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EXPERIMENTAL INVESTIGATION FOR MASONRY VAULTS/WALLS STRENGTHENED USING DIFFERENT TECHNIQUES

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ABSTRACT

Unreinforced masonry is the construction system of most of 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 frequently need for appropriate strengthening for such structures. Fiber reinforced polymer (FRP) composites have been successfully applied as externally bonded reinforcement for strengthening of reinforced concrete and masonry structural elements as well. Their excellent strength-to-weight ratio and easy installation make them an attractive alternative for traditional strengthening methods.

This paper presents experimental investigation of strengthening masonry walls and vaults using FRP composites, as well as other traditional methods such as steel reinforcement bars, ferro-cement layers and polymer mortar layers. The experimental program is explained and the maximum capacity and failure mode associated with each strengthening technique are presented and compared. The experimental results showed that FRP gave higher strengthening level and better failure mode than using traditional steel reinforcement bars or ferro-cement layers. Use of glass fiber composites makes it also as cheap as other techniques. Using polymer mortar was the least effective technique. Also, strengthening of masonry wall specimens using confining FRP layer was found to be a very efficient method, where the failure load was double that of the unstrengthened specimens.

Keywords: Strengthening, FRP, Steel Reinforcement, Ferro-cement, Unreinforced masonry, Masonry Walls, Vaults.

1. INTRODUCTION

Masonry is still widely used as a construction method and there is an increasing awareness of its advantages regarding economy, durability and sustainability. In addition, wall-bearing masonry construction is the structural system of much of the world's architectural heritage and such monuments often have also important social and economical values, and therefore need restoration or strengthening measures to maintain the stability and safety of such structures [1]. For these reasons, masonry structural behavior and strengthening are now regarded as important fields of research.

One of the important disadvantages of unreinforced masonry construction is its low resistance to tensile stresses and lateral loads [2], so there is need for appropriate strengthening. Fiber reinforced polymer (FRP) composites have been studied in many research work [3], and found to be effective for strengthening of unreinforced masonry walls [4], arches [5,6] and vaults [7,8]. The present research presents experimental investigation of different schemes for strengthening unreinforced masonry wallets and vaults. Several traditional techniques found in the literature such as steel reinforcement bars, ferro-cement layers and polymer mortar layers were applied on the masonry vaults [9]. FRP externally bonded layers were applied on unreinforced masonry wallets and vaults and all specimens were loaded till failure. The experimental program and results are presented and discussed in the following sections.

2. EXPERIMENTAL PROGRAM

A two-phase experimental program was conducted. The first phase was testing six masonry wallets constructed using local commercially produced bricks and having dimensions 700x700x120 mm. Two wallets (W1 and W2) were used as control samples, while the other four were strengthened by 200 mm wide strips of glass FRP rovings. The wallets were tested in typical indirect tension test, as illustrated in fig 1.The adopted strengthening pattern is similar to that reported in the literature [10].

In the second phase, twelve unreinforced masonry vaults were built using local bricks having half brick thickness (120mm) and having the dimensions shown in fig. 2. Three vaults V1, V2 and V3 were not strengthened to serve as control samples for comparison, while nine were strengthened using four different techniques, as illustrated in fig. 3. Each of the three vaults V4, V5 and V6 was strengthened using 12 steel bars of length 50 cm and diameter 6 mm inserted as near surface reinforcement, as shown in fig 3(a). Two vaults V7 and V8 were strengthened using glass FRP Roving 600 adhered by polyester, as shown in fig. 3(b). Two vaults V9 and V10, shown in fig. 3(c) were covered with sand polyester mortar in order to provide tensile strength to the external face of the vault, and the last two vaults V11 and V12 were reinforced with ferro-cement wire mesh 1.5 mm thickness, covered with 1cm mortar layer and shear studs to connect the wire mesh to the masonry vaults, as shown in fig. 3(d). 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.

