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STRENGTHENING OF UNREINFORCED MASONRY VAULTS AND WALLETS USING FRP COMPOSITES

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ABSTRACT

Unreinforced masonry is the construction system in most of the historic structures and a considerable percentage of existing residential buildings in Egypt. One of the important disadvantages of unreinforced masonry construction is its low resistance to tensile stresses and lateral loads, so there is a need for appropriate strengthening. Fiber reinforced polymer (FRP) composites have been successfully applied as externally bonded reinforcement for strengthening of reinforced concrete and masonry structural elements. Their excellent strength-to-weight ratio and ease of installation make it an attractive alternative for traditional strengthening methods.

This paper presents experimental investigation of strengthening masonry wallets and vaults using FRP composites, as well as other traditional methods such as steel reinforcement bars, ferrocement layers and polymer mortar layers.

The experimental results showed that FRP gave higher strengthening level and better failure mode than using traditional steel reinforcement bars or ferrocement layers. Use of glass fiber composites is also a cheap technique. Using polymer mortar was the least effective technique. Strengthening of masonry wallets using FRP surface layer was found to be an efficient method, where the failure load was double that of the control sample.

Keywords: Strengthening, FRP, Steel Reinforcement, Ferrocement, Unreinforced masonry, Masonry wallets, Vaults.

1. INTRODUCTION

Masonry is still widely used as a construction method. This is mainly justified by wide availability of the material, simplicity and economy of construction, as well as its good mechanical and aesthetic properties. Masonry was the only building material, together with timber, until the nineteenth century, when the use of masonry has become less important due to the progressive adoption of other structural materials, particularly concrete and steel. However, there is an awareness of the advantages of masonry construction regarding economy, durability and sustainability, and the need for increasing its quality is inevitable. There are many existing masonry structures have survived for centuries, and there is an acute need for strengthening tools to maintain the stability and the safety of such structures [1].

One of the important disadvantages of unreinforced masonry construction is its low resistance to tensile stresses and lateral loads. Fiber reinforced polymer (FRP) composites have been investigated in several research work [2], and found to be effective for strengthening of unreinforced masonry wallets [3] and vaults [4]. This research presents experimental investigation of different schemes for strengthening unreinforced masonry wallets and vaults. FRP externally bonded layers as well as other traditional methods found in the literature [5] such as steel reinforcement, ferrocement layers and polymer mortar layers were applied on masonry wallets and vaults which were loaded till failure. The experimental program and results are presented and discussed.

2. EXPERIMENTAL PROGRAM

A two-phase experimental program was conducted. The first phase was testing six unreinforced masonry wallet having dimensions of 700x700x120 mm, two of them W1 and W2 were un-strengthened to act as control samples, while the other four were strengthened by 200 mm wide stripes of glass FRP roving. The wallets were tested in typical indirect tension test, as shown in figure 1.

In the second phase twelve unreinforced masonry vaults were built using local commercially produced masonry units and nine the vaults were strengthened using four different techniques. Three vaults (V1, V2 and V3) were not strengthened to serve as control samples. Two vaults (V7 and V8) were strengthened with glass FRP Roving 600 adhered using polyester based adhesive. Three vaults (V4, V5 and V6) were near surface reinforced using 12 steel bars of length 50 cm and diameter 6 mm. Two vaults (V9 and V10) were covered with polyester based mortar on the external face of the vault. Last two vaults (V11 and V12) were reinforced with ferrocement wire mesh 1.5 mm thick, covered with 1cm mortar layer. Shear studs were used to connect the wire mesh to masonry vaults. All strengthening materials were applied on the extrados of the vaults, and location chosen near the hinges that were expected to occur. All vaults were loaded till failure to investigate the failure mode and to compare the effect of the strengthening techniques, as shown in figure 2.

3. MATERIALS

The material mechanical properties are very important issues for masonry assemblage. Therefore, experimental samples are tested to evaluate the mechanical properties for masonry units, mortar cubes, masonry prisms, FRP sheets, and ferro-cement welded wire mesh, [6], [7].

