Influence of FRP Composites Strengthening Configurations on In-plane Failure of Brick Masonry Walls

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Abstract: A high percentage of unreinforced load bearing masonry structures exist in many countries, these structures shown to be vulnerable to earthquakes, and exhibited important damages. The failure of each element of structure generates a problem in the load transmission. The seismic evaluation of unreinforced masonry walls is a complicated task, however, several research investigates the ability of reducing their seismic risk and ameliorates their mechanical characteristics by using different materials. The carbon fiber-reinforced polymer (CFRP) composites were used in numerous investigations to reinforce masonry walls, it offers significant advantages since the fibers can be externally bonded to the surface without affecting the aesthetics of the structure, and it could improve the strength of the structure. As part of this research, an experimental study was conducted to investigate the seismic behavior of masonry walls reinforced with unidirectional CFRP composites and subjected to in-plane loading. This paper evaluates the in-plane behavior of two groups of masonry walls strengthened with diverse percentage and orientations of CFRP composites.

1 INTRODUCTION

The damage caused by past earthquakes showed the seismic vulnerability of existing unreinforced masonry structures. The percentage of masonry buildings was estimated to be over 70% of the world's building inventory (Matthys and Noland, 1989). Moderate earthquakes could lead to significant human and material losses caused in the most cases by the masonry elements.

Several research studies highlighted the need for developping different effective techniques to enhance the seismic loading, the strength and the ductility of unreinforced walls with minimum impact on the aesthetics of the structure. Actually, repairing structures doesn't present just a technical challenge, but also an economical challenge that depends on the repairing conditions and the type of damages (cracks, reinforcement of load-bearing elements, etc.). Within the available systems is the organic matrix composite materials. The use of composite materials in recent years, continually been enhanced because of its multiple advantages and specifically for its weightlessness that does not influence the weight of the structure, its rigidities, durability and its significant resistances. Composite materials have low fatigue and sensitivity, their use improve the performance of the structures and present a high stiffness-resistance ratio while keeping the initial appearance of the structures (Mosallam et al, 2014). Taking into consideration the mechanical characteristics of the elements constituting the FRP composites, specifically the type of fibers and their orientation, the matrix and the interface between them, influence directly the behavior of the composite laminate. Several studies have been carried out to understand the FRP behavior and to determine the deformations and the failure modes of different types of structures subjected to cyclic loading, in order to predict the appropriate reinforcement system.The analysis of the work and results related to the behavior of the reinforced infill panels will be discussed. Different strengthening technique were studied in the literature (ElGawady et al, 2004; Chuang and Zhuge, 2005) to repair or to

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reinforce masonry walls using several products such as: reinforced plaster, projected concrete, ferrocement, injection of epoxy into voids or cracks, the addition of steel reinforcement injected into the voids drilled vertically through the mid-thickness of the wall, exterior reinforcement of the masonry with steel plates or tubes, confinement of the masonry, reinforced concrete columns and beams, post-tensioning of the wall with steel tendons. These techniques are effective, but they have several disadvantages such as their expensive prices, and they present a significant load and influence the aesthetics of the structure.

Textile reinforced cement matrix is widely used for reinforcing different masonry and concrete elements. Several studies evaluated the use of TRC for the reinforcement of reinforced concrete elements and especially for column confinement to improve their resistance to compression loads (Ortlepp et al, 2009) and torsion, for reinforcing beams and slabs subjected to shear and bending (Brückner et al, 2006).

Recycled or artificial aggregate composite materials of agricultural or industrial origin have been the subject of numerous studies carried out to determine the mechanical characteristics of composites contain renewable materials incorporated in a cement mortar matrix or concrete. These materials can be in the form of fibers, particles or aggregates from agricultural residues of vegetable origin (jute, palm trees, etc.) that sometimes require physical or chemical treatment before their use or both in some cases. Their mechanical characterization presents the subject of numerous publications (e.g. Boghossian et al, 2008; Mir et al, 2010; Kriker et al, 2005).

FRP composite laminates are designed to enhance both strength and ductility of masonry walls. Polymer composites strengthening can be applied either externally or using near surface-mounted (NSM) technique. NSM method has several advantages such as it doesn't influence the aesthetic of the structure and it ensures the fiber protection against fire.

