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CONSTRUCŢII. ARHITECTURĂ

IN-PLAN SHEAR RETROFIT OF MASONRY WALLS WITH FIBRE REINFORCED POLYMER COMPOSITES
EXPERIMENTAL INVESTIGATIONS

BY

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The paper presents the results from tests on clay brick masonry walls strengthened using fibre reinforced polymer (FRP) composites. Five 1.50×1.50 m wall specimens have been subjected to pure in-plan shear loads up to failure and then retrofitted on one side, with different types, percentages and lay-ups of the fibre sheets. Based on the experimental results, it was proven the effectiveness of using externally bonded composites for retrofitting brick masonry walls, with less disruption during strengthening, and in this way with reduced costs compared with other conventional repairing and strengthening techniques. Performances of the different strengthening configurations were compared in terms of ultimate load, strain in composite and failure mechanism.

1. Introduction

The seismic vulnerability of masonry buildings was obvious during major seismic events across the world. One of the last examples was the case of the residential building from Moldova Nouă city, Romania, which was seriously damaged after the earthquake in 2002. A significant number of masonry buildings suffered extensive damage and because of this, it was necessary an effective retrofit technique, as the fibre reinforced polymer (FRP) composites overlays, which increases the in-plan and out-of-plane strength and stiffness of the masonry walls.

In the past few years it was investigated, in many research centers of the world, a new strengthening solution, which involves fibre reinforced polymer (FRP) composites overlays, in this way increasing the in-plan and out-of-plane strength and stiffness of the walls. In the Department of Civil, Industrial and Agricultural Engineering of the Politehnica University of Timişoara, in collaboration with UNC Charlotte, NC, USA, this solution of retrofitting was studied in a frame of a joint research project. The objectives were to investigate the behaviour of the unreinforced clay brick masonry walls subjected to in-plan shear loads strengthened with FRP composites only on one side. For this reason, there were performed several finite element analysis (FEA) and five specimens were built and tested. Although the initial material cost of this solution is higher than the investigated traditional methods to retrofit masonry walls, such as reinforced concrete overlays, the efficiency and the easiness of application can lead to an economic result.

2. Numerical Analysis

In the first phase it was performed an analytical study with a simplified (theoretical) model of the wall. The goal was to conceive a device in which the load system creates a pure in-plane shear of the wall, without much influence from the bending moment. This system is auto-equilibrant and, theoretically, the crack should form in the diagonal direction. The loads applied to the specimen were a constant vertical (V) and an increasing horizontal (H) force. With this test set-up, a large number of FEA were analysed, by modifying the width to height ratio (d/h) of the elements ($d/h = 1$; 1.5 and 2), the quality of the brick and of the mortar, through the strength and the modulus of elasticity of the element, the horizontal load-steps, and, finally, by applying a constant vertical force of different magnitudes.

The first analyses were performed with the program BIOGRAF (Fig. 1), developed in the Department of Civil, Industrial and Agricultural Engineering from Timişoara, which permits a step-by-step modification in principal stresses and the formation of the cracks (Fig. 2), their angles and widths. After every step, the program calculates again the stiffness and the modulus of the element.

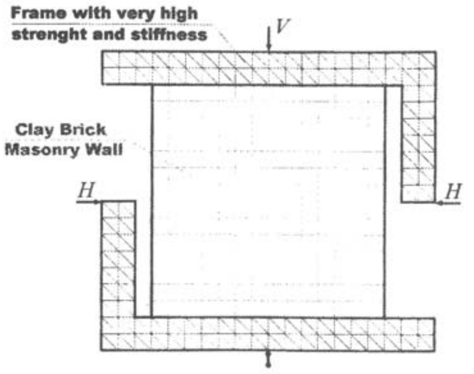

Fig. 1.- Structural model of the wall for FEA.