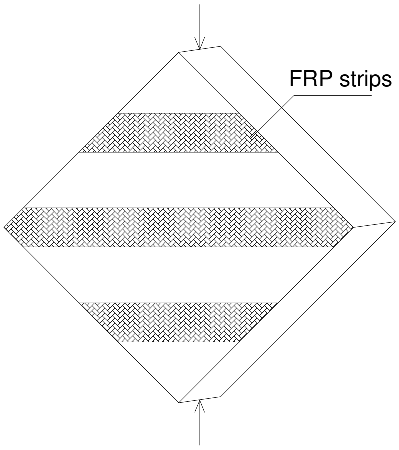
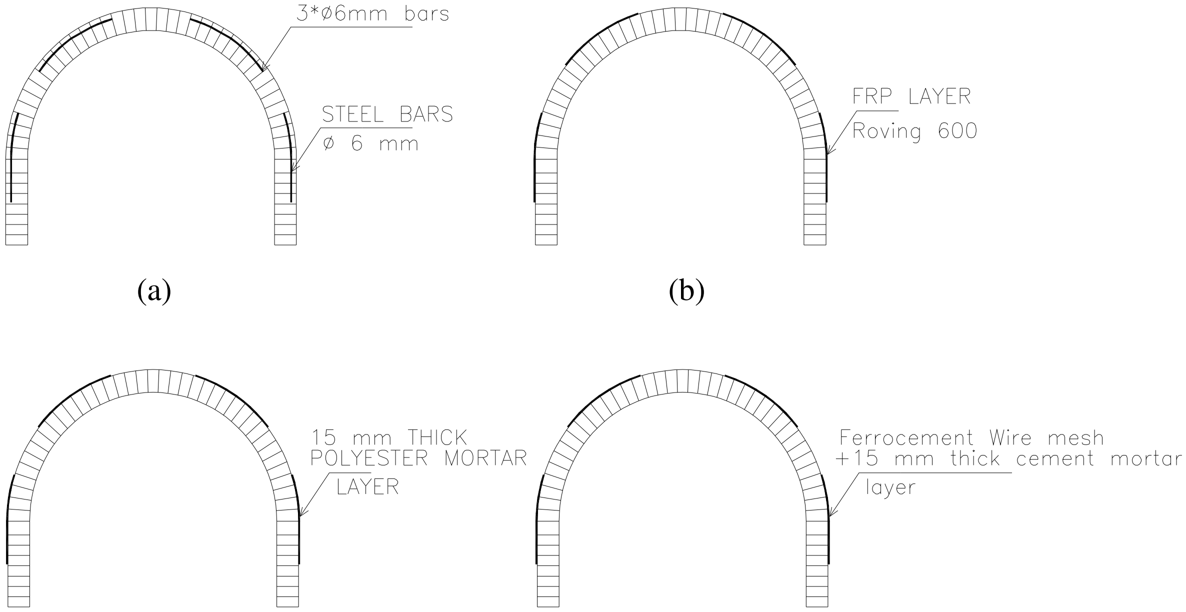


Figure 1: Strengthening techniques proposed for masonry wallets.



(a) (b)

(c) (d)

Figure 2: Strengthening techniques for vaults, a) steel reinforcement, b) FRP sheets, c) Polyester mortar external layer, d) Ferrocement.

3.1. Brick units

Compression test was made to three samples of locally produced brick units (Misr Brick) with dimensions (250 x 120x 60 mm) and it was found that the average compressive strength for the units equal 12.5 MPa. The results are shown below in table 1.

Table 1: Values for masonry unit compressive test.

BRICK UNIT	LOAD - KN	AREA - mm^2	STRENGTH - MPa
1	297	24000	12.3
2	292.4	24000	12.1
3	317	24000	13.2
Average compressive strength			12.5

3.2. Cement mortar

Three samples for mortar cubes with dimensions (100x100x100 mm), the mix for mortar type 1 in accordance with the Egyptian code for masonry structures [8]. The average for compressive strength equal was found to be 17.1 MPa. The results are shown below in table 2.