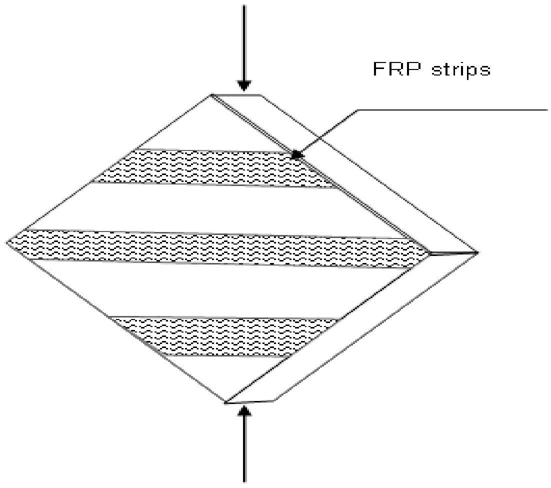


Figure 1 Strengthening and testing scheme proposed for masonry wallets.

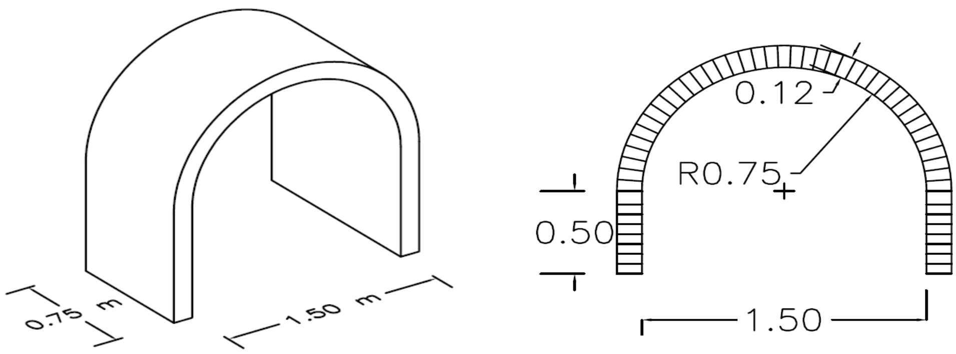


Figure 2 Dimensions of the masonry vaults.

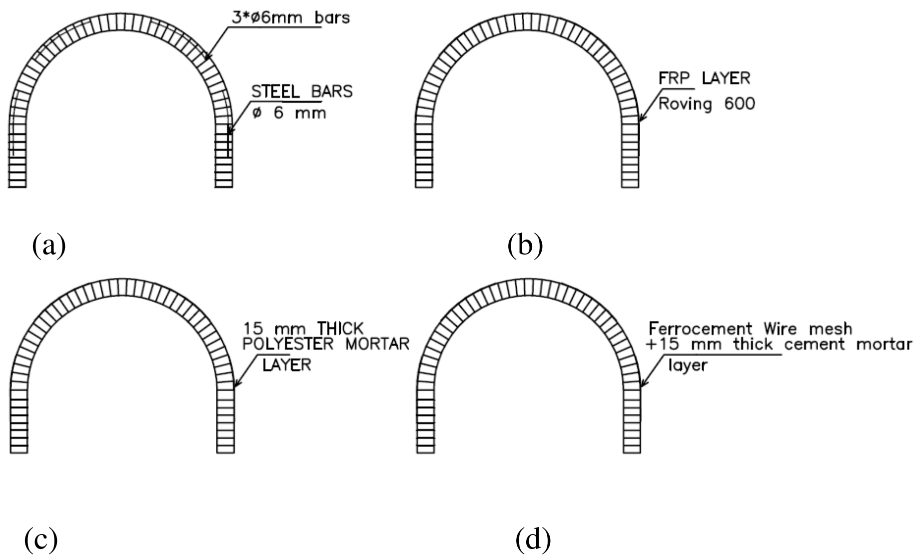


Figure 3 Strengthening techniques proposed for masonry vaults,
a) Steel reinforcement, **b)** FRP sheets, **c)** external polyester mortar layer, **d)** Ferro-cement wire mesh.

3. MATERIALS

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

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. Three bricks were tested in compression till failure; the results in table 1 show that the average compressive strength was 12.5 MPa.