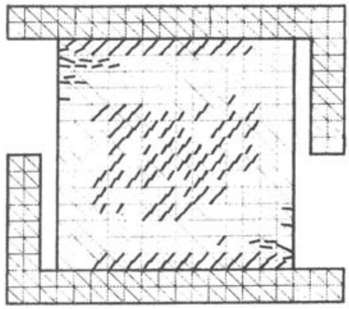

Fig. 2.- Crack distribution of the wall specimen (BIOGRAF).

Theoretically, the application of the vertical force is not necessary in the case of homogeneous materials, but the brick wall is composed of clay brick units and mortars, which have different characteristics. Therefore, to prevent a sliding failure mode, a vertical force was applied.

After these analyses it was decided to choose, for further detailed analysis, a wall specimen with height to width ratio equal to unit. This ratio also represents the masonry wall pier dimensions widely encountered in older brick structures. Thus, because of the dimensions of the bricks, the final width of the wall became 150 cm.

With this final specimen dimensions, further finite element analyses were performed using AXIS VM (Fig. 3). In these more detailed analyses the following parameters have been considered as well: the proper weight of the wall and of the bond beam, and the weight of the testing frame. With this model it was possible to obtain the distribution of the principal stresses (Fig. 4), the crack propagation in the wall, the probable failure load and the collapse mechanism.

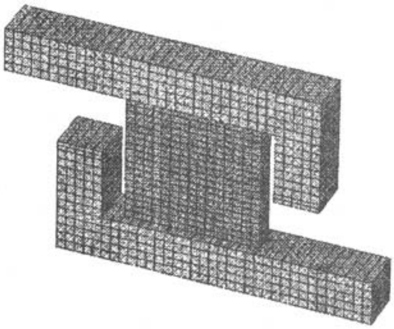

Fig. 3.- Discretization of the specimen.

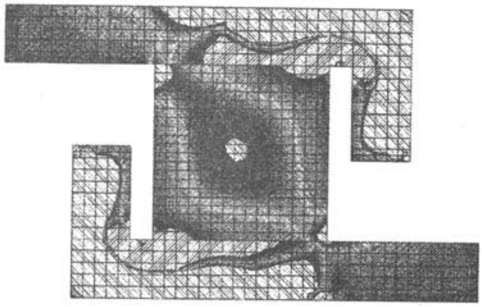

Fig. 4.- Distributions of principal stresses (AXIS VM).

3. Experimental Elements and the Test Set-up

The experimental specimens were 150 cm wide and 150 cm high, build of solid clay bricks with dimensions 6.3×24.0×11.5 cm and unit strength 9.0...10.0 N/mm^2, the mortar strength being 13...16 N/mm^2. At the top and at the bottom there were placed reinforced concrete beams (50×150×25 cm^3).

The walls were tested in a special device, composed by a pair of L-shaped steel elements attached to the concrete beams at the top and the bottom. The forces have been applied with hydraulic jacks. The vertical force was applied on the top

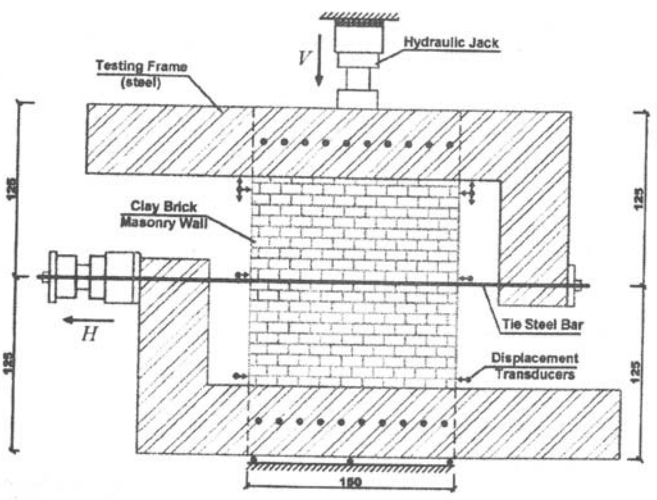

Fig. 5.- The specimen test set-up.

of the specimen, acting through the reinforced concrete bond beam. The horizontal (shear) force was applied through a series of steel bolts embedded in the reinforced concrete block and mounted to the L-shaped steel elements at the top as well as at the bottom.