Table 2: Values for cement mortar cubes compressive test.

MORTAR CUBE	LOAD - KN	AREA - mm^2	STRENGTH - MPa
1	206	10000	20
2	155	10000	15
3	169	10000	16.3

Average comp. stress	17.1

3.3. Masonry prism mechanical properties

Five samples of masonry prisms were tested to evaluate sample behavior in compression, and found average strength of 4.4 MPa, the results are listed in table 3.

Table 3: Compressive test results for masonry prism.

PRISM	LOAD - KN	AREA - mm^2	STRENGTH - MPa
1	112	30000	4.6
2	101	30000	4.2
3	109	30000	4.5
Average comp. stress			4.4

3.4. FRP sheets (Roving 600)

Fiber-Reinforced Polymer composites (FRP) are being widely used during the last few years, in order to increase the out of plane flexural resistance as well as in-plane shear resistance. In fact, composite materials can be advantageously applied at the interior and exterior surfaces of both flat and vaulted masonry structures. The used FRP roving is E glass fiber woven roving EWR600, this type has breaking strength of 3800 Mpa and modulus of elasticity 75 Gpa [9]. The FRP sheets should be adhered with resin (polymer material), the resin should be mixed with hardener to accelerate the setting time with volume ratio 2 cm^3 for each liter of polymer material [9].

Figure 3: FRP roving 600 sheets

Table 4: Mechanical properties for FRP roving 600.

Product code	Fiber diameter - µm		Fabric density - root/cm		Mass per unit area - g/m^2	Breaking Strength - MPa	
	Warp	Weft	Warp	Weft		Warp	Weft
EWR600	17	17	2.6	2.5	600 ± 30	4000	3800

3.5. Steel reinforcement bars

Reinforcement may be generally used for all elements or may be provided at special critical locations, such as at wall ends, top, edges of openings, locations of concentrated loads and high tension zones. Steel reinforcement is typically used in form of ordinary steel bars, with diameter 6 mm. This type of reinforcement is the same as that used for reinforced concrete construction, mild steel bars with yield stress 240 Mpa.

3.6. Reinforcement with Ferrocement wire mesh

Ferrocement wire mesh is another type of reinforcement, the wire mesh used to cover the strengthened part with shear studs and covered with 15 mm cement mortar, this techniques used to increase the tensile resistance of the masonry, as shown in figure 4. The wire-mesh reinforcement specifications are listed below [10]

- Wire diameter 1.5 mm.
- Type of mesh is welded wire mesh.
- Wire galvanized mesh.
- Size of mesh openings 25 mm.

Figure 4: Ferrocement wire mesh

3.7. Polyester mortar

Polyester mortar is a type of mortar used as alternative for the ordinary mortar or used as a repairing material, due to its higher tensile resistance. Experimental samples made and tested to get the mechanical properties for compression and tension of this material is shown in figure 5. Six cubes of polyester mortar (70 x 70 x 70 mm) were made to evaluate the compressive and tensile strength, as shown in tables 5 and table 6. Mix proportions used for the polyester mortar was 3:1 volume ratio for sand:polymer respectively, the polymer material is mixed with hardener to accelerate the setting time with volume ratio 2 cm^3 for each liter of polymer material [9].


Figure 5: Polyester Mortar cubes for indirect tension testing, 70x70x70 mm, [11].

Table 5: Results of compressive test for polyester mortar cubes.

POLYSTER CUBE COMPRESION 70X70X70 mm	LOAD - KN	AREA - mm^2	STRENGTH - MPa
1	399	4900	81.4
2	280	4900	57.1
3	367	4900	74.8
Average compressive strength			71.1

Table 6: Results of indirect tension test for polyester mortar cubes [11].

