Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (40) No. (4) October, 2018

Experimental Investigation of Unreinforced Masonry Walls with Openings Strengthened by Different Techniques

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ملخص البحث

تكتسب المباني التاريخيه والأثريه مكانه كبيره ومهمه لما تمثله من قيمه تراثيه ومعماريه قيمه, بالاضافه الي المباني الاثريه فتوجد الالاف من المباني السكنيه المبنيه بنظام الحوائط الحامله, من اكثر التحديات التي تمثل هذه المنشأت هي الرغبة في عمل اي تعديلات معماريه وما يتطلبه ذلك الاجراء من عمل فتحات في العناصر الحامله للمباني (الحوائط), ولذا يهدف هذا البحث الي الدراسة العمليه والنظريه لمجموعه من الحوائط بهدف عمل فتحه داخلها ومن ثم دراسة افضل طريقه لتدعيم الفتحه ومحاولة نقل الاحمال و تعويض الجزء المفقود من قطاع الحائط. وتتم الدراسة التحليلية عن طريق التمثيل الرقمي والتحليل اللاخطى باستخدام برامج الحاسب. كما يتم استعراض نتائج الدراسة التحليلية ومناقشة ومقارنة النتائج وعرض الاستنتاجات والتوصيات.

ABSTRACT:

This paper presents experimental investigation of the effectiveness of different strengthening techniques applied around openings in unreinforced brick masonry walls. An experimental program is conducted where 18 masonry walls of dimensions 1200x1200x110 mm were built using clay brick units and cement mortar. Different strengthening techniques such as glass reinforced polymers sheets and strips, near-surface mounted steel bars and ferro-cement layer were made around the intended opening. In-plane loading is applied vertically on the top of the walls up to the service load level, an opening having dimensions 400x800 mm is made in the wall, then the load is gradually increased until failure. The experimental results of load-displacement behavior, ultimate capacity, cracking pattern and failure mode are presented and discussed. The experimental results demonstrate the efficiency of all the studied strengthening schemes in increasing the wall strength. The ferro-cement overlay was demonstrated to be the most efficient and also economic strengthening scheme. The failure load is almost equal to that of the unopened wall, thus the opening made in the wall do not cause decrease in the wall capacity.

Keywords: Masonry, Wall openings, In-plane behavior, Strengthening, NSM bars, FRP strengthening, Ferro-cement.

INTRODUCTION

Masonry wall bearing is the most spread structural system in the world for low rise buildings because of economy and ease in construction. Although masonry walls can carry substantial loads in compression, its load capacity in tension and shear is relatively low, additionally damage may occur in case of earthquakes and if modifications or openings are made in the walls [1].

The main structural elements resisting the vertical loads in masonry buildings are the walls which were originally designed to resist gravity loads. In many cases there is need for architectural modifications requiring introducing doors, windows or any other mechanical openings; thereby the ability of masonry walls to resist vertical loads is significantly weakened. Strengthening will be therefore needed for the unreinforced masonry (URM) wall in order to raise its load carrying capacity and compensate for the openings created in the wall.

Several strengthening techniques may be applied for unreinforced masonry walls. Fiber reinforced polymer (FRP) composites have been reported in many research work [2], and found to be effective for strengthening of unreinforced masonry walls [3, 4], arches [5] and vaults [6]. Also ferro-cement overlay has been used successfully for strengthening of masonry walls [7]. Several strengthening techniques were applied on brick masonry walls and vaults and experimental testing showed their effectiveness in raising the load-carrying capacity and improving the failure mode [8].

Existence of openings reduces the capacity of load bearing walls. Experimental research showed that the load capacity of wall decreases as the opening size increases. The load capacity of wall with small opening was 10% lower than that of plain wall without opening. Large opening wall had a load capacity 80% lower than plain wall without opening [9].

This research presents an experimental program where of several techniques are applied for strengthening of loaded masonry walls in order to be able to make openings. Strengthening is made using glass fiber reinforced polymer (GFRP) laminates and strips, steel bars and ferro-cement layers. The experimental program and results are presented and discussed in the following sections. Conclusions regarding the effectiveness of the studied techniques are given.

EXPERIMENTAL PROGRAM

SPECIMENS AND STRENGTHENING SCHEMES

An experimental program was designed and conducted with the aim of investigating the efficiency of various strengthening scheme for loaded masonry walls in preserving the wall strength after an opening is made in the wall. In order to achieve this aim, an experimental program was conducted where wall samples were built using solid clay bricks common in bearing walls of old buildings. Different strengthening schemes were made to compare their efficiency in preserving the wall capacity after the opening is made. The experimental work was conducted in the Material Testing Laboratory and Reinforced Concrete Research Laboratory of the Faculty of Engineering at Shoubra, Benha University.