The displacement of the wall was measured with displacement transducers, which were placed along the height of the wall, on left and the right, measuring the specimen's horizontal displacement. Other transducers measured the vertical displacements on each side of the specimen, being placed on the steel frame at the first and the last mortar bed joints, respectively (Fig. 5).

The specimens were tested in as-built condition up to failure and then retrofitted on one side with FRP composite layers and retested afterwards. The recorded data was the horizontal load, the horizontal and vertical displacements, the strain in the composite and the specimen failure modes.

4. Test Results and Discussion

4.1. Experimental Tests of the UM1 and RM1 Elements

The UM1 (UM - Unreinforced Masonry) wall was initially tested in the as-built condition. A constant vertical force, $V = 200$ kN, and the monotonous increased horizontal force, H, were applied by an increment of 5 kN up to failure, which generated the required in-plane shear forces in the specimen. The failure mechanism of the wall was produced through a diagonal crack from the top-right to bottom-left corner, as expected. The load *vs.* displacement diagrams at the top of the wall are typical for unreinforced masonry. The specimen's behaviour is close to linear. The load at the specimen failure was 190 kN, meanwhile the maximum horizontal displacement reached 7 mm.

To rehabilitate the pre-cracked wall, three carbon FRP sheets were applied vertically on one side (Fig. 6). The FRP was applied to just one side because, in many situations, the modification of the façades is not permitted or it is very expensive to perform. Therefore, in these cases only the inside surfaces of the walls are accessible.

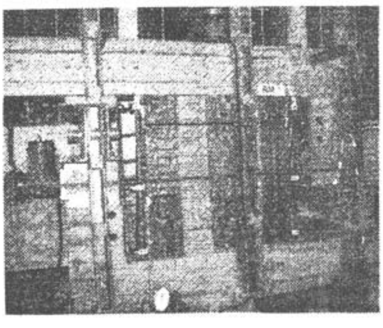

Fig. 6.- RM1 retrofitted wall test.

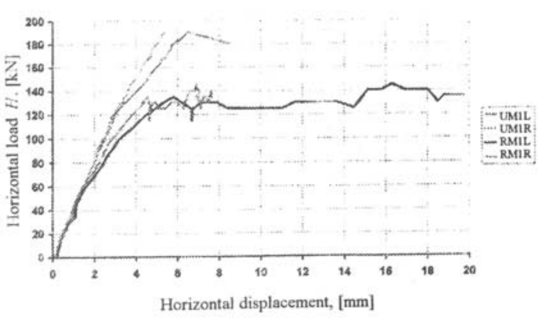

Fig. 7.- Load *vs.* displacement diagram of UM1 and RM1 (L - left side, R - right side).

The test set-up for RM1 (RM - Retrofitted Masonry) wall specimen was identical to the baseline test set-up (UM1), additional strain gages were attached to the composite in the maximum stress zones and were aligned in the direction of the carbon fibres. The retrofitted wall reached a peak lateral load of 145 kN and a maximum horizontal displacement of 19 mm (Fig. 7). The peak tensile stresses in the composite laminates reached approximately 33% of the ultimate value, which corresponded to an ultimate strain of 0.5%. This is a very good result, demonstrating that this solution worked really well with clay brick masonry. The dominant wall failure mode was extensive brick masonry cracking, followed by composite debonding at the cracks.

4.2. Experimental Tests of the UM2 and RM3 Elements

Another set of experiments was performed on the elements UM2 and RM3. The applied constant vertical force was $V = 300$ kN and the monotonous horizontal force H was increased by an increment of 5 kN. The wall failure was very brittle through a diagonal crack. It can be mentioned that the constant vertical force was increased with 100 kN, correlating with the previous case, because the quality of the wall was superior to the first element and it was necessary to avoid the sliding in the horizontal bed joint. The horizontal force (H) at the failure was 300 kN and the maximum horizontal displacement exceeded 8 mm.