POLYSTER CUBE TENSION 70X70X70 mm	LOAD - KN	AREA - mm^2	STRENGTH - MPa
1	27.9	4900	3.6
2	45.3	4900	5.9
3	26.6	4900	3.4
Average tensile strength			4.3

4. EXPERIMENTAL RESULTS

Masonry wallets:

The failure mode for the control samples W1 and W2 showed a typical diagonal tension crack, extending from the upper tip to the lower tip of the wall, and the average failure load for the two wallets was 130 KN, as shown in figure 6. The failure of all strengthened wallets W3, W4, W5 and W6 was by crushing of the top part of the wallets, with failure load of average value of 260 KN, as can be seen in table 7. The obtained results can be explained by the strengthening gained by FRP, which delayed failure, nearly doubled the failure load and prevented the formation of the diagonal cracks observed in the control samples.

Figure 6: Failure mode for Control wallets.

Figure 7: Failure modes for strengthened masonry wallets.

As mentioned all strengthening wallets load capacity were increased to almost 200 % of the control sample. Final displacement is increased from 11 mm for control samples to 16 mm for strengthened wallets. This indicated that the strengthening techniques is able to increase the ductility of the wallets, and this leads to improving the brittle failure mode for masonry assemblage. Table 7 and figure 8 present the failure loads of the control and strengthened samples, also the load displacement curve are shown in figure 9.

Table 7: Failure loads of masonry wallets.

VAULT SAMPLE ID	FALUIRE LOAD - KN	Percentage of sample failure load to average load failure of control samples
W1	138.9	Control
W2	131	Control
W3	258	192 %
W4	270	200 %
W5	249	185 %
W6	261	193 %

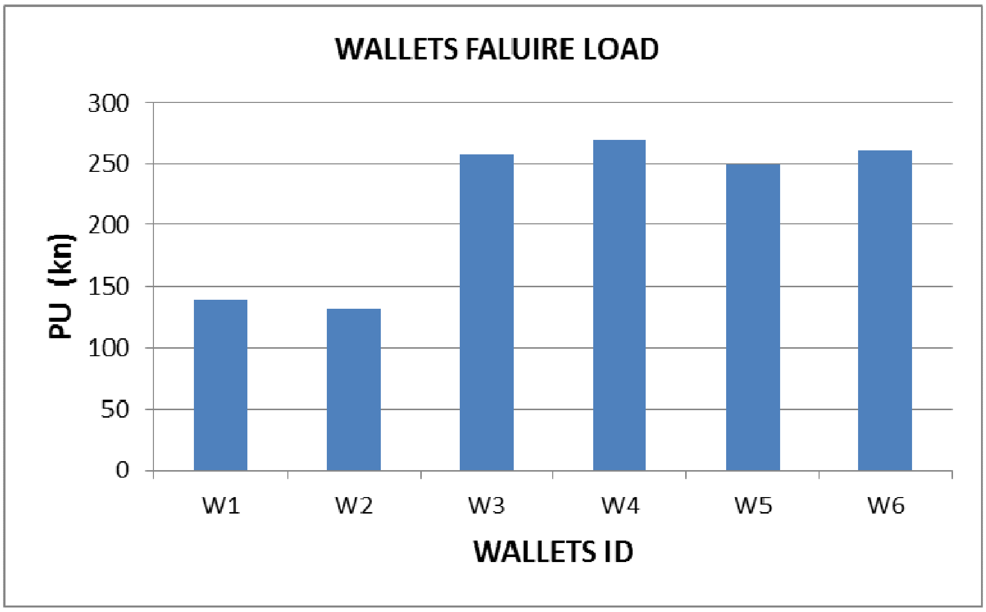


Figure 8: Failure loads of masonry wallets.