The experimental program is summarized in table 1. Eighteen (18) walls are built having dimensions are (1200x1200x110mm) using solid clay brick units. The tested walls are divided into six types, each comprised of three walls: three control walls (WCC1,WCC2,WCC3) have no opening or strengthening; three walls (WOC1,WOC2,WOC3) are not strengthened and have an opening with dimensions (800x400x60 mm); three walls (WLF1,WLF2,WLF3) are strengthened by GFRP sheets; three walls (WSF1,WSF2,WSF3) are strengthened by GFRP strips adhered surrounding the opening; three walls (WFC1,WFC2,WFC3) are strengthened by 15 mm thick layer of ferro-cement; and three walls (WSB1,WSB2,WSB3) strengthened by steel reinforcement bars at the opening edge. The strengthening schemes and dimensions of the walls are shown in Fig. 1.

Additionally, experimental samples were tested to evaluate the mechanical properties of masonry units, mortar cubes, masonry prisms, FRP sheets, FRP strips, ferro-cement welded wire mesh and steel bars.

MATERIALS AND MATERIAL PROPERTIES

Mechanical properties of masonry units, mortar cubes, masonry prisms, FRP sheets, FRP strips, ferro-cement welded wire mesh and steel bars were evaluated by testing of samples.

Table 1: Experimental program

Wall ID	Strengthening scheme
WCC1, WCC2, WCC3	No strengthening – no opening
WOC1, WOC2, WOC3	No strengthening – with opening
WLF1, WLF2, WLF3	GFRP sheets covering the wall
WSF1, WSF2, WSF3	GFRP strips at edges surrounding opening
WFC1, WFC2, WFC3	Ferro-cement overlay of 15 mm thickness
WSB1, WSB2, WSB3	NSM Steel reinforcement bars at opening edge

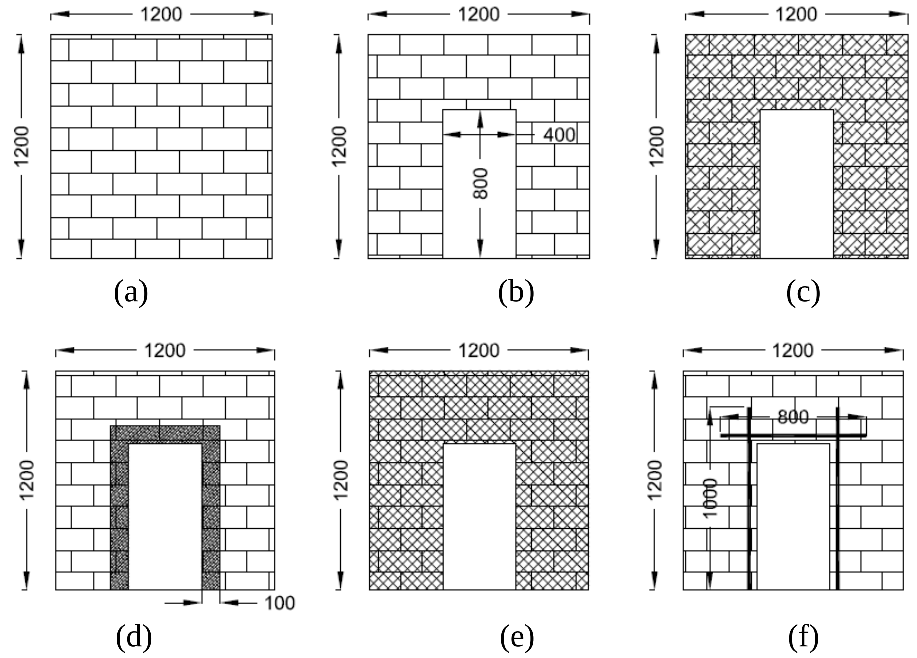

Fig. 1: Dimensions and strengthening techniques of wall samples

a) WCC, b) WOC, c) WLF, d) WSF, e) WFC, f) WSB.

Brick units: Solid clay brick units are used having nominal dimensions (250x120x60 mm). Three bricks were tested by compression test machine till failure as shown in Fig. 2(a). The results are given in table 2, where the average compressive strength is 10.97 MPa.