External bonding composites is one of the most widely used reinforcement methods to repair or to reinforce different types of structures in order to improve their mechanical performance. The fabrics are dry or pre-impregnated with a polymeric matrix, and for the plate they are glued with the epoxy resin (Khalifa et al, 1998). By definition the external bonding is the method by which the FRP laminates are bonded to the surface of a wall using two-part of the epoxy adhesive. Prior to FRP application, the wall surface is cleaned and a fill layer is applied to create a flat surface to which the FRP will be bonded (Stratford et al, 2004). External reinforcement with FRP can be partial by using strips or total by applying reinforcement to the entire surface of the walls (Mosallam and Banerjee, 2011).

The efficiency of the reinforcement depends on its laminate orientation, type of fibers and matrix, as well as the number of plies. For Valluzzi et al, (2002), the shear strength of the walls reinforced by diagonal reinforcement is higher than the orthogonal mesh reinforcement. On the other hand, results described in (Santa-Maria et al, 2004) showed that the shear behavior of masonry walls reinforced by CFRP plates is influenced by their orientations, the strength results of walls with diagonal reinforcement has increased considerably compared to the horizontal reinforcement.

Konthesingha et al, (2013) tested the repaired damaged masonry walls reinforced by near surface mounted (NSM) CFRP plate in three configurations; namely: horizontal reinforcement of one side, horizontal reinforcement on both sides, and cross-ply reinforcements on both sides of the wall. Their results indicated that wall specimen externally reinforced by horizontal and vertical system had the highest energy dissipation, strength and deformation capacities.

2 SPECIMEN PREPARATION

In this study, wall specimens with dimension of 1200X1200X115mm were constructed using clay brick units of 240X115X63mm. The mortar thickness used in building wall specimens is 10 mm, 28 days later and before applying the composites, the substrate surfaces were cleaned by high air pressure. Then, the substrates were wet by water then it was covered by a thin layer of epoxy primer followed immediately by the application of mortar with thickness of 12mm, after it hardened, the first layer of resin was applied to bond the composite, then a second layer of epoxy polymer is applied to fix and to protect the composite. During these operations, it is necessary to ensure that the composite was well impregnated with resin. The walls were reinforced using different configurations of the unidirectional carbon fibers reinforced polymer. The CFRP were applied on the front and back sides of each wall. After seven days, the specimens were tested under in-plane loadings. Then the in-plane performance of the masonry elements to failure were experimentally evaluated. In-plane tests were performed in two groups of the specimens (refer to Table 1 and data used in (Elmalyh et al, 2020).

3 TEST PROTOCOL

After the specimens were prepared, they were tested according to (ASTM E519, 2002), first the wall was fixed between two steel shoes to permit the transmission of the load machine (see Figure 1). Then the linear variable differential transducers (LVDTs) were attached on the both diagonals to measure the displacements and the deformations in the both directions. The load was applied at the top corner in the gravity direction by hydraulic actuator fixed to the supporting frame.

4 RESULTS AND COMPARISON

The performance of the composite materials depends mainly on the characteristics of the interface between the fibers and the matrix. The interface ensures the transfer of the applied load from the matrix to the reinforcement system. Various studies and analyses evaluated the influence of the type and thickness of the interface on the composite properties.

Wall subjected to compressive loads incur a regular loss of rigidity which is compensated by the presence of the composite that absorbs energy and increase deformability and failure load of the wall. However, the energy dissipation depends also on the reinforcement configuration. The strengthening ratio details of the first and the second group are illustrated in the table 1. Experimental data presented in the table 2 is compared to evaluate the performance of the strengthening configuration in improving the behavior of URM wall under in-plane compressive loading. It should be highlighted that all the CFRP composite reinforcement configurations evaluated in this study were effective in improving the integrity and the load bearing capacity of the masonry walls. Comparing failure of unreinforced wall with the reinforced specimens, the URM specimen exhibited rapid crack propagation, indeed in all cases the response of the reinforced walls had high strength and the crack propagation was obstructed by the CFRP caused by the shear tensile transmitted via the masonry-CFRP interface.

Regarding the experimental results illustrated in the figure 1, 2 and 3, all the strengthened walls showed similar failure modes (shear failure at the ends of the vertical diagonal, delamination of the CFRP and compression failure of masonry). Nevertheless, for wall specimen reinforced with one diagonal composite strip at each side (W-1D-CFRP), the failure mode was similar to unreinforced wall. The tensile resistance of the compressive loads was higher than the URM wall by 59.56%, even if the diagonal reinforcement presented 41% of each side.