Table 1 Values for masonry units compressive test.

Brick unit	Failure load (kN)	Area (mm^2)	Compressive 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

The mortar used for all experimental work was mortar type 1 in accordance with the Egyptian code for masonry structures [11].Three mortar cubes were prepared having dimensions 100x100x100 mm. and tested in compression till failure. The results are given in table 2. The average for compressive strength was found to be 17.1 MPa,

Table 2 Values for cement mortar cubes compressive test.

Mortar cube	Failure load (kN)	Area (mm^2)	Compressive strength (MPa)
1	206	10000	20
2	155	10000	15
3	169	10000	16.3
Average compressive strength			17.1

3.3. Masonry prism strength

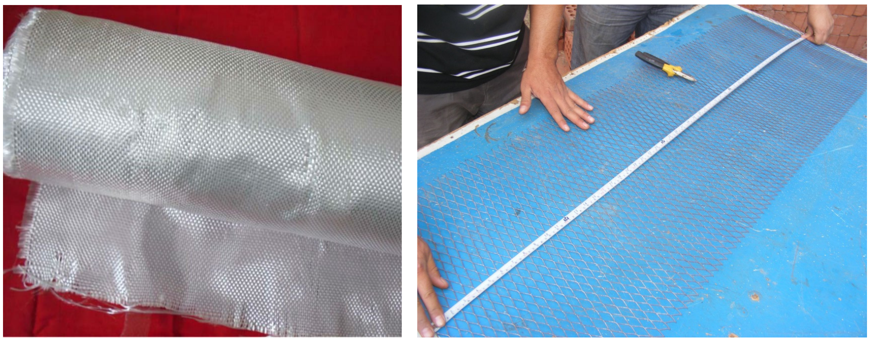
Five samples of masonry prisms were prepared as specified by Egyptian code [11], and tested in compression to evaluate the masonry prism compressive strength. Experimental results given in table 3 indicate an average value of 4.4 MPa.

Table 3 Compression test results for masonry prism.

Masonry prism	Failure load (kN)	Area (mm^2)	Max. compressive stress (MPa)
1	112	30000	4.6
2	101	30000	4.2
3	109	30000	4.5
Average masonry prism strength			4.4

3.4. FRP sheets used for external strengthening

Fiber-Reinforced Polymer composites (FRP) were being widely used in order to increase the-out-of-plane flexural resistance as well as in-plane shear resistance of masonry elements [3, 4]. Composite materials can be externally applied at the interior and the exterior surfaces of both flat and vaulted masonry structures. The used FRP sheets are E-glass fiber woven roving EWR600, shown in fig. 4(a) and having the properties given in table 4 [12]. The breaking strength is 3800 MPa and modulus of elasticity 75 GPa [12]. 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 [12].



(a) (b)

Figure 4 Strengthening materials (a) FRP Roving 600 sheets, (b) Ferro-cement wire mesh

Table 4 Mechanical properties for FRP roving 600.

Product code	Fiber diameter(□m)		Fabric density(root/cm)		Mass per unit area(g/m2)	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

Structural strength of masonry construction is achieved and enhanced through the use of steel reinforcement. Reinforcement may be generally used for all elements or may be provided at special critical locations, such as at wall ends, tops, edges of openings, locations of concentrated loads and high tension zones. Steel reinforcement used is in form of ordinary steel bars, with diameter 6 mm and yield stress 240 MPa.

3.6. Reinforcement with Ferro-cement wire mesh

Ferro-cement wire mesh is another type of reinforcement, shown in fig. 4(b). The wire mesh was used to cover the part required to be strengthened using shear studs and covered with 15 mm cement mortar, in order to increase the tensile resistance of masonry.

