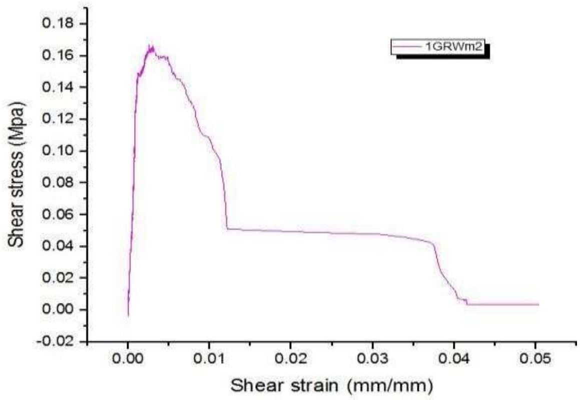
a) W1



b) W2



c) W3



d) W4

Fig. 13 - Stress-strain diagrams of wall specimens/ *Diagrama eforturi unitare tangențiale – deformații specifice a peretelui de referință*

4.Conclusion

The paper summarizes the outcomes of an experiment performed to evaluate and compare the effectiveness of two different techniques which strengthen masonry walls based on the application of FRP and FRCM systems.

The experimental results proved the technical feasibility of shear strengthening of URM walls using TRM system both in terms of ultimate load and failure mode. Using an accurate coverage of Glass FRCM on one and both faces, respectively, increments ranged between 1.4 and 2.0 times the value of the clay brick control wall in terms of ultimate in-plane load. Also, from the substrate at failure, the AR Glass FRCM showed no delamination of the system. Furthermore, experiments showed that a shear strength increase occurred on specimens reinforced with Glass and Carbon FRP system and a better post-peak response was attained with the Glass FRP.

Experimental results confirmed the effectiveness of FRP technique to increase the masonry panel shear strength (up to 1.48 times that of the control panel).

Comparing results from walls strengthened with carbon and Glass FRP reinforcements, it turns out that the load increase does not follow the different mechanical strength of fibres, suggesting the reach of the peak value when the maximum shear capacity of the masonry panel occurred.

To produce reliable conclusions, much more experimental investigations studying the influence of various strengthening parameters on the capacity of the masonry walls, type and number of fibre grids, mortar and connectors should validate the outcomes.

Conflict of interest

None.

Acknowledgments

Tests ran in the Laboratory of composite materials of the Faculty of Civil Engineering and Building Services at "Gheorghe Asachi" Technical University of Iași, Romania. The authors gratefully acknowledge laboratory staff for assistance during tests.

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