Strengthening loaded masonry walls to enable making openings – experimental and numerical investigation

Gehan Hamdy, Tarik El-Salakawy, Ahmed El-Gendy

Abstract— Wall bearing masonry is the structural system of a considerable portion of residential buildings worldwide. Occasionally it is required to make window or door openings in the loaded walls, which presents a threat to the building safety unless strengthening of the wall is performed before making the required opening. This paper presents testing, numerical modeling and nonlinear analysis of several external strengthening schemes performed on vertically loaded masonry walls prior to making openings in the walls. An experimental program was conducted where eighteen unreinforced brick masonry walls with dimensions of 1200x1200x110mm are loaded by service load, twelve of the walls are strengthened by different materials and schemes, the openings is made, then the vertical load on the wall is increased until failure. The strengthening schemes are made in the loaded wall surrounding the intended opening using fiber reinforced polymer sheets and strips, steel reinforcement bars and ferro-cement layer. The obtained experimental results demonstrate the efficiency of the strengthening methods in compensating the reduction of wall capacity due to opening. Numerical modeling of the tested walls by finite elements and nonlinear analysis are carried out using commercial software. Agreement between numerical and experimental results demonstrates the efficiency of the numerical approach. Application is made on an actual case where a door opening was required to be made in a wall in the ground floor of an old building. Numerical modeling and nonlinear analysis are made to design strengthening and study its efficiency in preserving the wall carrying capacity. The obtained results illustrate the applicability of the proposed approach as a practical and valid tool for design of strengthening measures for the frequent requirement of making openings in existing load-bearing masonry walls while subjected to service loads.

Index Terms — masonry wall, openings, strengthening, experimental, finite elements, nonlinear analysis.

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1 Introduction

UNREINFORCED masonry walls constitute the load-bearing elements of most of the existing buildings. In some cases, there is need to make openings in such load-bearing wall for architectural or functionality reasons. Making an opening in a masonry wall reduces the wall stiffness, load carrying capacity and ductility [1]. Brick walls with small and large openings were tested by Moussa and Aly [2] and Bahaa et al [3] under in-plane diagonal load increasing up to failure; the decrease in the load capacity was 10-30% and 50-80% for walls with small and large opening, respectively. Masonry walls with openings tested under compression by Etman et al. [4] showed reduction of the failure load and stiffness and increase of deflection. The increase in the opening size decreased the overall stiffness and reduced the strain capacity of the wall leading to earlier failure [4].

If it is required to make a large opening in a masonry wall, strengthening is needed in order to compensate the reduction of wall stiffness and preserve the carrying capacity of the wall. Several strengthening methods are available for retrofitting existing masonry elements and structures [5]. Amanat et al [6] tested a masonry infill walls rehabilitated with ferrocement coating (layer of mortar and a steel wire mesh) under vertical load and reported significant improvement in wall strength, ductility and failure mode. Yardim and Lalaj [7] tested masonry walls retrofitted with ferrocement and other techniques under diagonal compression test; the walls with ferrocement and polypropylene mortar plaster showed significant improvement in shear strength capacity of up to 412% compared to control specimen [7]. Brick masonry panels strengthened by welded steel wire mesh were tested by Kadam et al. [8] and Shermi and Dubey [9] showed increase in out-of-plane capacity by about 10 times and increase of ductility. Benerjee et al [10] tested masonry wall specimens strengthened by polypropylene band and steel wire mesh showed that both techniques enhanced the flexural strength and ductility and delayed the wall collapse.

Fiber reinforced polymers (FRP) were used as external strengthening for masonry walls and enhanced the performance under in-plane monotonic or cyclic loading; improvement of deformability, ductility and seismic behavior were reported [11], [12]. Masonry walls with openings strengthened using externally adhered glass fiber reinforced polymer (GFRP) sheets were tested by Moussa and Aly [2] and showed increase of load carrying capacity 150% for solid walls, 94% for walls with small opening and 280% for walls with large opening. Walls strengthened with FRP strips around openings achieved 80-90% of the failure load of the walls strengthened on the whole surface, indicating the effectiveness of FRP laminate strips in retrofitting of walls with openings. Application of GFRP laminates on brick wall panels was demonstrated by Bahaa et al [3] to increase the compression capacity, stiffness and toughness up to 41%, 59% and 256%, respectively. Strengthening by GFRP also increased shear capacity, rigidity and ductility up to 68 %, 63% and 139%, respectively [3]. Velazques et al. [13] and Kalali and Kabir [14] tested masonry walls with window openings retrofitted with vertical or diagonal GFRP strips under lateral cyclic load.

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Strengthening by GFRP significantly increased the in-plane resistance by a factor of 1.5–4 and improved the deformation capacity, ductility and energy absorption. Nasser [15] tested brick masonry walls with openings under compressive loading; strengthening was made around the opening by longitudinal or diagonal GFRP laminates and fiber-reinforced mortar, and the efficiency of both retrofitting schemes was observed. El-Diasity et al. [16] tested confined masonry walls with and without openings retrofitted using ferrocement and GFRP and subjected to inplane cyclic loading. The upgrading techniques improved the lateral resistance of the walls by 25-32 % and also improved the total energy dissipation by 33-85%.

However, the design of such strengthening for the wall to introduce openings is made based on experience and construction practice rather than accurate design, and is often overdesigned to provide excessive safety. Precise prediction of the structural behavior of the strengthened wall after making the opening is quite complicated since nonlinear analysis is required and the interaction between masonry and the strengthening materials should be represented. The need for an accurate design tool for such a case is thus pointed out.

This paper presents experimental and numerical analysis of unreinforced masonry walls strengthened by different schemes when openings are made while the walls are loaded with the service load. The suggested moderate-cost external strengthening techniques use near-surface-mounted steel bars, ferrocement layers and glass fibre reinforced polymer (GFRP) sheets and strips. The effectiveness of the strengthening in preserving the load capacity of the walls is evaluated. Finite element modeling and nonlinear analysis are performed for the tested walls using commercially available computer software ANSYS v.12 [17]. The numerical procedure is presented and the results are compared with the experimental results. Moreover, the proposed numerical approach is applied on an existing building; where numerical study is conducted for study of strengthening for a brick masonry wall to opening is made in the wall.

2 Experimental Program

2.1 Overview of Experimental Program

An experimental program was conducted to investigate the efficiency of suggested strengthening techniques in preserving the capacity of masonry walls after openings are made. The experimental setup is designed to simulate the actual case; brick wall specimens were loaded vertically with service loads, strengthened by different techniques, openings were made in the loaded wall, then the load was increased gradually until failure. Laboratory tests were also carried out to determine the mechanical properties of masonry units, mortar, masonry prisms and the strengthening materials. The experimental program was performed at the Concrete and Composite Structures Laboratory of the Faculty of Engineering at Shoubra, Cairo, Egypt.

2.2 Materials and Material Tests

Masonry units: The masonry units used are solid clay bricks clay brick (230 x 110 x 65 mm). Three brick units were tested in compression until failure according to Egyptian Standard Specifications ESS: 1524/1993 [18] as shown in Fig. 1 (a); the average compressive strength was 10.97 MPa.

Mortar: The mortar used for all experimental work was mortar type 1 according to the Egyptian code for masonry structures (ECP 204- 2005) [19]. Ordinary Portland cement 32.5N confirming to ESS requirements and medium well-graded sand of fineness modulus 2.2 were used for mortar. The ratio of cement: sand was 1:3 by volume. Three mortar cubes of dimensions 100x100x100 mm were cast and tested after 28 days in compression; the average compressive strength was 19.06 MPa

Masonry prism: Three samples of masonry prisms were prepared consisting of 3 stacked units and tested in compression as per ECP 204-2005 [19], the average compressive strength (fm') was 6.76 MPa.