The wire-mesh reinforcement specifications are listed below [13]

- Wire diameter 1.5 mm.
- Type of mesh is welded wire mesh
- Wire galvanized mesh
- Size of mesh openings 25 mm
- Reinforcement corresponding to up to 630 kilograms per cubic meter

3.7. Polyester mortar

Polyester mortar is a type of mortar used as a repairing material since it has tensile resistance higher than the ordinary cement mortar. The mix proportions used for the polyester mortar throughout this experimental work was 3:1 volume ratio for sand and polymer, respectively, hardener is added to accelerate the setting time with volume ratio 2 cm^3 for each liter of polymer material [12]. Six cubes of polyester mortar (70 x 70 x 70 mm) were prepared and experimentally tested to determine the compressive and tensile strength as shown in fig. 5. The tensile strength is evaluated through the indirect splitting test [13]. Results are shown in tables 5 and 6.

Figure 5. Indirect tension test for polyester mortar cubes.

Table 5 Results of compressive test for polyester mortar cubes.

Polyester cube ID	Failure compression load (kN)	Area (mm^2)	Compressive stress (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.

Polyester cube ID	Failure tension load (kN)	Area (mm^2)	Tensile stress (MPa)
4	27.9	4900	3.6
5	45.3	4900	5.9
6	26.6	4900	3.4
Average tensile strength			4.3

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Masonry wallets

The experimental results for the six wallets were as follows. 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, as shown in fig. 6(a), and the average failure load for the two wallets was 130 kN. As for the FRP-strengthened wallets W3, W4, W5 and W6, failure of all wallets was by crushing of the top part of the wallets, as can be seen in fig. 6(b), at failure load of average value of 260 kN.

The failure loads of the control and strengthened samples are given in table 7 and fig. 7. The load displacement curves are given in fig. 8.

The obtained results can be attributed to 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. Thus, for all FRP-strengthened wallets the load capacity was increased to almost 200 % of the control sample. The final displacement increased from 11 mm for control samples to 16 mm for strengthened wallets, indicating that the strengthening technique increased the ductility, and thus improved the brittle failure mode.

(a) (b)

Figure 6 Failure modes for a) control wallets, b) FRP-strengthened masonry wallets

Table 7 Failure loads of masonry wallets.

Vault sample ID	Pu (Failure 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 %

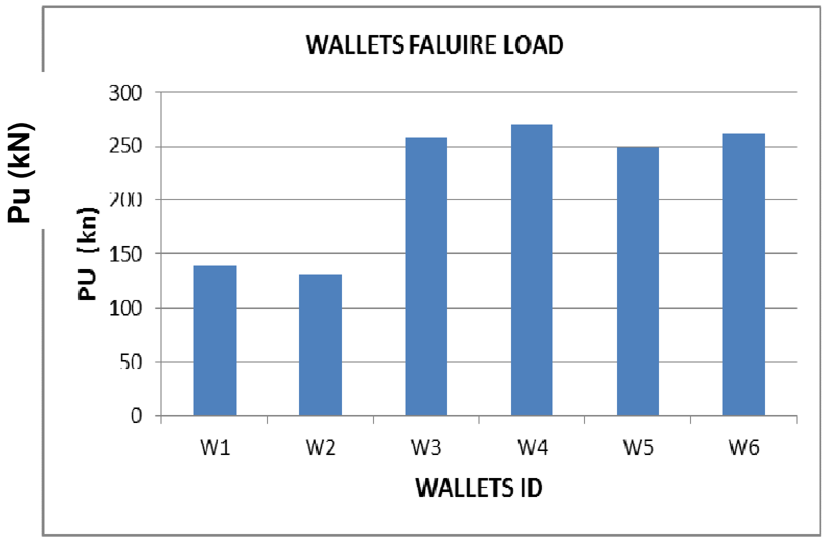


Figure 7 Failure loads of masonry wallets.