From the results obtained from this study, it is clearly seen that the walls W-CFRP-W1, W-3D-CFRP, W-2DX-2V-CFRP had the highest shear strength, which correspond to the following load bearing capacities 32.3 kN and 37.8 kN. Despite the amount of composites applied to specimen W-3D-CFRP which is 47% lesser than the specimen W-CFRP-W1 that was fully reinforced on its both sides. It seems that applying just 53% of composites per side provided a higher flexible response and the most important lateral deformations. Nevertheless, the lateral deformations for the specimen W-CFRP-W1 had significantly increased too.

Table 1: Retrofit details applied on each side

Designation	Ratio (%)	Configuration	CFRP (mm)
Groupe N°1			
W-CFRP-W1	100	Full face	1200X1200
W-CFRP-W2	50	3 Vertical	200X1200
W-CFRP-W3	75	3Verticals & 3 horizontals	6X200X1200
Groupe N°2			
W-1D-CFRP	41	One diagonal	350
W-3D-CFRP	53	Three parallel diagonals	300 & 2X200
W-2DX-CFRP	74	Diagonal X	2X350
W-2DX-2V-CFRP	90	Two verticals & diagonal X	2X350 & 2X200

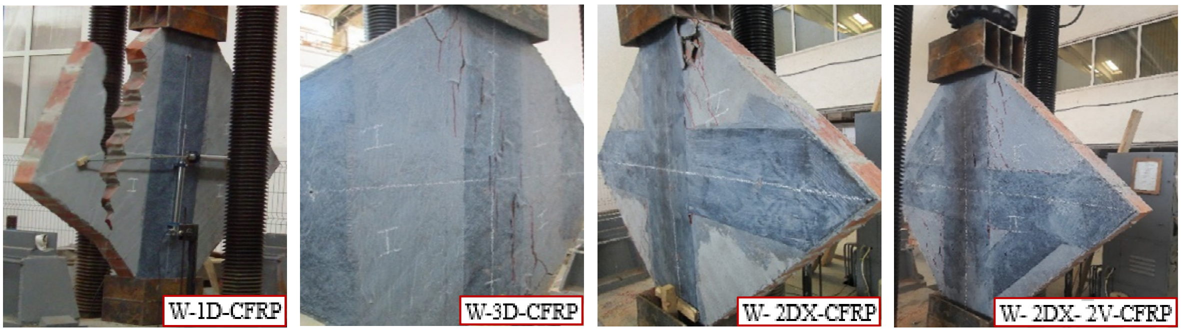
* URM-W-CFRP-W-X-: URM: unreinforced masonry, W: wall, CFRP-W: carbon fiber reinforced polymer, W: wrap, X: number of walls.

Comparing the specimen W-CFRP-W3 (reinforced by three verticals and three horizontals CFRP (cross play composites) that covered 75% of each substrate) with W-2DX-CFRP (reinforced by two perpendicular diagonal CFRP applied on 74% of each substrate), their response and their load bearing capacities, which correspond to 26.2 kN, 27.4 kN were almost similar.

Experimental results indicated that wall specimen W-2DX-2V-CFRP, with CFRP composites covering 90% of each wall side, has the highest load bearing capacity of 39 kN. The behavior of this wall specimen is similar to W- CFRP-W 1 specimen.

The strengthening ratio used in those two cases enhanced the tensile strength of the retrofitted walls, which developed a larger strain that leads to high lateral deformations.

Shear crack formation along the diagonal and the delamination of CFRP (Group N°1)



Wall shear cracking (Group N°2) CFRP delamination and the wall shear cracking (Group N°2)