Steel reinforcement: The steel reinforcement used was high strength steel bars (Grade 360/400) with diameter 10 mm, yield stress (fy) of 360 MPa, ultimate tensile strength (fu) 400 MPa and modulus of elasticity (Es) 200 GPa. Epoxy is used to fix the steel bars in grooves made in the masonry wall surrounding the intended opening.

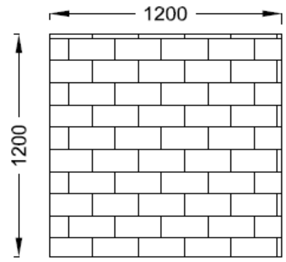
GFRP sheets: The used FRP sheets were E-glass fiber woven roving EWR600, shown in Fig. 1 (b), having fiber diameter 17 µm, density 600 gm/m2, breaking strength 3800 MPa and modulus of elasticity 75 GPa. The FRP sheets were adhered with polyester resin h tensile strength 41 MPa, flexural strength 79 MPa, tensile elongation 1.2%.

GFRP strips: GFRP laminates of 100 mm width and 2 mm thickness are used, shown in Fig. 1 (c), having specific gravity 2.56, tensile strength 875 MPa, tensile modulus 60 GPa, maximum tensile strain 0.0146.

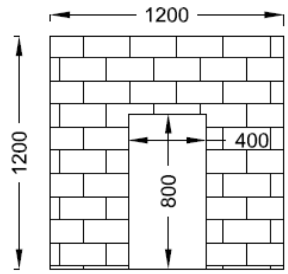
Steel wire mesh: Galvanized steel welded wire mesh with opening size 25 mm is used, Fig. 1(d), weight 630 kg/m^3 (0.945 kg/m^2), wire diameter 1.5 mm made of mild steel having yield stress fy 240 MPa, ultimate tensile strength fu 350 MPa and modulus of elasticity Es 200 GPa.

(a) solid clay brick | (b) GFRP sheets | (c) GFRP strips | (d) steel wire mesh

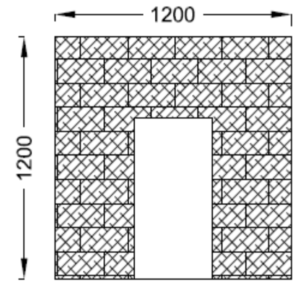
Fig. 1. Material used in the experimental work



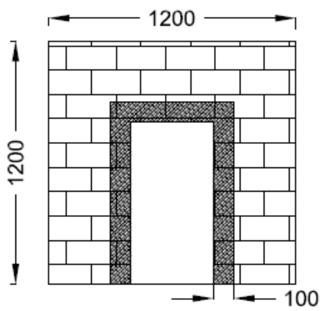
(a) WCC unstrengthened wall



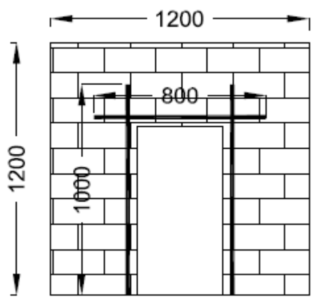
(b) WOC unstrengthened wall



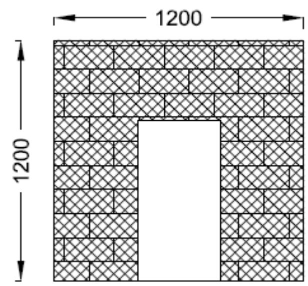
(c) WLF wall strengthened by GFRP sheets



(d) WSF wall strengthened by GFRP strips



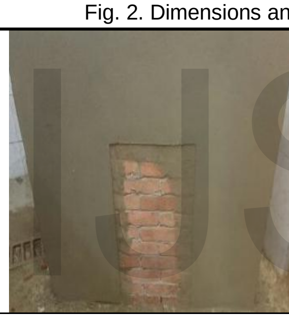
(e) WSB wall strengthened by steel bars



(f) WFC wall strengthened by ferrocement

Fig. 2. Dimensions and strengthening techniques of the tested walls

(a) expanded wire mesh fixed on wall



(b) covering wire mesh by cement mortar

(c) GFRP sheets

(d) GFRP strips

(e) steel bars

Fig. 3. Walls specimens strengthened using the suggested schemes

2.3 Preparation of Wall Specimens

Eighteen unreinforced masonry walls were constructed with dimensions 1200x1200x110 mm. Six walls are not strengthened and are considered control walls; three of these walls will not be opened (WCC1, WCC2, WCC3) and the other three walls (WOC1, WOC2, WOC3) are to be opened during loading, the opening is 400mm wide and 800mm high with area about 22.2% of the wall area, illustrated in Fig. 2. Twelve walls are strengthened around the intended opening using four suggested techniques: three walls (WLF1, WLF2, WLF3) are strengthened by externally adhered GFRP sheets; three walls (WSF1, WSF2, WSF3) by GFRP strips; three walls (WSB1, WSB2, WSB3) strengthened by steel bars of diameter 10 mm inserted into grooves and adhered by epoxy; and three walls (WFC1, WFC2, WFC3) by ferro-cement layer made by fixing the galvanized steel wire mesh to the masonry wall after spatter dashing it by nails every 100 mm in both directions and then covering with cement mortar layer to a total thickness of 20 mm, the strengthened walls are shown in Fig. 3.

2.4 Test Set-up and Testing Procedure for Walls

The walls were tested by applying vertical load in a compression machine of capacity 500 kN that uses low profile pancake-type load cells with the threaded hole running completely through the center of the cell. A steel I-beam was placed on the top to distribute the compression load on the wall, also a steel U-beam under the wall was used for fixing. To measure displacement, LVDT and strain gauges were installed 350 mm from the top of all walls, and connected to the computer to record the displacement with time, as shown in Fig. 4. The loading speed is controlled by adjusting the hydraulic control and resistors in the machine until half the load of the closed control walls is achieved, found to be 170 kN. Then an opening with dimensions of 400 x 800 mm is made in the wall, and the vertical load is gradually increased until failure, Fig. 5.

(a) testing machine | (b) strain gauges installed in wall | (c) data logger

Fig. 4. Test setup and instrumentation for walls

(a) making opening in the loaded wall | (b) increasing load on the opened wall | (c) failure of wall with opening

Fig. 5. Making the opening in the loaded walls and loading until failue

2.5 Experimental Results

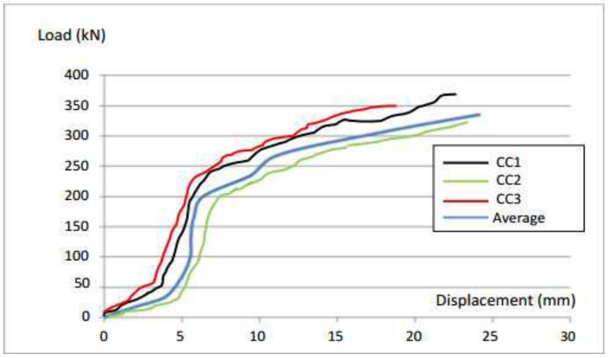
The obtained experimental results for all the tested walls regarding ultimate vertical load and maximum recorded displacement before failure are listed in Table 1. For the solid control walls WCC, the first vertical crack appeared at vertical load of 160 kN in the middle of the wall, by increasing the load more vertical cracks appeared until failure happened at an average load of 335 kN (average of the three tested walls). For all the other walls with openings, the walls were loaded up to 170 kN, representing the service load (calculated as 50% of the ultimate load of the solid control wall), then the opening was made and the load increased. The average ultimate failure load for solid control walls (WCC) was 335 kN, and for control walls with openings (WOC) the average ultimate failure load was 215 kN. The opening thus decreased the ultimate wall load by an average of 35.8% and increased the vertical displacement before failure by 27.7%. As given in Table 1, the average ultimate failure loads of walls strengthened with GFRP sheets, GFRP strips, steel bars and ferro-cement were 226kN, 234 kN, 263 kN and 325 kN, with efficiency 67.4%, 69.85%, 78.5% and 97%, respectively, of the control wall with no opening. The stress-strain relations for all the tested walls are shown in Fig. 6.