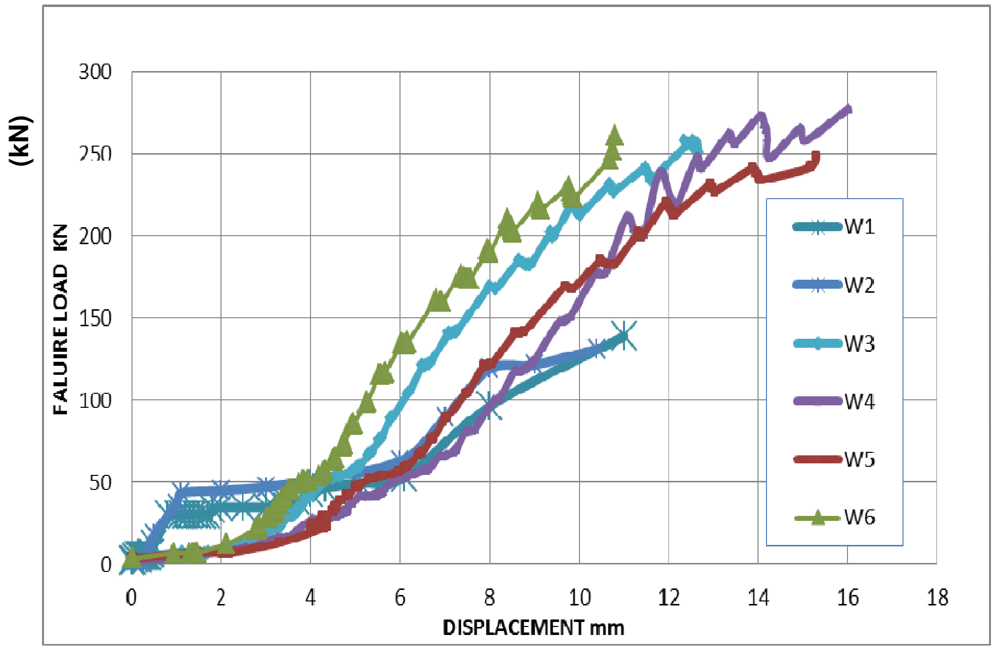


Figure 8 Load-displacement curves for masonry wallets.

4.2 Masonry vaults

The experimental results of the tested vaults showed that failure of the unstrengthened control vaults V1, V2 and V3 occurred when three hinges were formed at the extrados, as shown in fig. 9. The proposed strengthening technique managed to change the crack location as shown in fig. 10. The control vaults gave an average failure load 8 kN, also 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, ferro-cement layer and polymer mortar layer, respectively. The failure loads are given in fig 11 and table 8.