Figure 1: Failure mode of the tested walls

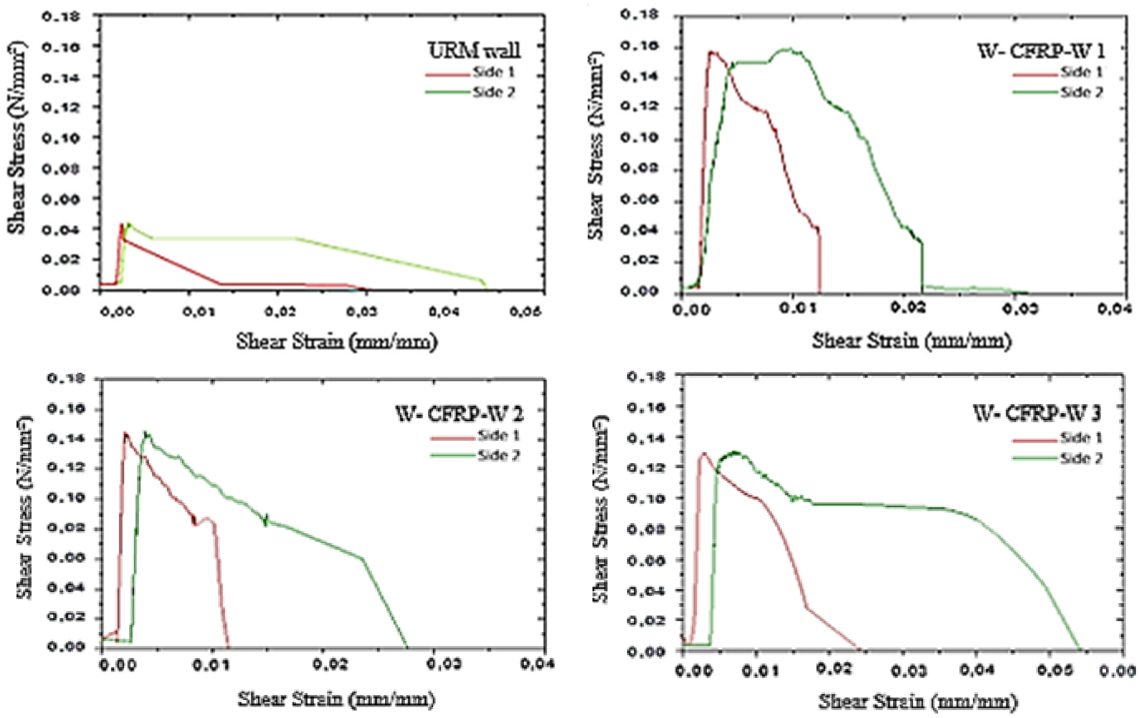


Figure 2: Shear Stress-Strain curves of the tested walls (Group N°1)

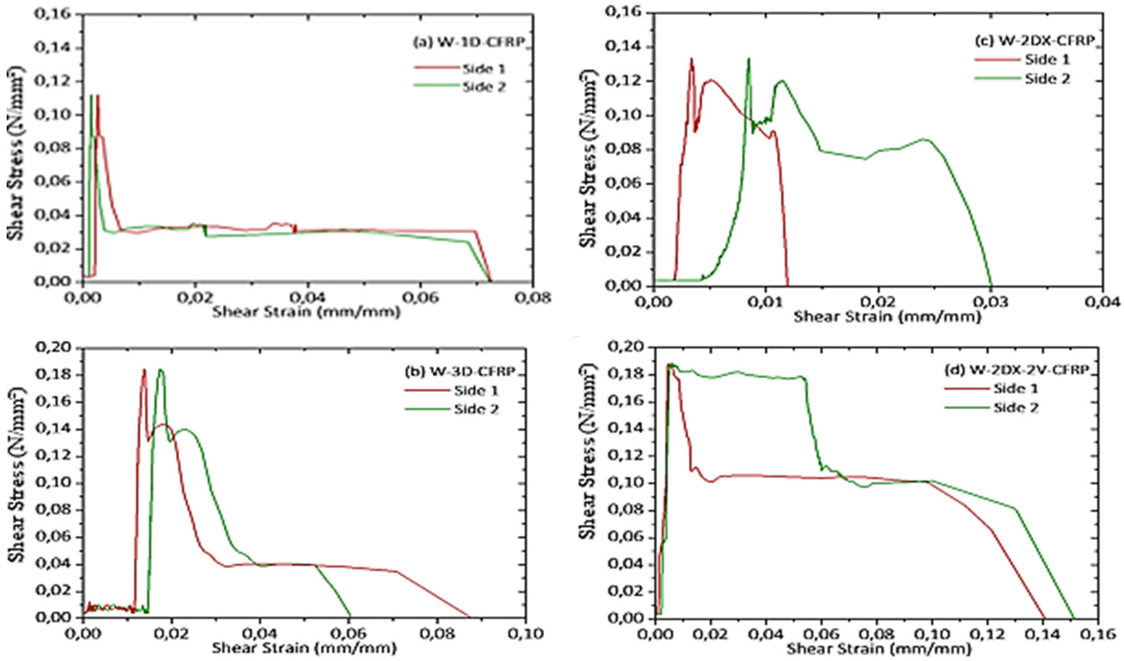


Figure 3: Shear Stress-Strain curves of the tested walls (Group N°2)