***Cement mortar*:** The mortar used for all experimental work was mortar type 1 in accordance with the Egyptian code for masonry structures [10]. Three mortar cubes were prepared with dimensions 100x100x100 mm. and tested in compression till failure, as shown in Fig. 3(b). The results are given in table 2, where the average for compressive strength was found to be 19.06 MPa.

***Masonry prism strength*:** Three samples of masonry prisms were prepared as specified by Egyptian code [10] and tested in compression to evaluate the masonry prism compressive strength as shown in Fig. 3(c). The results are given in table 2, where the average compressive strength was found to be 6.76 MPa.

Table 2: Experimental results for compression tests on masonry samples

Test sample		Failure load (kN)	Area (mm^2)	Compressive strength (MPa)
Brick unit	1	317.9	30000	10.6
	2	326.9	30000	10.9
	3	341.5	30000	11.4
	Average compressive strength			10.97
Mortar cube	1	195.3	10000	19.53
	2	197.9	10000	19.79
	3	178.6	10000	17.86
	Average compressive strength			19.06
Masonry prism	1	188.9	30000	6.29
	2	211.5	30000	7.05
	3	208.3	30000	6.94
	Average compressive strength			6.76

(a) (b) (c)

Fig. 2: Compression tests made for a) brick unit, b) cement mortar cube, and c) standard masonry prisms

FRP sheets: The used FRP sheets are E-glass fiber woven roving EWR600, shown in Fig. 3(a) and having the properties given in table 3. The breaking strength is 3800 MPa, and modulus of elasticity 75 GPa. The FRP sheets are adhered using resin composed of polymer material mixed with hardener to accelerate the setting time with volume ratio 2 cm^3 for each liter of polymer material [11].

FRP strips: The used GFRP strip has 100 mm width, 2 mm thickness, mechanical properties given in table 4 and the mode of failure shown in Fig 3(b).

Table 3: Mechanical properties of GFRP sheets [11]

Product code	Fiber diameter (mm)		Mass per unit area (g/m^2)	Breaking strength (MPa)	
	warp	weft		warp	weft
EWR600	17	17	600±30	4000	3800

Ferro-cement wire mesh: Ferro-cement wire mesh is a type of reinforcement used for strengthening of masonry walls in order to increase the tensile and compressive resistance of masonry. The wire mesh shown in Fig.3 (c) is attached to the masonry wall using shear studs and covered with 15 mm cement mortar,
The wire-mesh is made of galvanized wire of diameter 1.5 mm with mesh openings 25 mm, having overall weight of 630 kilograms per cubic meter [12].

Steel reinforcement bars**:** Steel reinforcement used is high grade steel bars, with diameter 10 mm and yield stress 360 MPa.

Table 4: Mechanical properties of GFRP strip

Specific gravity	2.56
Effective strip thickness	0.43 mm
Young's modulus of elasticity	75.9 GPa
Tensile modulus	60 GPa
Tensile Strength	875 MPa
Ultimate strain	0.0146

(a) (b) (c)

Fig. 3: Strengthening materials: a) GFRP sheets, b) GFRP strip, c) steel wire mesh

Fig. 4: Test setup for loading and displacement measurement

TEST SETUP AND EXPERIMENTAL PROCEDURE

The walls are tested by applying vertical load in a 1000 kN testing machine. To simulate the actual condition of making openings in existing masonry buildings, the tested walls are loaded vertically with the working loads, the strengthening measures are executed, the required openings are created and then the load is increased until failure. The experimental procedure consists of three phases, the first phase is to apply vertical load to the masonry wall that increases gradually until 50% of the failure load, in the second phase the strengthening is applied to the wall according to the schemes presented above and then the opening is cut, the third phase is to continue increasing the applied loading until failure. Displacement is measured by strain gauges. The test setup for loading and displacement measurement is shown in Fig. 4.

EXPERIMENTAL RESULTS AND DISCUSSION

CONTROL WALLS

The experimental results for three closed control walls and three control walls with openings are as follows. The failure loads for the closed control walls WCC1, WCC2, WCC3 are 357, 327 and 332 kN, respectively, with an average value of 335 kN for the three walls. The failure modes for all three walls show typical vertical crack along the wall, as seen in Fig. 5.

The failure load for the three control walls with openings WOC1, WOC2, WOC3 are 212, 208 and 224 kN, respectively. The average failure load is 215 KN, which means decrease of vertical load carrying capacity of wall by 33% due to the opening. The failure mode for the three walls show a vertical crack starting at the edge of the opening which is regarded the typical weak point and propagating upwards, as shown in Fig.6.