The strengthening was performed by applying carbon fibre fabric on one side in vertical direction, covering the entire surface of the element (Fig. 8).

The retrofitted wall (RM3) reached a peak horizontal load (H) of 370 kN, the maximum horizontal displacement being 17 mm (Fig. 9). The peak tensile stresses in the composite laminates reached approximately 10% of the ultimate value, which corresponded to an ultimate strain of 0.15%. This demonstrates that the composite had high reserves in the moment of the specimen failure. It can be mentioned that the failure was produced through the development of a new crack and through it's the extensive opening. The composite was debonded just in the crack zone, but it was not broken.

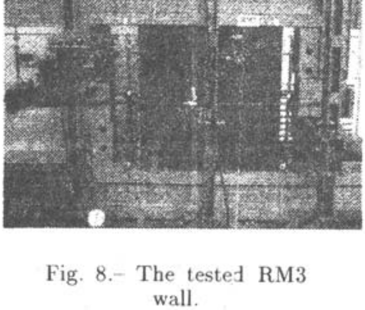

Fig. 8.– The tested RM3 wall.

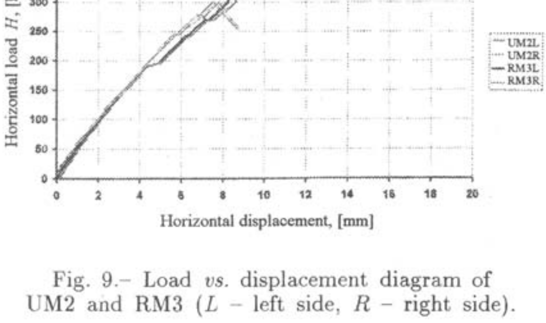

Fig. 9.– Load *vs.* displacement diagram of UM2 and RM3 (L – left side, R – right side).

4.3. Experimental Tests of the UM3 and RM4 Elements

In the next set of experiments it was tested firstly the UM3 specimen. The constant vertical force was $V = 300$ kN and the monotonous applied horizontal force, H, had an increment of 5 kN up to failure. The wall failure was also very brittle through a diagonal crack, which opened approximately 1.5 cm. The horizontal force (H) at the failure was 325 kN and maximum horizontal displacement did not exceed 3 mm.

The retrofitting was realized by applying a carbon fibre fabric in vertical direction on one side, which covered the entire surface of the element (Fig. 10). The differences compared with the first two elements were the need of the crack injection and filling, which were realized with cement mortar.

The retrofitted wall (RM4) reached a peak horizontal load (H) of 270 kN, the horizontal displacement being 9 mm (Fig. 11). The maximum tensile stresses in the composite laminates reached just 8% of the ultimate value, which corresponded to an ultimate strain of 0.12%. The failure has been produced through the extensive opening of the existing crack. The composite was debonded just in the crack zone, but it wasn't broken.

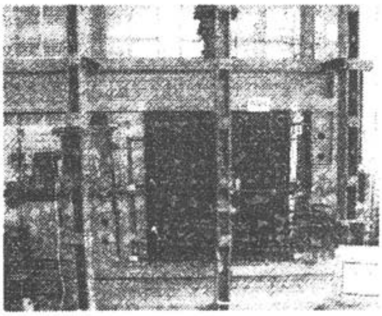

Fig. 10.- The RM4 wall before the test.

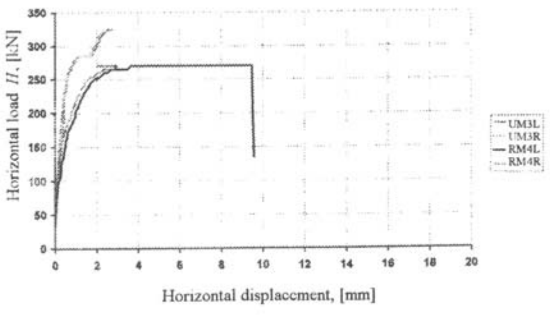

Fig. 11.- Load *vs.* displacement diagram of UM3 and RM4 (L – left side, R – right side).