For the strengthened walls, the first vertical crack initiated at the middle of the opening at an average load of 164 kN, 162 kN, 163 kN and 168 kN for walls strengthened by GFRP strips, GFRP sheets, steel bars and ferro-cement layer, respectively, in the brick unit at the middle of the wall. After making the opening and increasing the load, a diagonal stepped crack

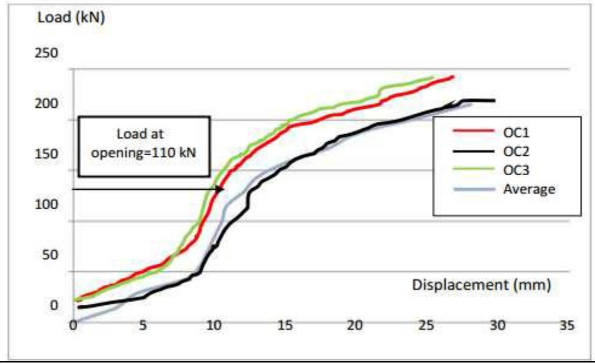
TABLE 1
EXPERIMENTAL RESULTS FOR CONTROL AND STRENGTHENED WALLS

Wall ID	Strengthening	Max. disp. (mm)	Failure load (kN)	Failure load av. (kN)	% inc. over WOC	% of Pult/Pult of WCC	Avg. max. disp. (mm)
WCC1		26.3	23.3				
WCC2	none	21	20.5	335	---	---	22.0
WCC3		25	22.2				
WOC1		212	32.2				
WOC2	none	208	26.4	215	---	64.2 %	28.1
WOC3		224	25.7				
WLF1		230	14.2				
WLF2	GFRP sheets	218	11.1	226	105 %	67.4 %	13.3
WLF3		221	14.6				
WSF1		223	12.5				
WSF2	GFRP strips	227	10.2	231.3	108.8 %	70 %	11.1
WSF3		244	10.6				
WSB1		245	21.4				
WSB2	steel bars	270	22.8	263	122.3 %	78 %	20.5
WSB3		268	17.3				
WFC1		335	10.5				
WFC2	ferro-cement	318	8.7	325	151.2 %	97%	9.5
WFC3		322	9.3				

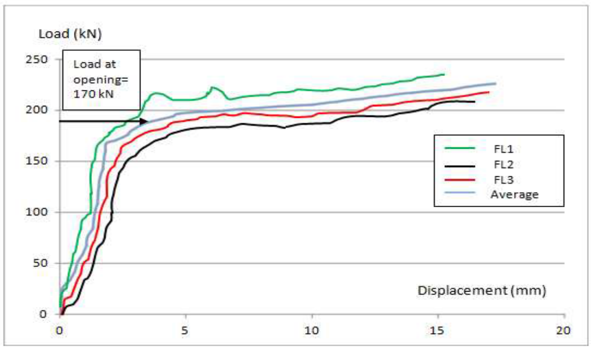
started to appear between the corner of the opening and the corner of the wall and extended towards the corners until the wall failure, thus the mode of failure transitioned from shear failure to diagonal tension failure, and debonding occurred between the wall and the strengthening at failure. For walls strengthened by ferro-cement layer, vertical shear crack at the corner of the opening and extended to the wall top until fail-



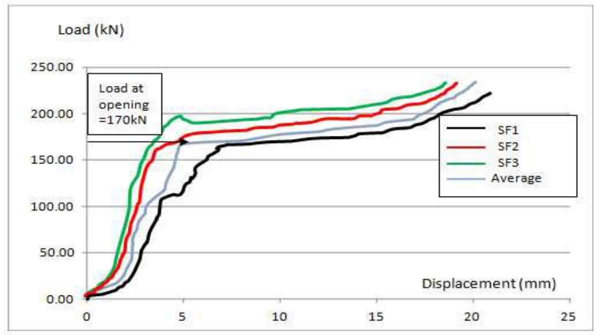
(a) unstrengthened closed walls WCC



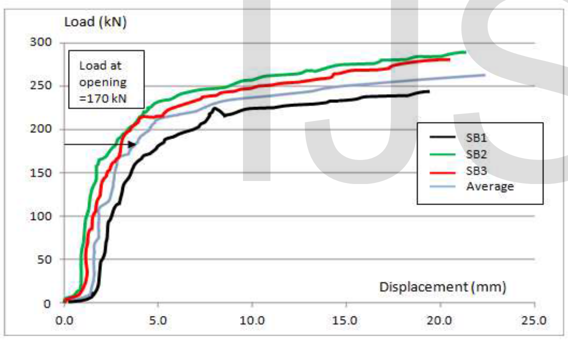
(b) unstrengthened opened walls WOC



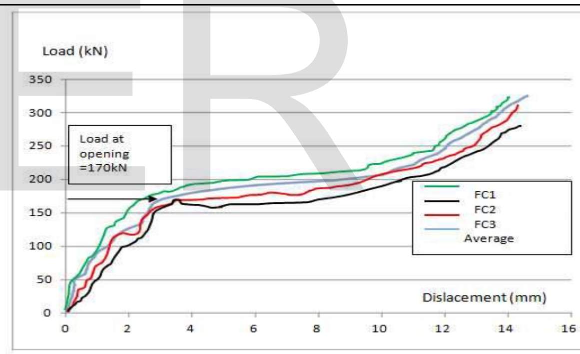
(c) WSL strengthened by GFRP sheets



(d) WSF strengthened by GFRP strips



(d) WSB strengthened by steel bars



(e) WFC strengthened by ferrocement layer

Fig. 6 Load-displacement relations for tested walls

ure load of average value of 325 kN, i.e. approaching the ultimate load of the unopened wall. The modes of failure of the tested walls, shown in Fig. 7, are similar to test results of other researchers. Moussa and Aly [2] reported that brick walls without openings subjected to in-plane diagonal load showed splitting and local crushing at the loading zones, followed by shear sliding over the whole length of the wall. Walls with openings had splitting along the vertical axis from the opening corner towards the loading points, then sliding along the mortar joint [2].

3 Numerical Modeling and and nonlinear analysis of the Tested masonry walls

3.1 Approaches for masonry numerical analysis

Numerical representation of the structural behaviour of masonry is complicated due to its non-homogeneous nature (being composed of masonry units and mortar), in addition to the nonlinear and directional properties. The Finite Element Method (FEM) is one of the most used approaches for structural analysis, where the structure is divided into a number of elements with well-defined mechanical and physical properties. Two main approaches can be followed for modelling masonry using FEM; these are the micro-modelling and macro-modelling approaches [20]. In the detailed micro-modelling approach, masonry units and mortar joints are described using continuum finite elements, and the unit-mortar interface is represented by discontinuous elements accounting for potential crack or slip planes [21]. In this approach, details of the geometry and composing elements and materials are required, as well as the elastic and inelastic mechanical properties. Detailed micro-modelling yields accurate results, but it requires much computational effort and time, which makes it unpractical and suitable for studying localized areas. Simplified micro-models were developed that use interface elements to represent bond-slip between brick and mortar and reduces compu-

(a) WCC	(b) WOC	(c) WFL	(d) WFS	(e) WSB	(f) WFC

Fig. 7. Failure modes of the experimentally tested walls

tation time [22]. On the other hand, the macro-modelling (homogeneous or continuous modelling) approach considers masonry units and mortar as continuum and establishes a relation between the average extensions and stresses of the masonry [23]. Macro-modelling requires less computation time and is therefore more common and suited for analysis of large members or full structures [24]. The smeared crack scalar damage models used for reinforced concrete structures were adapted for macro-modelling of masonry, where damage is defined in a given point by a scalar value which varies from the elastic state until collapse, and the cracking is considered distributed along the structure [25].