Fig 5. Failure mode of closed control wall WCC

Fig 6. Failure mode of control walls with openings WOC

Strengthened Walls

For the walls strengthened with GFRP strips (WSF1, WSF2, WSF3), the failure loads are 223, 227 and 244 kN, respectively, and average failure load for wa

lls strengthened by GFRP strips is 231 kN. Failure mode for the three walls is by a typical vertical crack extending from the upper wall edge to the upper tip of the openings at connection of the openings and around opening, as shown in Fig. 7. The walls strengthened with steel bars (WSB1, WSB2, WSB3) the failure load are 245, 270 and 268 kN, respectively, and average failure load for the walls strengthened walls by steel bars walls is 263 kN. Vertical crack extends from the upper wall edge to the upper tip of the openings at connection of the openings a round openings and the bars were detached from walls, as shown in Fig. 8.

The failure loads for walls strengthened with ferro-cement layer (WFC1, WFC2, WFC3) are 335, 318 and 322 kN, respectively, and the average failure load for walls strengthened with ferro-cement layer is 325 KN. The failure mode shows flexure cracks at the top of openings in addition to a vertical crack extending from the upper wall edge to the upper tip of the openings at connection of the openings around the openings, as shown in Fig. 9.

As for the three walls strengthened with GFRP sheets (WFL1, WFL2, WFL3) the failure loads are 230, 218 and 221 kN, respectively, and the average failure load is thus 226 KN. Cracks are formed at the upper edge of the openings beneath the GFRP sheets extending from the upper edge of the wall to the upper tip of the openings at connection of the openings and around openings, as shown in Fig. 10.

The samples average failure loads and percentage of load capacity of strengthened walls to the closed walls are listed in table 5 and plotted in Fig. 11, compared to the control closed and opened walls

Fig. 7: Failure mode for walls strengthened with GFRP strips

Fig. 8: Failure mode for walls strengthened with steel bars

Fig. 9: Failure mode for walls strengthened with ferro-cement layer

Fig. 10: Failure mode for walls strengthened with GFRP sheets

Table 5 Failure loads of masonry walls.

Wall	Strengthening	Average failure load (kN)	Failure load compared to control closed wall	Failure load compared to control opened wall
WCC1,2,3	Control – no opening	335	--------	
WOC1,2,3	Control with opening	215	64.2 %	------
WSF1,2,3	GFRP strips	231	69.9 %	108.8 %
WSB1,2,3	Steel bars	263	78.5 %	122.3 %
WFC1,2,3	Ferro-cement	325	97.0 %	151.2 %
WFL1,2,3	GFRP sheets	226	67.5 %	105.1 %

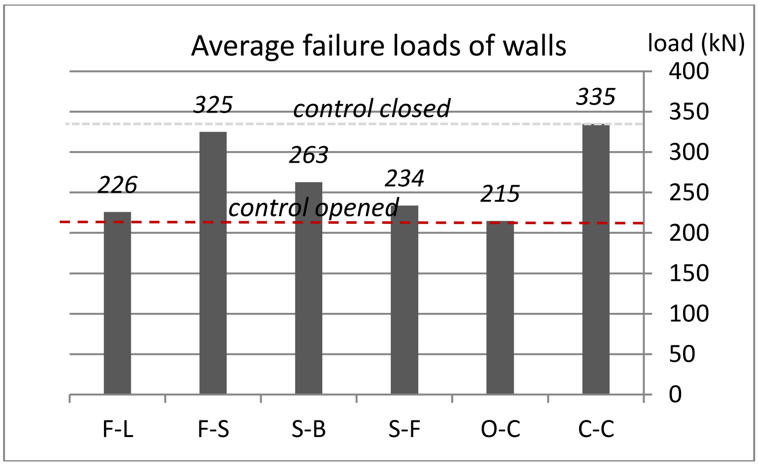

Fig. 11: Failure loads of masonry walls

CONCLUSIONS

In this research, an experimental program was conducted to study the efficiency of different strengthening techniques to make openings in already existing loaded masonry walls safely and economically. The obtained experimental results demonstrated that the studied strengthening techniques increased the capacity of the opened walls by an average increase of 5 and 8% for strengthening options by GFRP sheets and GFRP strips, respectively, while the walls strengthened with steel bars increased by 22% over the opened wall and reached 78% of the control wall capacity. The most efficient and economic technique for strengthening masonry walls to make openings is demonstrated to be Ferro-cement overlay in which the capacity of the strengthened walls with openings is almost the same as the control closed wall.

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