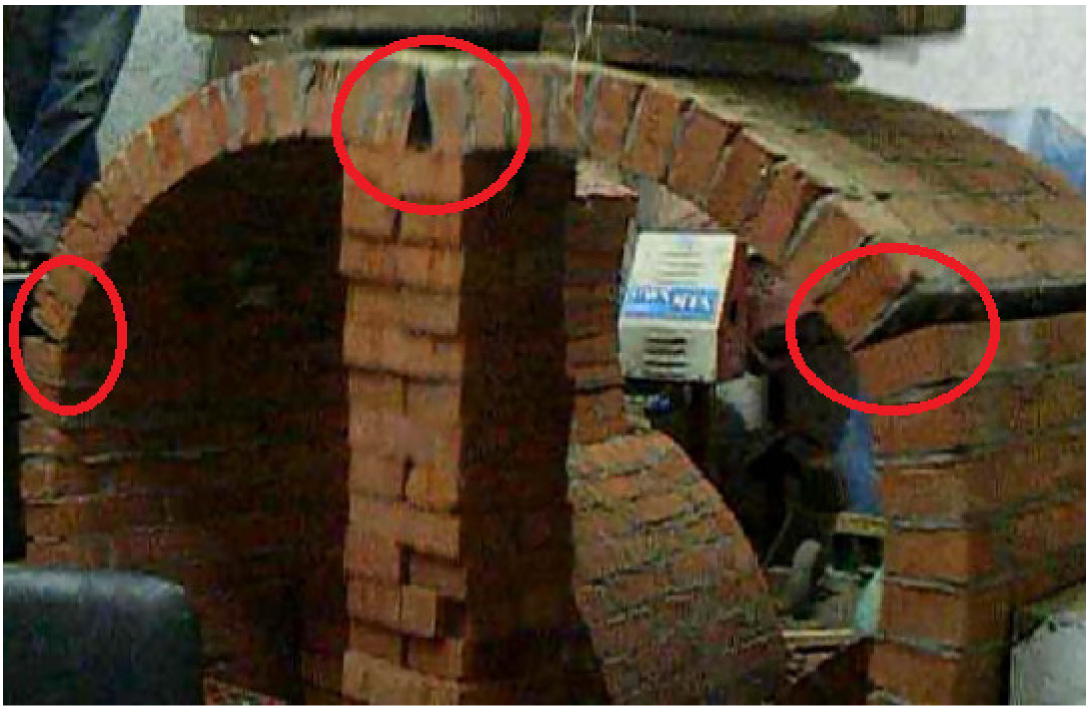


Figure 9 Control masonry vaults failure pattern.

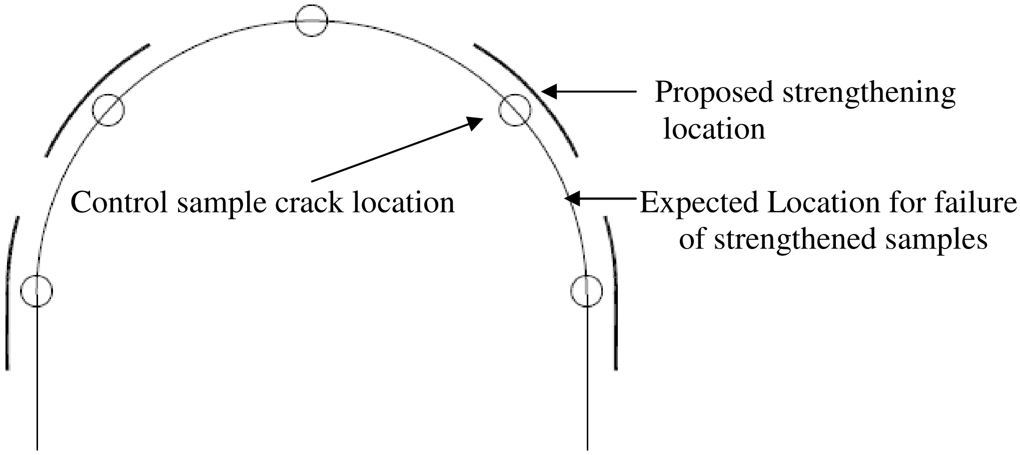


Figure 10 Schematic diagram for strengthening locations, and expected crack locations.

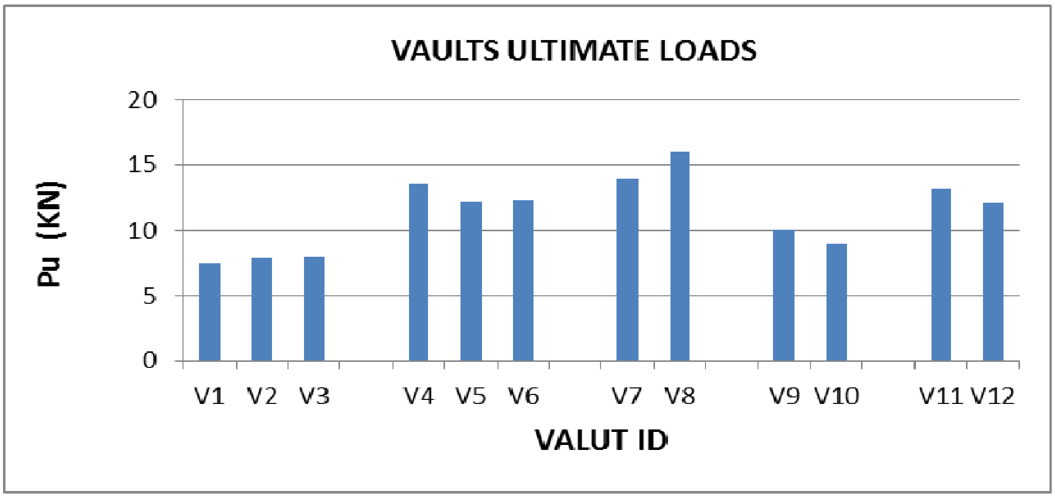


Figure 11 Failure loads of masonry vaults.