Masonry structures demonstrate nonlinear behaviour at small loads because of the low tensile strength of masonry; therefore using linear analysis cannot properly describe initiation and propagation of cracks up to final collapse, which can be described by nonlinear analysis only [23]. Nonlinear macro models define elastic and inelastic parameters based on experimental study of units, mortar and assemblages or numerical homogenization techniques. Use of volumetric 3D elements in the numerical model allows more accurate representation of the stresses within the thickness of a wall and at the intersection zones.

Unreinforced brick masonry walls with openings were modelled by Kalali and Kabir [26] using finite elements and nonlinear analysis was performed using commercial program ANSYS v.12. Numerical modelling of strengthened masonry elements is more difficult because of the complex interaction mechanisms between masonry and strengthening material. Gattulli et al [27] used simplified 2D finite element modelling strategy where the nonlinear behavior of the masonry was represented by a macroscopic smeared crack approach, while the FRP strips were modelled using truss elements directly connected to the nodes of the mesh of the panel without using interface elements. Grande et al. [28] modelled masonry panels and a building façade reinforced with FRP strips using finite elements for the masonry, for the FRP, and for the masonry-FRP interaction, through using specific constitutive material models for each case study. Gabor et al. [29] analysed the in-plane shear behaviour of unreinforced masonry panels using detailed modelling of the bricks and mortar and simplified models based on homogenized masonry continuum. For masonry panels reinforced with FRP strips, masonry is modeled with elements characterized by membrane stiffness and tension-only behaviour, the nodes of the masonry elements are coupled with those of the composite strips assuming perfect bonding between the two elements. Kabir et al [30] presented a finite element smeared crack homogenization approach for modelling FRP strengthened brick walls with openings, using the commercial software ANSYS.

3.2 Developed Numerical Analysis Procedure

In this work, numerical modelling and nonlinear analysis are made for unstrengthened and strengthened masonry walls using commercial software ANSYS V.15 [17]. Macro-modelling approach is considered where masonry is considered an isotropic material with homogenized properties. The smeared cracking approach is adopted, where cracking of the masonry occurs when the principal tensile stress exceeds the ultimate tensile strength. The elastic modulus of the material is then assumed to be zero in the direction parallel to the principal tensile stress direction. The SOLID65 element is capable of cracking in tension and also crushing in compression. A failure model developed by Willam and Warnke [31] for multiaxial stress state is considered which uses the Von Mises yield criteria coupled with an isotropic work hardening assumption to account for crushing and cracking of concrete.

Masonry material behavior is described by a piece-wise linear total stress-total strain curve, starting at the origin, with initial slope corresponding to the elastic modulus [32]. The user defines the material tensile strength, compressive strength, and shear transfer coefficient which represents shear strength reduction factor for subsequent loads that induce sliding shear across the crack face and ranges from zero to 1.0. Suggestions for shear transfer coefficient are found in the literature; Sandeep et al. [33] suggested 0.3 and 0.6 for open and closed cracks, respectively. Isotropic hardening material simulates the steel bars, steel wire mesh and FRP layers, with a bilinear stress-strain curve starting at the origin with initial slope taken as the elastic modulus of the material and, the curve continues after the specified yield stress at a lower slope defined by the tangent modulus. Full bond is assumed to occur between masonry and the strengthening materials. Finite element analysis with the smeared crack approach (using SOLID65 element) has been previously used by several researchers to simulate the behavior of unreinforced [26] and FRP strengthened walls [30], and showed agreement with experimental results. Also, this modelling approach has been previously developed and applied to strengthened masonry elements, it has managed to describe efficiently the experimental behaviour and explain the observed cracks [34].

International Journal of Scientific & Engineering Research Volume 9, Issue 11, November-2018
ISSN 2229-5518

3.3 Numerical Analysis of the Tested Masonry Walls

3.3.1 Finite Elements Used

Masonry material (brick and mortar) is modelled in macro-modeling strategy using three-dimensional solid elements, SOLID 65, having eight nodes with three translational degrees of freedom at each node, the element is capable of directional integration point crushing and cracking. Steel reinforcement bars and grid are modelled by the 2-node bar element LINK 8, where elasticity, creep, swelling, stress stiffening, and large deflection capabilities are included. The GFRP sheets and strips are modelled using the 4-node element SHELL 41 having six degrees of freedom at each node, plasticity, stress, creep, large deflection, stiffening, and large strain capabilities.

The finite element meshes of the different wall types and strengthening are shown in Fig. 8.

3.3.2 Material Properties

The material properties used in modelling of masonry and strengthening material are based on experimentally evaluated properties, and are listed as follows:

1. Masonry: compressive strength f'm = 6.76 MPa, modulus of elasticity Em = 595 MPa, weight density = 16 kN/m3, Major Poisson's ratio = 0.15, tensile strength = 0.1f'm = 0.676 MPa, stress-strain relation in Fig. 9.
2. Steel reinforcement: yield stress fy = 360 MPa.
3. GFRP: ultimate tensile strength = 3800 MPa, modulus of elasticity = 75000 MPa
4. GFRP strips: tensile strength = 875 MPa
5. Ferro-cement steel wire mesh: steel yield stress = 240 MPa, mortar compressive strength = 19 MPa.