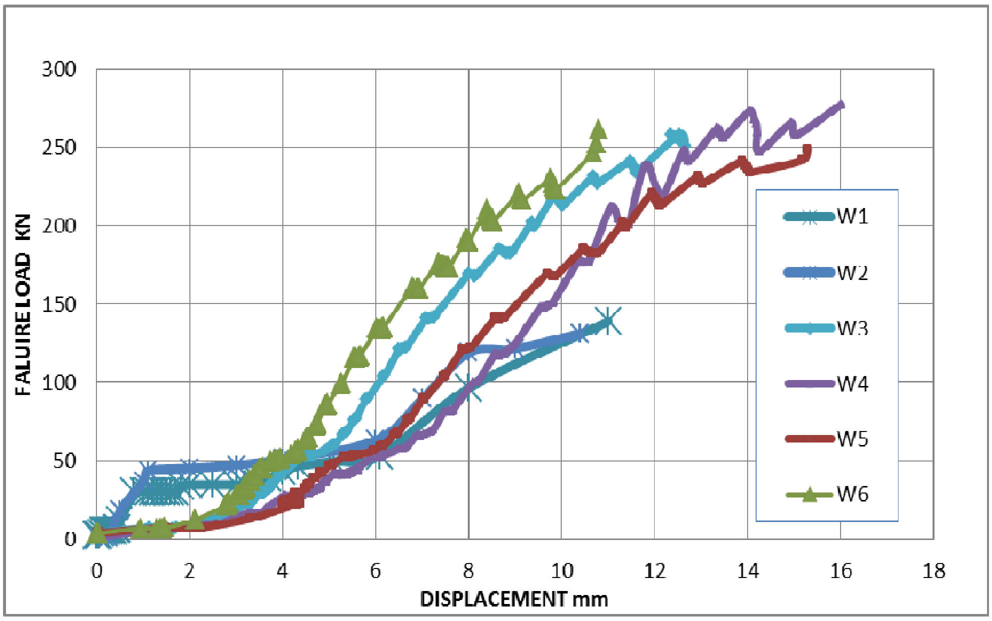


Figure 9: load displacement curve for all masonry wallets.

Masonry vaults:

The experimental results of the tested vaults showed that failure of the un-strengthened control vaults V1, V2 and V3 occurred when three hinges were formed at the extrados, as shown in figure 10. The proposed strengthening technique used to change the crack location illustrated in figure 11. The control vaults gave an average failure load 8 KN. The average failure loads for the strengthened vaults were 15 KN, 12.63 KN, 12.56 KN and 9.55 KN for vaults strengthened by FRP, steel reinforcement, ferrocement layer and polymer mortar layer, respectively. The failure loads are shown in figure 12 and table 8 .

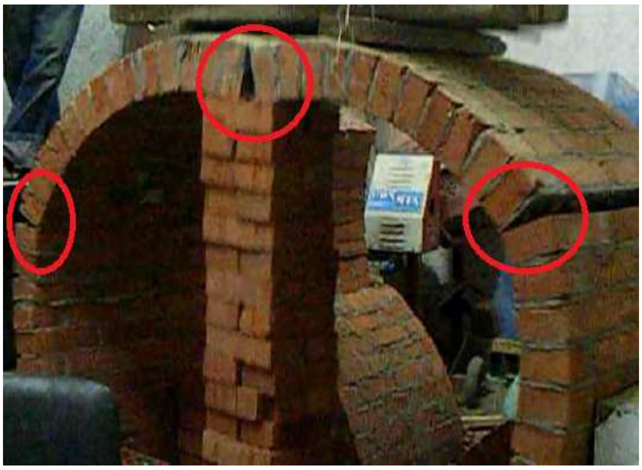


Figure 10 Control masonry vaults failure pattern.