4.4. Experimental Tests of the UM4 and RM5 Elements

In what follows there were tested the UM4 and the RM5 specimens. The applied forces were: a constant vertical force $V = 300$ kN and the monotonously increased horizontal force up to failure. The wall failure was also very brittle through a diagonal crack, which opened approximately 1 cm. The maximum horizontal force (H) was 320 kN and maximum horizontal displacement reached 16 mm.

The retrofitting was performed by applying a glass fibre fabric in the vertical direction on one side, which covered the whole surface of the element (Fig. 12), the crack also being filled with cement mortar.

The retrofitted wall (RM5) reached a peak horizontal load (H) of 335 kN, the horizontal displacement being over 38 mm (Fig. 13). The maximum tensile stresses in

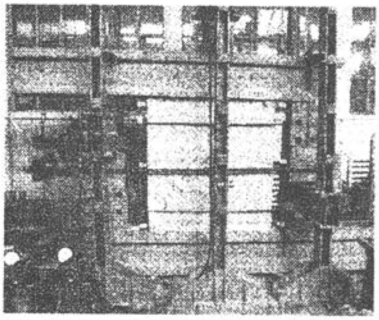

Fig. 12.– The tested RM5 wall.

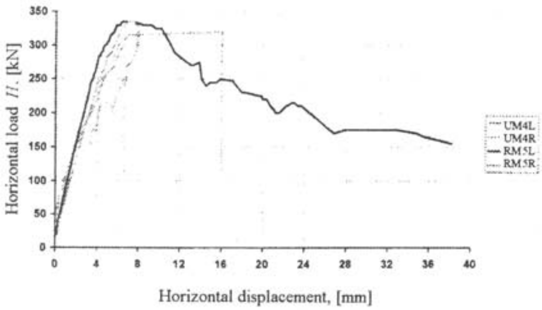

Fig. 13.– Load *vs.* displacement diagram of UM4 and RM5 (L – left side, R – right side).

the composite laminates reached 1.78% of the ultimate value, which corresponded to an ultimate strain of 48%. The failure was produced through the extensive opening of the existing crack, in the same time with the composite debonding in the crack zone, but without its rupture.

4.5. Experimental Tests of the UM5 and RM6 Elements

In the last set of the experiments there were tested the UM5 and the RM6 specimens. The applied forces were: a constant vertical force $V = 300$ kN and the monotonously increased horizontal force (H) up to failure. The wall failed through a diagonal crack at the maximum horizontal force (H) of 251 kN, with the maximum horizontal displacement being just 4 mm.

The retrofitting was done by applying a carbon fibre fabric in the horizontal direction on one side, which covered the whole surface of the element (Fig. 14). The retrofitted wall (RM6) reached a peak horizontal load (H) of 277 kN, the horizontal

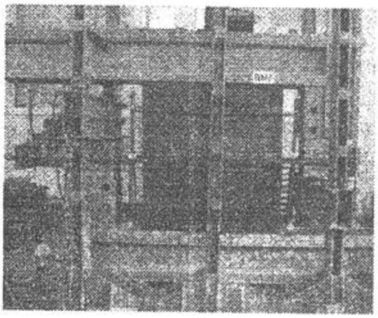

Fig. 14.– The tested RM6 wall.

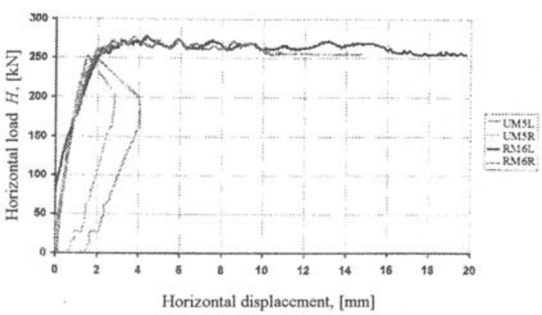

Fig. 15.– Load *vs.* displacement diagram of UM5 and RM6 (L – left side, R – right side).

displacement being almost 20 mm (Fig. 15). The maximum tensile stresses in the composite laminates reached 12% of the ultimate value, which corresponded to an ultimate strain of 0.18%. The failure of the elements was produced by forming many new cracks and through the extensive opening of the existing one. The composite debonded on large areas, near the crack zone, but it was not broken.