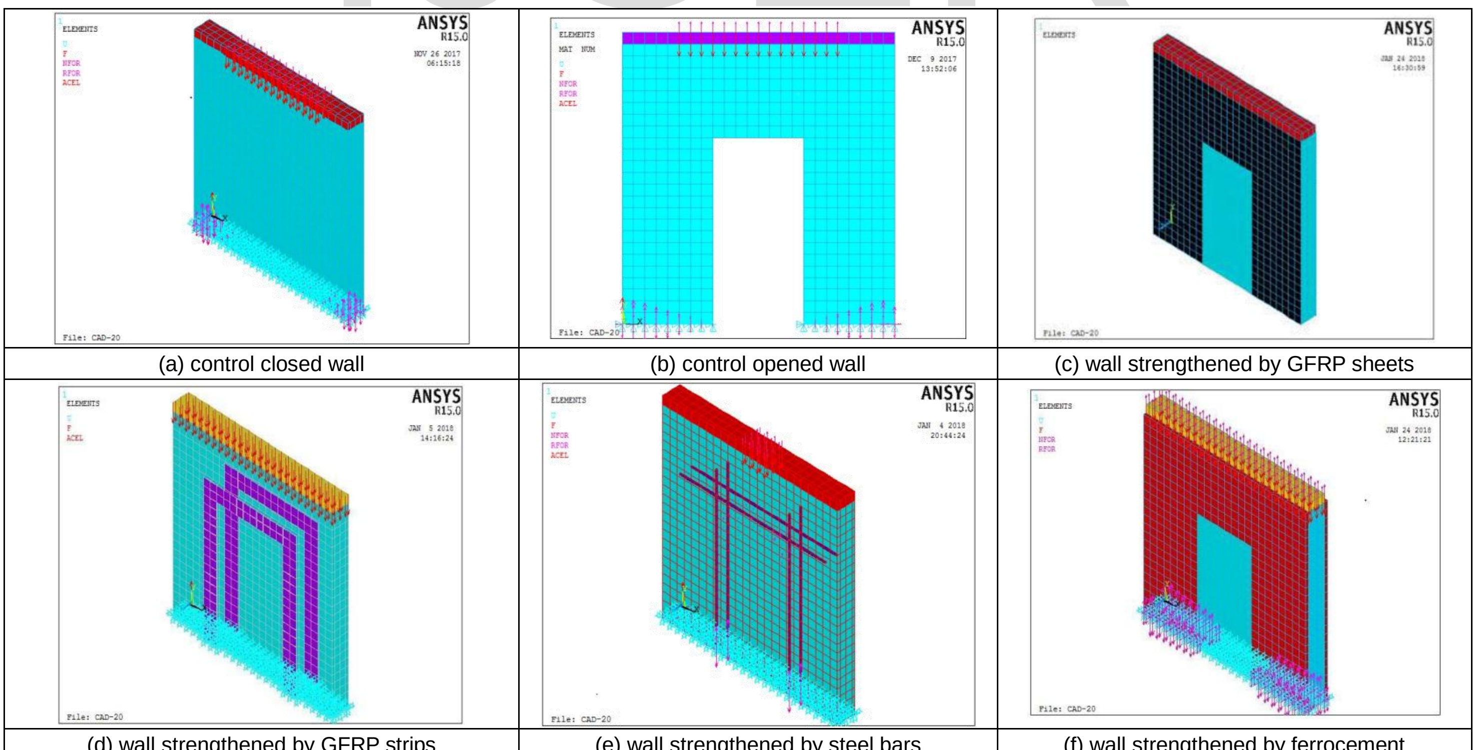
3.3.3 Loading and Boundary Conditions

An incremental load was applied on the top of the walls similar to that conducted in the experimental program. The load on the control solid wall was increased until failure. For the opened and strengthened walls, the vertical load was increased up to the service load (50% of expected ultimate load). Then the elements representing the opening with dimension 800x800x110mm are removed by using 'kill element' feature in ANSYS, where the element is still present in the solution but inactive, then the loading is increased until failure. The self-weight is included in the analysis.

3.3.4 Nonlinear Analysis Parameters

Iterative solution procedure based on the modified Newton–Raphson method was employed in order to simulate nonlinear behaviour. The load is applied at 20 load steps; within each load step, equilibrium iterations are made until convergence criteria are satisfied and a converged solution is reached. The coefficients and parameters for nonlinear analysis are assigned the following values.

1. Shear coefficient along opening cracks (ShrCf-pO) = 0.2
2. Shear coefficient along closed cracks (ShCf-Cl) = 0.8
3. Tension limit, cracking limit (UnTensSt) = 0.676 MPa
4. Compression / crushing limit, (UnCompSt) = 6.76 MPa
5. Number of load substeps solution = 20
6. Convergence criteria: program chosen.



(a) control closed wall | (b) control opened wall | (c) wall strengthened by GFRP sheets

(d) wall strengthened by GFRP strips | (e) wall strengthened by steel bars | (f) wall strengthened by ferrocement

Fig. 8. Finite element 3D mesh of the tested walls

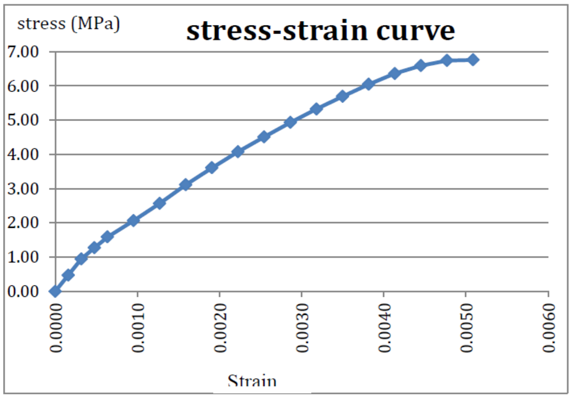


Fig. 9. Adopted stress strain relationship for masonry

3.4 Numerical Results

The ultimate loads and maximum displacements for walls are listed in Table 2, compared to the experimental results. The numerically evaluated stresses, maximum deformations and crack pattern at failure load are shown in Figs. 10 and 11 for the unstrengthened closed and open wall, respectively. For the strengthened walls, the stresses, deformations before failure and crack pattern are shown in Figs. 12- 15. The numerically estimated load-displacement relations for the studied walls are plotted in Fig. 16 compared to the experimentally determined relations.

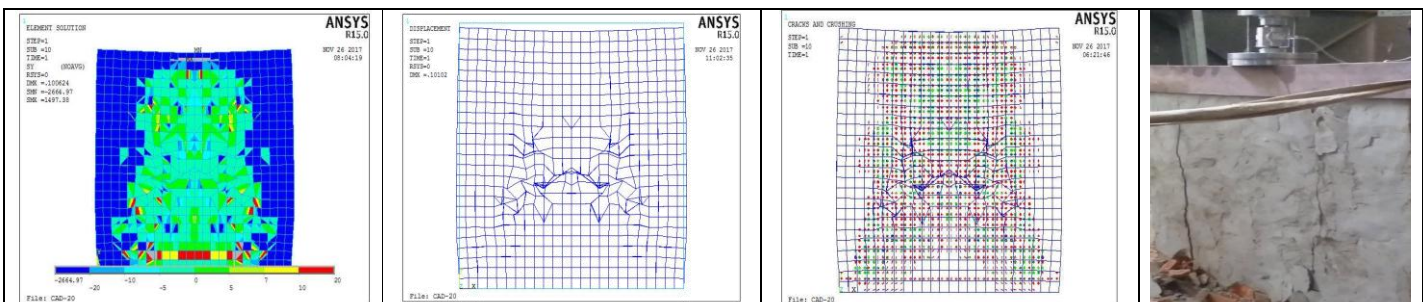
TABLE 2
NUMERICAL AND EXPERIMENTAL RESULTS FOR ULTIMATE LOADS AND MAXIMUM DISPLACEMENTS

Wall	Strengthening	Max.load (kN)			Max.disp. (mm)		
		Avg. exp.	Num.	Num/ Exp	Avg. exp.	Num.	Num/ Exp
WCC	------	335	340	1.015	22	20.0	0.91
WCO	------	215	230	1.069	28.1	25.0	0.89
WFL	GFRP sheets	226	241	1.066	13.3	10.7	0.80
WSF	GFRP strips	231	252	1.091	11.1	9.5	0.85
WSB	Steel bars	263	350	1.331	20.5	15.2	0.74
WFC	Ferrocement	325	355	1.092	9.5	8.0	0.85

3.5 Comparison with Experimental Results

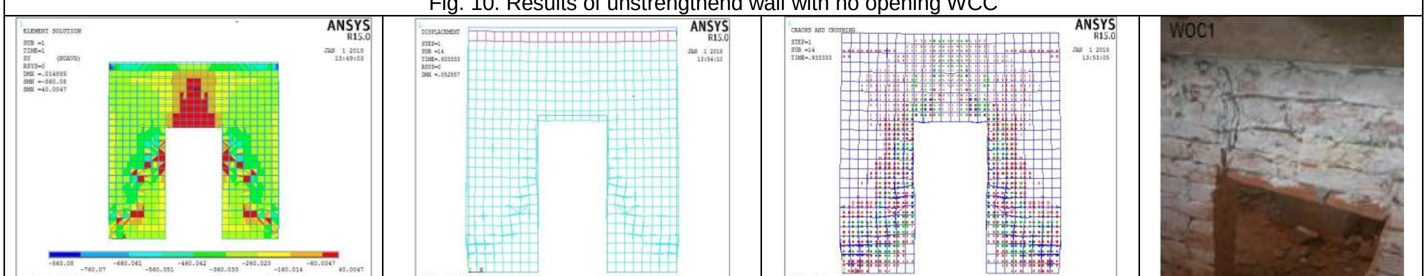
The ultimate loads and maximum displacement of walls in Table 2 and plotted in Fig. 17, show good agreement between numerical and experimental results.

It can be observed from Fig. 17 that the numerical analysis slightly overestimates the maximum load capacity (1.5 -9.2 % except for the walls strengthened with steel bars 33 %) and underestimates the maximum displacement (74% up to 91% of the experimental values). For the load-displacement curves obtained by numerical analysis, shown in Fig. 16 compared to the average experimental curve, acceptable match is observed especially for the first part of the curve. This proves that the numerical model is capable to represent the behaviour of the strengthened masonry structure and estimate the failure loads and maximum displacement with acceptable accuracy. However, the middle part of the curve shows deviation between the numerical and experimental curve; this can be explained that the numerical solution assumes uniformly distribution of the applied load and homogenous mechanical properties, which is not the case in the real wall samples.