Table 2: Results of diagonal compression tests

Configuration type	Side N°	Load (kN)	ΔV (mm)	ΔH (mm)	Shear stress (N/mm²)	Shear strain (mm/mm)	Modulus of Rigidity (MPa)
W- CFRP-W 1	1	32.3	1.2	0.18	0.17	0.0028	60.71
	2		4.83	0.37		0.01	17.00
W- CFRP-W 2	1	29.4	1.03	0.15	0.15	0.0023	65.22
	2		1.90	1		0.0058	25.86
W- CFRP-W 3	1	26.2	1.02	0.7	0.13	0.0034	38.24
	2		1.46	3.02		0.009	14.44
W- 1D-CFRP	1	23	0.273	0.51	0.12	0.0016	75.25
	2		0.467	0.887		0.0027	43.51
W- 3D-CFRP	1	37.8	1.592	7.188	0.194	0.0176	11.03
	2		1.219	5.751		0.0139	13.89
W-2DX-CFRP	1	27.4	1.141	0.571	0.1404	0.0034	41
	2		0.884	3.359		0.0085	16.54
W-2DX-2V-CFRI	1	39	2.05	0.493	0.1998	0.0051	39.30
	2		2.263	0.989		0.0065	30.72

5 CONCLUSION

The in-plane behaviour URM walls strengthened with external CFRP composites was tested to evaluate the effectiveness of using different configuration. The following conclusions can be drawn:

The retrofitted walls load bearing capacities has known an increase from 26.2 kN to 32.3 kN compared to the reference wall. Specimens reinforced with three parallel and vertical CFRP strips (50% reinforcement ratio) indicated a significant enhancement in ductility and deformability, despite the small amount of CFRP used for reinforcement.

This study showed that the vertical and/or horizontal reinforcement system increased the safety of structures during an earthquake by improving strength, energy dissipation and the ductility of the URM walls. For example, the strength of the first group was experimentally observed to be 181.72% to 247.31% higher than the URM wall. By using three vertical CFRP strips, the strength of the externally reinforced wall significantly improved with a gain of 216.13% as compared to the reference unreinforced wall specimen.

The ultimate strength of all wall specimens with diagonal reinforcement configurations significantly increased by 2.5 to 4.2 times the capacity of the corresponding unreinforced wall specimens. In addition, the shear strength of the wall specimens increased considerably by 319%. The ultimate strength of the walls strengthened with the second reinforcement scheme group is 147.31 to 319.35% higher than that of the unreinforced specimens.

CFRP reinforcement configuration with two perpendicular diagonal strips and parallel vertical strips applied on each side reached the highest in-plane shear strength. Results also indicated that the configuration with three parallel diagonal CFRP strips is the optimum reinforcement ratio that improves the in-plane response of the wall with minimum cost. For example, the strength gain obtained from this specimen with 53% CFRP reinforcement ratio is 306% as compared to the unreinforced wall specimen.

The model reinforced by a single diagonal CFRP composite applied on each side showed a less strength. The wall strength degrades quickly and the reinforcement did not show a remarkable decrease in rigidity. On the other hand, the wall rigidity deteriorates rapidly, and it was accompanied by large deformations, which provide the wall failure at a low load of 23 kN. The strength of the wall reinforced with diagonal stripes is the lowest compared to the other configurations.

Experimental comparisons of the performance of CFRP strengthening systems demonstrate that the strength of the reinforced wall depends on the percentage, the orientation and the position of the CFRP reinforcement.

The results of this study confirmed the ability of CFRP reinforcement in improving the mechanical behavior of URM walls. The diagonal composite reinforcement scheme presents a high potential strengthening alternative as compared to full-surface reinforcement scheme.

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