5. Conclusions

Based on the obtained test results, the following conclusions can be drawn:

1. The correction and injection mortars had an important role in restoring the load bearing capacity. The width of the initial crack is decisive in the evolution of the final capacity of the strengthened wall. If the crack was tight, the capacity increased significantly over the reference value, but if the crack was wide. the ultimate load capacity was approximately equal to the initial value.

2. A considerable capacity increase was observed for the precracked shear walls retrofitted with FRP composites (practically, the load bearing capacity of the cracked walls was negligible). The most advantageous strengthening system seems to be the composite with glass fibres, because it uses up to 50% of the load bearing capacity of the fibres.

3. The failure of the retrofitted walls was caused by extensive cracking followed by FRP debonding and not due to tensile or shear failure of the FRP.

4. The maximum horizontal displacements increased two times compared with the displacements of the baseline specimens that demonstrate the increase of the ductility and energy absorbing capacity of the retrofitted walls.

5. Strengthening with FRP composites using unidirectional fabrics placed in vertical direction on one side of the wall has an important contribution in increasing or restoring the shear capacity of the structural masonry walls, in spite of the opinion of some researchers who recommend neglecting the contribution of vertical FRP reinforcement, due to the dowel action effect.

Unreinforced masonry walls subjected to shear forces behave in a very brittle way and fail with or without warning. By strengthening such a non-ductile structural element with composites the characteristic behaviour became rather ductile than elastic.

This research project will continue with other three elements, using two directional fabrics, investigating the masonry – composite interface for different masonry units and composites, repeating some of the tests performed in this project with some other variables, such as the composite systems (other fabrics, resins, orientations).

The obtained results of the tests performed up-to-date are presented analytically in Table 1.

Table 1
Synthetic Presentation of the Experimental Test Results

Specimen	UM1	RM1	UM2	RM3	UM3	RM4	UM4	RM5	UM5	RM6
Mortar strength N/mm^2	16.9		13.1		14.9		13.1		11.5	
Brick unite strength N/mm^2	10.6		9.5		9.5		9.5		9.5	
Strengthened surface %	–	60	–	100	–	100	–	100	–	100
Used composite system (HEX)	230C	–	103C	–	103C	–	100G	–	103C	
Constant vertical load V, [kN]	200		300		300		300		300	
Maximum horizontal load H, [kN]	190	145	300	370	325	270	320	335	251	277
Differences in capacity, [%]	−23,7		+23,3		−16.9		+4.7		+10.3	
Maximum horizontal displacement, [mm]	8.5	19.7	8.7	17.5	2.8	9.5	16.0	38.1	4.0	19.7
Maximum strain in composite, [%]	–	0.50	–	0.15	–	0.12	–	1.78	–	0.18
The wall failure mode	shear	shear	shear	shear	shear	shear	shear	shear	shear	shear

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CONSOLIDAREA PEREŢILOR DIN ZIDĂRIE LA FORFECARE ÎN PLANUL ELEMENTULUI FOLOSIND COMPOZITE POLIMERICE

Cercetări experimentale

(Rezumat)

Se prezintă rezultatele unor studii teoretice şi experimentale efectuate pe zidării de cărămidă consolidate cu materiale compozite polimerice armate cu diferite tipuri de fibre, dispuse în diferite moduri. Sunt descrise analizele numerice, metodologia de încercare, metodele de consolidare şi comportarea pereţilor înainte şi după consolidare. Experimentele au arătat viabilitatea soluţiilor propuse, modul în care se pot îmbunătăţi performanţele pereţilor avariaţi şi direcţiile de continuare a cercetărilor folosind alte tipuri de fibre şi alte moduri de aşezare.