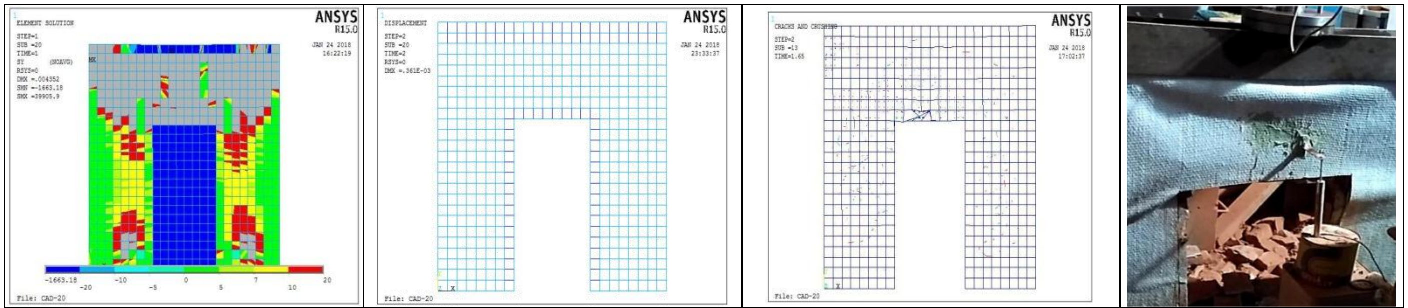
(a) stresses | (b) deformation | (c) crack pattern | (d) experimental failure

Fig. 10. Results of unstrengthend wall with no opening WCC



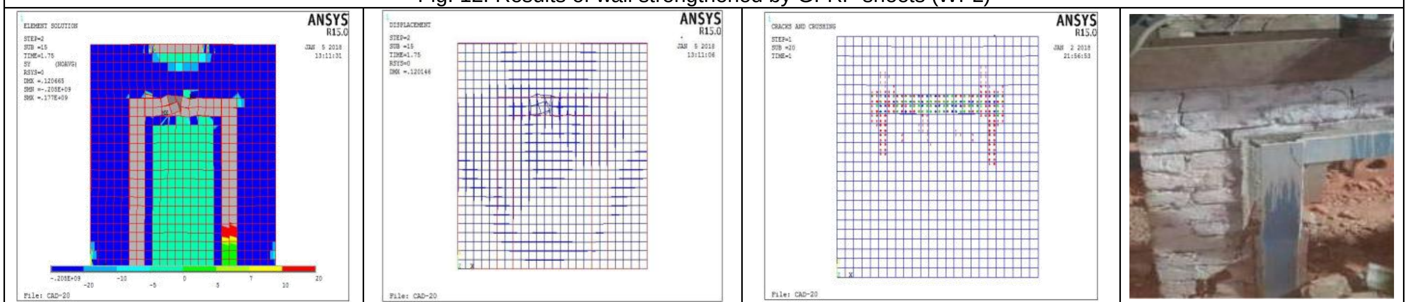
(a) stresses | (b) deformation | (c) crack pattern | (d) experimental failure

Fig.11. Resultsof unstrengthend wall with opening WOC



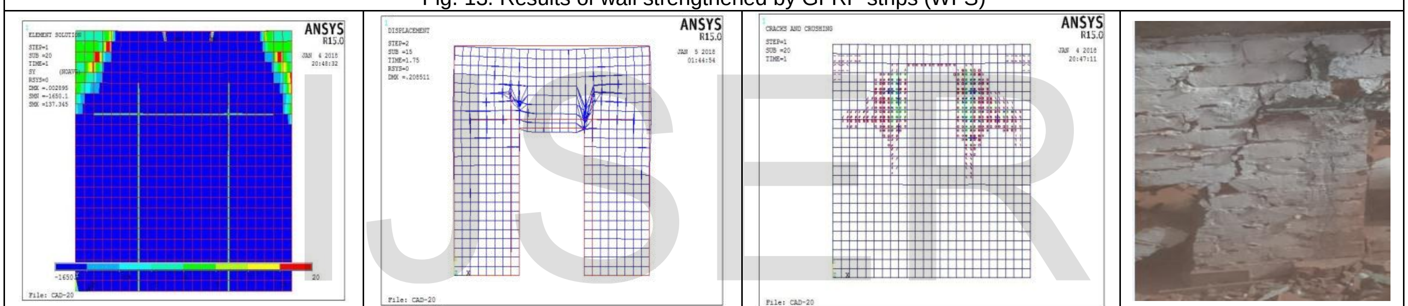
(a) stresses | (b) deformation | (c) crack pattern | (d) experimental failure

Fig. 12. Results of wall strengthened by GFRP sheets (WFL)



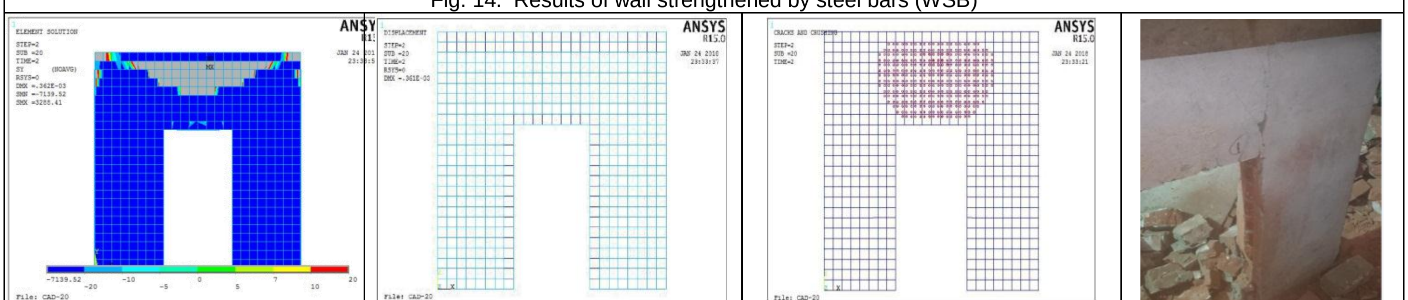
(a) stresses | (b) deformation | (c) crack pattern | (d) experimental failure

Fig. 13. Results of wall strengthened by GFRP strips (WFS)



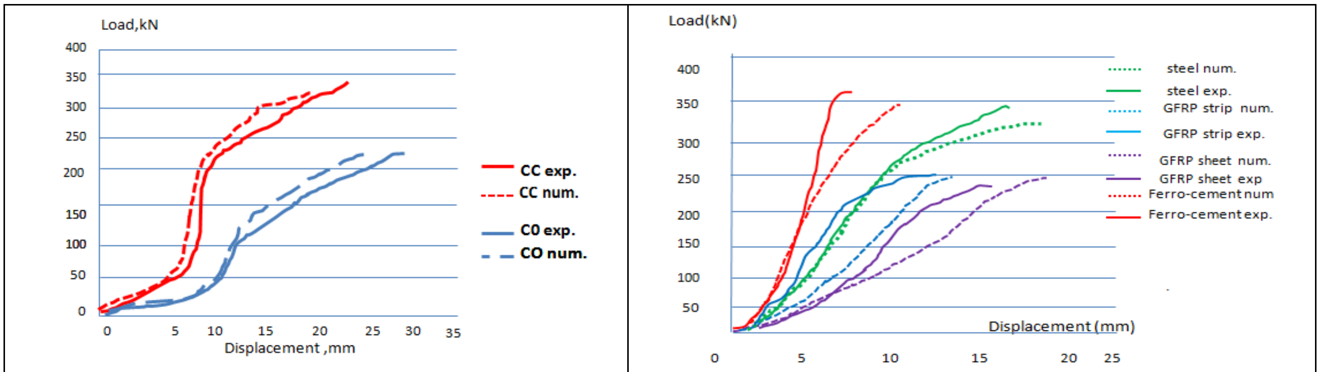
(a) stresses | (b) deformation | (c) crack pattern | (d) experimental failure