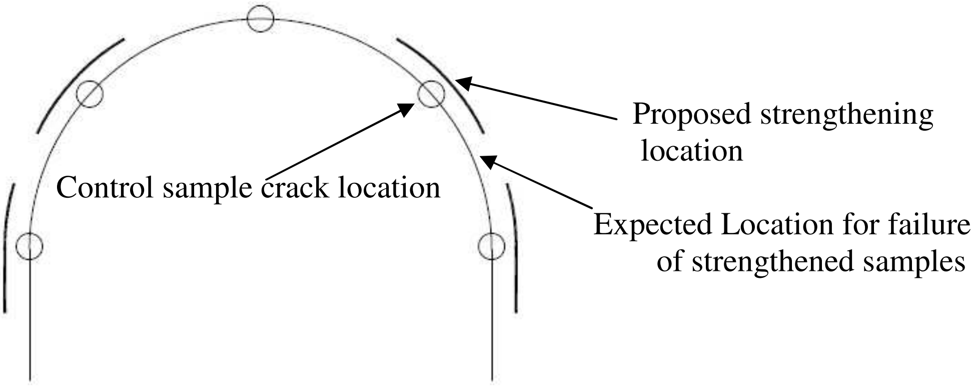


Figure 11 Schematic diagram for strengthening locations, and Expected crack locations.

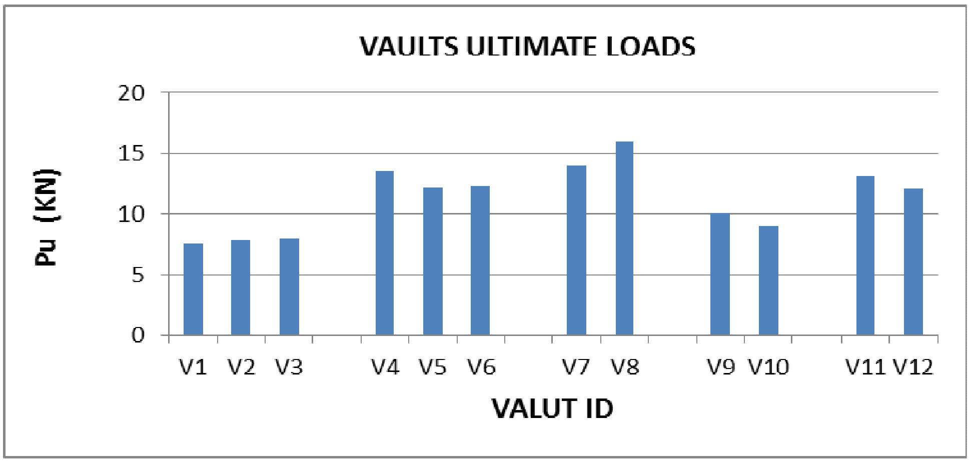


Figure 12: Failure loads of masonry vaults.

Table 8: Failure load of masonry vaults.

Vault ID	Strengthening techniques	FALUIRE LOAD - KN	Increase compared to control sample - %
V1	Control	7.50	Control
V2		7.90	Control
V3		8.30	Control
V4	Steel Reinforcement	13.50	168 %
V5		12.11	151 %
V6		12.29	153 %
V7	FRP	13.91	173 %
V8		16.04	200 %
V9	Polymer mortar	10.10	126 %
V10		9.00	112 %
V11	Ferro-cement	13.00	162 %
V12		12.00	150 %

The final load displacement curves for all vaults shows that the strengthening decreased final displacement (strain) than the control vaults. Strengthening did not improve the ductility of the vaults as they still fail in brittle manner. Figure 13, shows the Load – Displacement curves for all the tested vaults.