Table 8 Failure loads of masonry vaults.

Vault ID	Strengthening techniques	Pu (FALUIRE LOAD) (kN)	Increase of Pu 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 %

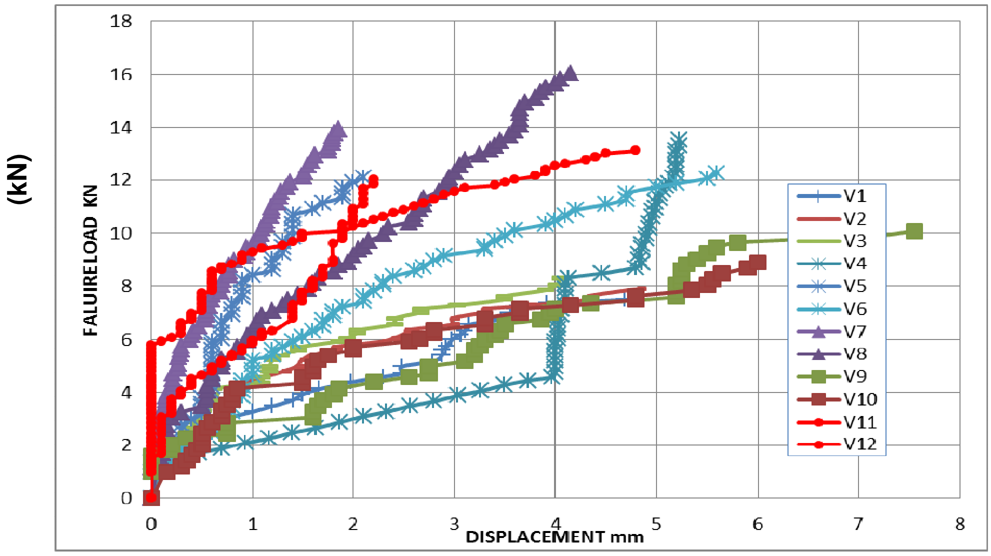


Figure 12 Load-displacement curves for masonry vaults.

The load displacement curves for all vaults, given in fig. 12, indicate that the strengthening increased the stiffness of the vaults, thus causing the final displacements to be less than those of control vaults. However, the adopted partial strengthening did not improve the ductility of the vaults since there are zones which are not strengthened. This means that there are still brittle failure zones causing the observed brittle failure behavior.

The mode of failure mode for vaults strengthened with steel reinforcement, FRP sheets, ferro-cement wire mesh and polyester mortar are shown in figs, 13(a), 13(b), 14(a) and 14(b), respectively. It is observed that the strengthening can stop the crack propagation, and transmit it to the expected location, except for the vaults strengthened with polyester mortar which failed to achieve the proposed behavior. The obtained experimental results demonstrate that the carefully selected position of the applied strengthening succeeded in closing the tension cracks at the location observed in the control vaults and thus moved the formed hinges causing the vault failure away from the location in the unstrengthened case.

Thus, the vaults strengthened with steel reinforcement, FRP and ferro-cement wire mesh succeeded to improve the structural behavior and transmitted the crack formed on the control samples to the unstrengthened location of these vaults. The failure loads indicated that the strengthening using steel reinforcement, FRP and ferro-cement wire mesh increased the ultimate loads to 150 %, 190% and 150%, respectively. The vault strengthened with polyester mortar failed to transmit the crack outside the strengthened zone and slightly improved the failure load with 118%.

(b) (b)

Figure 13 Mode of failure for vaults strengthened by a) steel reinforcement b) FRP sheets

(a) (b)

Figure 14 Mode of failure for vaults strengthened by (a) ferro-cement wire mesh, b) Polyester mortar

From the results of the ultimate loads and the experimentally determined load-displacement curves, it can be concluded that using steel reinforcement bars, ferro-cement layers and externally applied FRP sheets are very effective methods for strengthening unreinforced masonry vaults.