Fig. 14. Results of wall strengthened by steel bars (WSB)



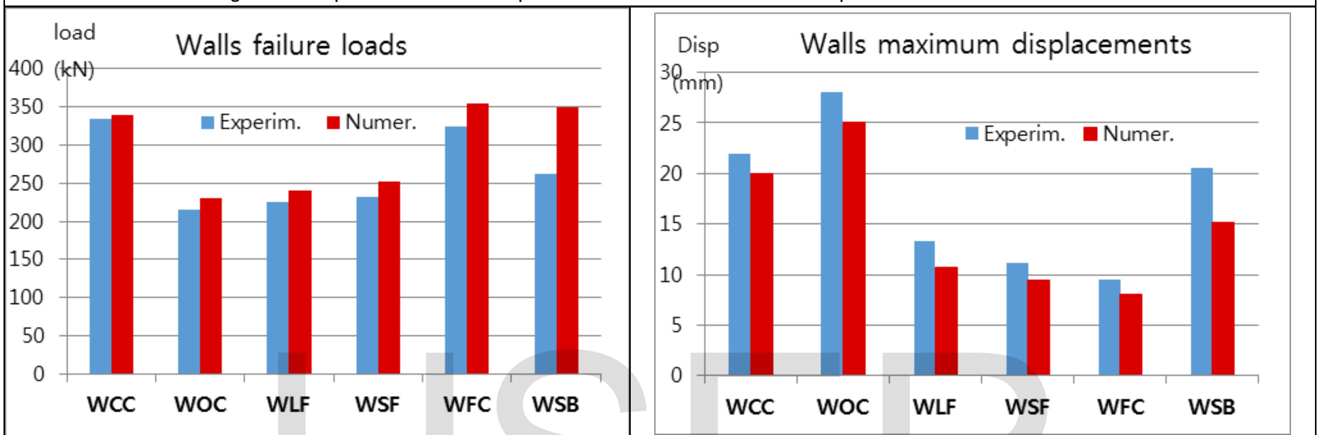
(a) stresses | (b) deformation | (c) crack pattern | (d) experimental failure

Fig. 15. Results of wall strengthened by ferrocement (WFC)



(a) unstrengthened walls | (b) walls strengthened by different systems

Fig. 16. Comparison between experimental and numerical load-displacement relations for walls



(a) unstrengthened walls | (b) walls strengthened by different systems

Fig. 17. Experimental and numerical results of failure loads and maximum displacements

4 Case Study

4.1 Description and Methodology for Analysis

Applicabilition of the adopted numerical approach was made on a realistic design problem. The study case is a residential building located in Shoubra district of Cairo and built of clay brick masonry load-bearing walls in 1953. The front façade of the building is shown in Fig. 18 (a). The building consists of a ground floor and three typical floors with floor area about 130 m2 and total height of 13 m. The load bearing walls of the ground floor have 38 cm thickness and 4 m height, the upper three storeys' walls are 25 cm thick and 3 m high. It was required to make a door opening between two rooms in the ground floor. In order to carry out the necessary modifications while avoiding damage, cracking or partial collapse, it was decided to strengthen the wall before making the required opening.

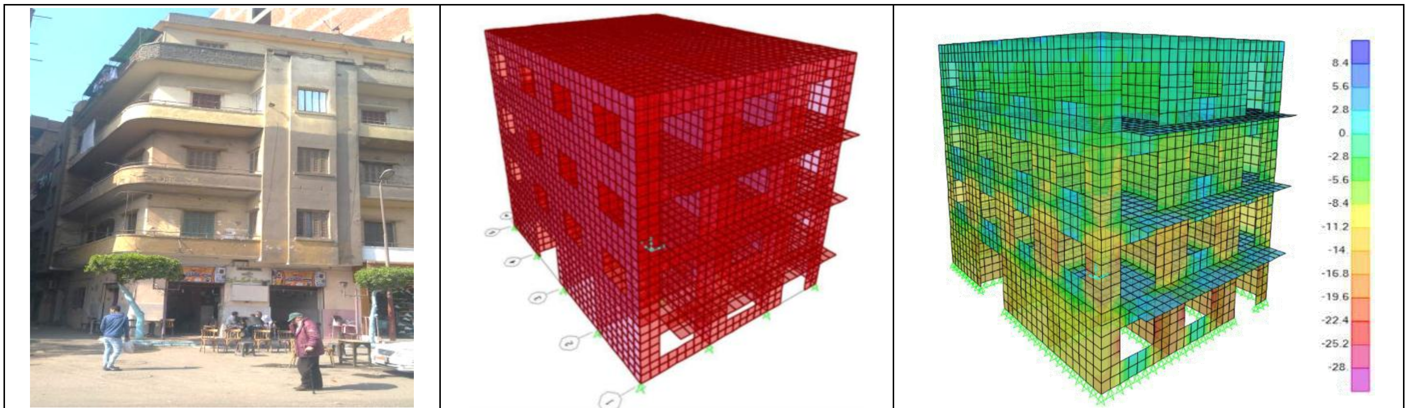
The loads acting on the building are estimated according to the Egyptian Code of Practice ECP201-2012 [35]. Then the whole building is modelled by finite elements and linear static is carried out for the whole building using the commercial program SAP2000.V19 [36] in order to evaluate the service load acting on the studied wall. The 3D model of the building is shown in Fig. 18 (b). The results shown in Fig. 18 (c) indicate that the vertical load acting on the studied wall is 205kN/m.

4.2 Nonlinear Analysis of the Studied Wall

Nonlinear analysis was conducted for the wall using the commercial software ANSYS v 12 [17] and adopting the developed procedure. The compressive strength of brick units and cement mortar are taken as 10.9 and 19 MPa, respectively. The compressive strength of cement mortar used in the strengthening ferrocement layer is also 19 MPa. In the first study, the solid wall was loaded with the calculated working loads, then the opening was created using the kill element technique and the load was increased until failure. In the second study, the wall strengthed by ferrocement was loaded with the service load, then the opening was made, then the load was increased on the wall until failure.

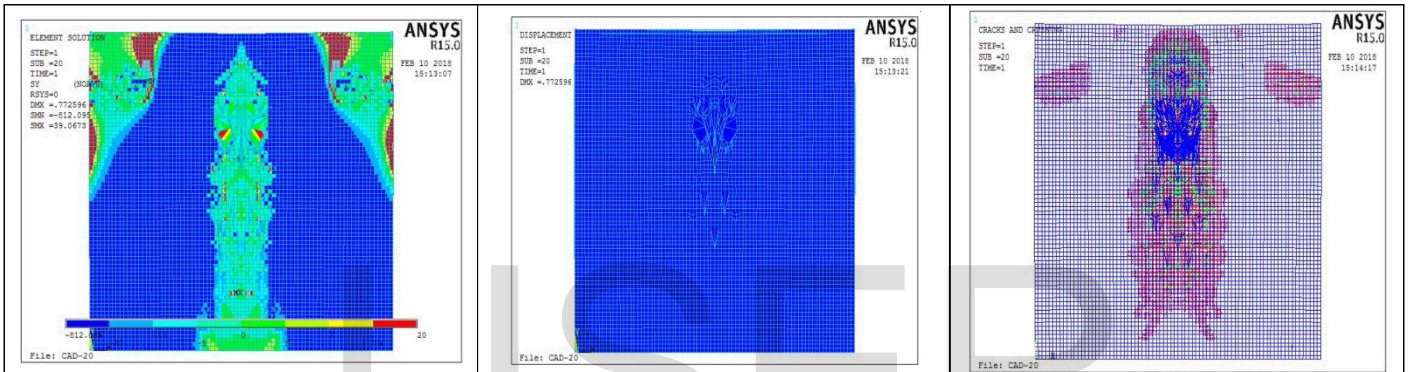
4.3 Numerical Results and Discussion

For the unstrengthened wall loaded with increasing vertical load until failure, ultimate load was found 910 kN, equivalent to 227.5 kN/m of wall. The numerical results for the unstrengthened wall regarding stresses, deformation and crack pattern at service load before creating the opening are shown in Fig. 19. After creating the opening and increasing the load, the numerical results are shown in Fig. 20. Failure of the wall occurred shortly after making the opening, at an ultimate load of 210.8 kN, i.e. 23% of the unopened wall capacity, indicating the threat to the building by opening this wall.