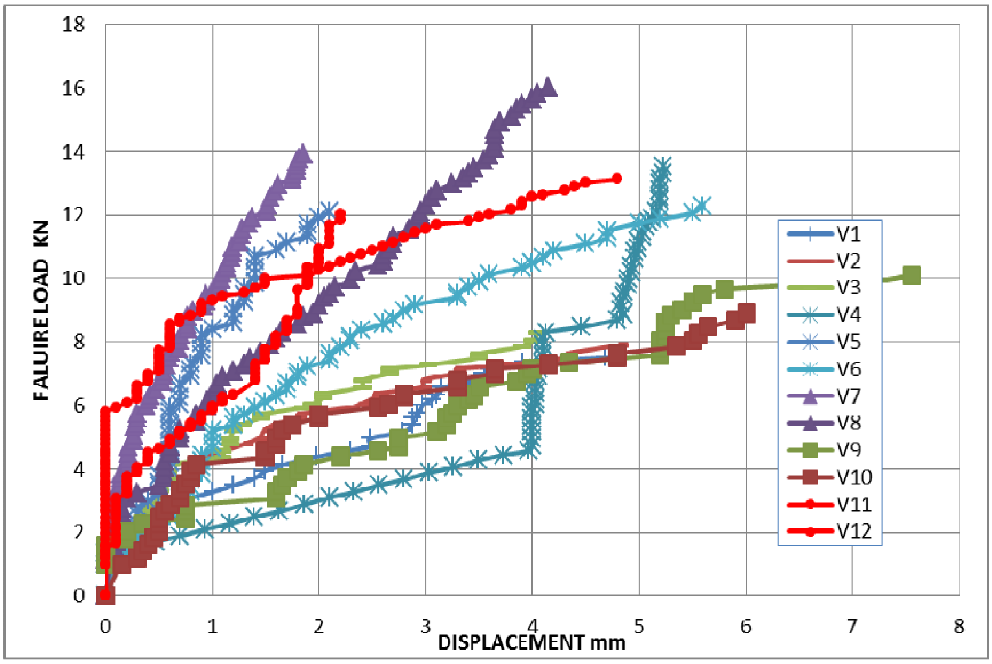


Figure 13: Load displacement curve for all masonry vaults.

A typical failure mode observed for all strengthened vaults where the strengthening can improve the stressed section and transmit failure to further location, with the exception of vaults strengthened with polyester mortar which failed in a similar pattern to that of control samples, as shown in figure 17. Failure mode for vaults strengthened with steel reinforcement is shown in figure 14. The failure mode for vaults strengthened with FRP sheets is shown in figure 15, while the failure mode for vaults strengthened with ferrocement wire mesh is shown in figure 16.


Figure 14: Mode of failure for vaults strengthened by steel reinforcement


Figure 15: Mode of failure for vaults strengthened by FRP sheets


Figure 16: Mode of failure for vaults strengthened by ferrocement wire mesh.

Figure 17: Mode of failure for vaults strengthened by polyester mortar

For the twelve masonry vaults, the initial testing of three un-strengthened masonry vaults served as the reference series where the influences of the strengthening using different techniques were demonstrated. Control vaults developed failure mode with typical three hinges as discussed before. The strengthened vaults with steel reinforcement, FRP and ferrocement wire mesh succeed to improve the structural behavior and transmit the crack formed on the control samples to the un-strengthened location of theses vaults. The failure loads indicated that the strengthening using steel reinforcement, FRP and ferrocement wire mesh increase the ultimate loads to 150 %, 190% and 150% respectively.

The vaults strengthened with polyester mortar failed to transmit the crack outside the strengthened zone and slightly improved the failure load with 118%.

The obtained experimental results demonstrated that the carefully selected position of the applied strengthening succeeded in arresting the tension cracks at the location observed in the control vaults and moved the formed hinges, causing the vault failure, away from its location in the un-strengthened case.

Finally it can be concluded that the results of the ultimate loads and laboratory produced load displacement curves, show that the strengthening techniques using steel reinforcement bars, ferrocement and FRP are effective methods, and the strengthening technique using FRP roving 600 strips is more efficient for strengthening of such structures for its excellent strength-to-weight ratio, easy installation, and low cost.

5. CONCLUSIONS

In this work, an experimental program was conducted to study the efficiency of externally bonded FRP sheets for strengthening unreinforced masonry wallets and vaults. The failure load of masonry wallets strengthened using glass FRP was double that of the control wallets.

The experimental results for the strengthened wallets and vaults showed that FRP gave higher strengthening level and better failure mode than using traditional steel reinforcement bars or ferrocement layers, use of glass fiber composites make it also as cheap as other techniques. While using these traditional strengthening techniques are efficient as well. Using polymer mortar was the least effective technique.

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