5. CONCLUSION

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 vaults showed that using steel reinforcement and ferro-cement layers placed increased the ultimate load. Using polymer mortar was the least effective technique. The use of externally adhered FRP sheets gave higher strengthening level and better failure mode, in addition to its excellent strength-to-weight ratio, easy installation and the relatively low cost when using glass fiber composites.

6. REFERENCES

1. Croci, G. The Conservation and Structural Restoration of Architectural Heritage. Technical report, Advances in Architectures Series, Computational Mechanical Publications, Southampton UK, 1998, 295 pp.
2. Drysdale, R.G., Hamid, A.A. and Baker, L.R. Masonry Structures: Behavior and Design. Prentice-Hall, Englewood Cliffs, New Jersey, 2001, 883 pp.
3. Lissel, S. L. and Gayevoy, A. The use of FRP in masonry: a state of the art review. In Proc. International Conference on the Performance of Construction Materials, Cairo, Egypt, April 22-25, 2003, pp. 1243–1252.
4. Tan, K.H., Patoary, M. Strengthening of masonry walls against out-of-plane loads using fiber-reinforced polymer reinforcement. Journal of Computations in Construction, ASCE, 2004; 8:79–87.
5. Oliveira, D., Basilio, I., Lourenço, P. Experimental behavior of FRP strengthened masonry arches. Journal of Composites in Construction, ASCE, 2010; 14(3): 312–22.
6. Tao, Y. Fibre reinforced polymer (FRP) strengthened masonry arch structures. PhD Thesis, College of Engineering, University of Edinburgh, UK, December 2012.
7. Valluzzi, M.R, Valdemarca, M., Modena, C. Behavior of brick masonry vaults strengthened by FRP laminates. Journal of Composites for Construction, ASCE; 5(3), 2001:163–9.

8. Anania L., Badalà A., D'Agata, G. The post strengthening of masonry vaults by the -Wrap technique based on the use of CFRP. Construction and Building Materials, 2013; 47, 1053–1068.
9. Sabrah, T.B., Hodhod, O.A., El-Hefnawy, A.A. Simple design approach to rehabilitate unreinforced masonry wallets using ferro-cement overlays. International Workshop for Use of Advanced Composites in Infrastructure, Housing and Building Research Center, Cairo, Egypt, Dec. 2005.
10. Albert M.L., Elwi A.E., Cheng, J.J.R. Strengthening of unreinforced masonry wallets using FRPs. Journal of Composites for Construction, ASCE, 5(2), 2001;76-84.
11. ECP 204-2005. Egyptian Code for Design of Masonry Structures, Ministry of Housing and Urban Communities, Egypt, 2005.
12. Ganzhou Guangjian Fiberglass Company, www.http//en.gjgf.cn, china.
13. Guanda hardware wire mesh company, www.cnmetalwiremesh.com, LTD.
14. Shaikh Zahoor Khalid & S.B. Shinde, "Seismic Response of FRP Strengthened RC Frame" International Journal of Civil Engineering & Technology (IJCIET), Volume 3, Issue 2, 2012, pp. 305 - 321, ISSN Print: 0976 – 6308, ISSN Online: 0976 – 6316.
15. Samir A.Al Mashhadi and Ahmed Hassan Hadi, "Strengthening Reinforced Concrete One Way Slabs by Overlay Technique & Using Cfrp" International Journal of Civil Engineering & Technology (IJCIET), Volume 5, Issue 2, 2014, pp. 52 - 70, ISSN Print: 0976 – 6308, ISSN Online: 0976 – 6316.
16. Dr. Suchita Hirde and Ms. Dhanshri Bhoite, "Effect of Modeling of Infill Walls On Performance of Multi Story Rc Building" International Journal of Civil Engineering & Technology (IJCIET), Volume 4, Issue 4, 2013, pp. 243 - 250, ISSN Print: 0976 – 6308, ISSN Online: 0976 – 6316.