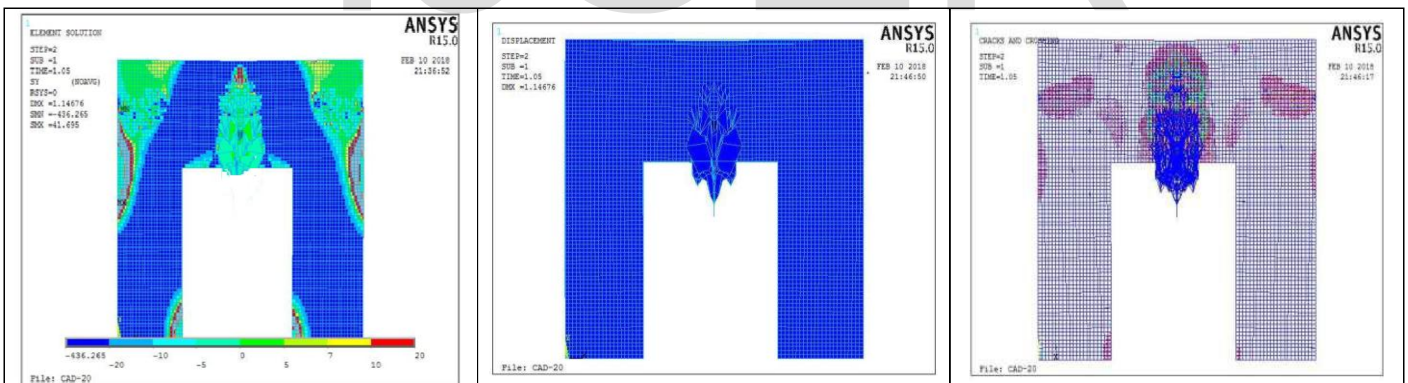
(a) building exterior	(b) 3D model using SAP	(b) stresses in the walls and slabs

Fig. 18. The studied wall-bearing masonry residential building



(a) stresses	(b) deformation	(b) crack pattern

Fig. 19. The unstrengthened wall before making the opening at service load



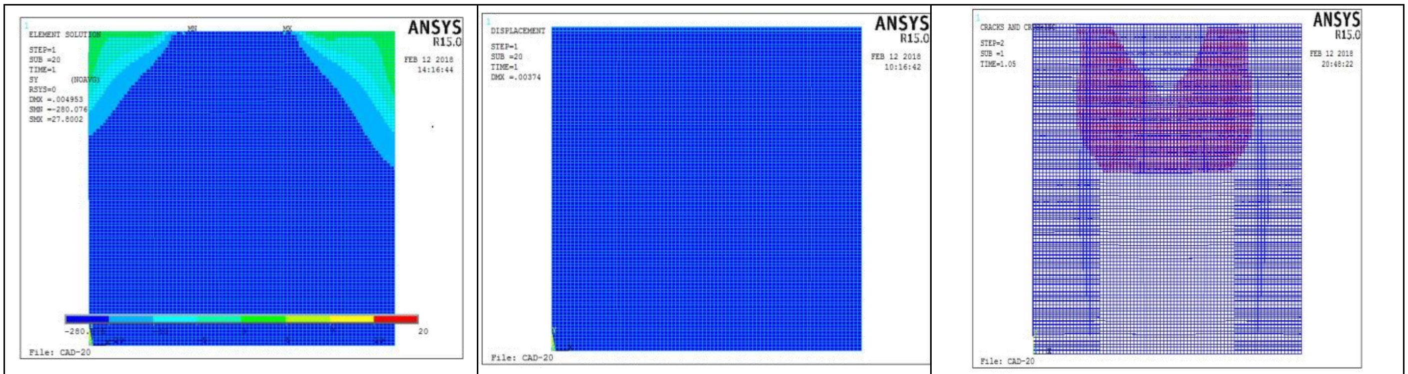
(a) stresses	(b) deformations	(b) crack pattern

Fig. 20. The unstrengthened wall after making the opening at ultimate loading condition

For the wall strengthened by ferrocement layer, opened then the load increased until failure, the numerical results regarding stresses, deformations and crack patterns before and after opening are shown in Figs 21 and 22, respectively.
The numerically calculated ultimate load is 945 kN =236.25 kN/m. Thus the suggested strengthening enables making the opening in the wall loaded by service loads without causing decrease in carrying capacity or excessive cracks.

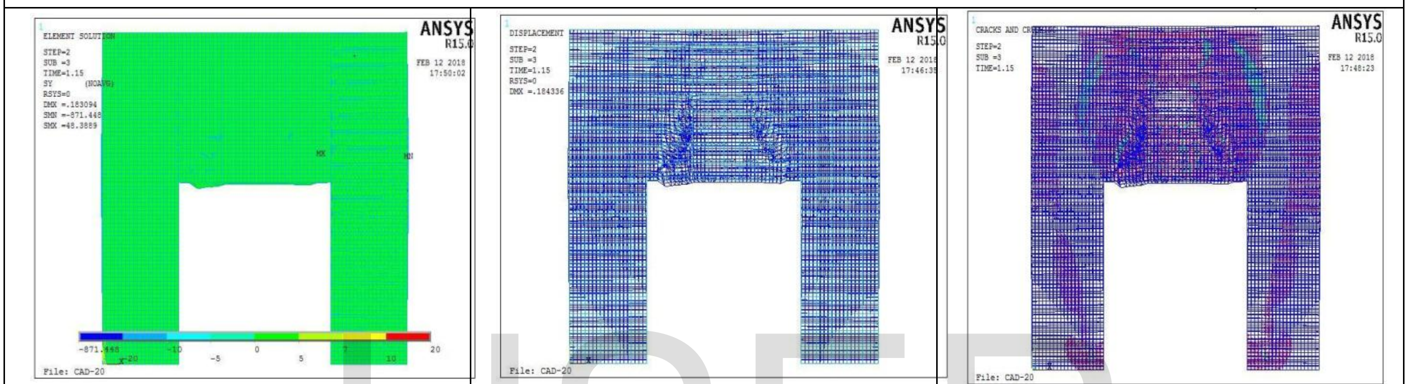
5 Conclusion

This paper presented experimental and numerical investigation of different external strengthening schemes for unreinforced masonry walls made in order to enable making openings in the loaded walls. An experimental program was conducted where 18 vertically loaded brick walls were strengthened by 4 different techniques then openings were made and the load was increased until failure. Numerical modeling by finite elements and nonlinear analysis using commercial soft-



(a) stresses (b) deformations (b) crack pattern

Fig. 21 The strengthened wall under service loads – before making the opening



(a) stresses (b) deformations (b) crack pattern

Fig. 22 The strengthened wall after making the opening at failure

ware ANSYS v.12 were performed to investigate and compare the efficiency of the strengthening schemes. Additionally, application was made on an existing building; strengthening of a wall was proposed and a numerical study was conducted to predict the behavior of the strengthened wall after making the opening.

The main conclusions drawn from these studies may be summarized in the following points.

- Making an opening in vertically loaded unreinforced masonry wall was shown to decrease the ultimate load capacity by 35% and increase the maximum vertical displacement by 27%.
- The tested walls with openings strengthened by GFRP sheets, GFRP strips, steel bars, and ferrocement showed an increase of the average ultimate load by 5%, 9%, 22%, and 51%, respectively, compared to the unstrengthened walls with opening.
- Near-surface mounted steel bars, externally bonded FRP sheets or strips and ferro-cement overlays proved to be effective low cost methods for strengthening masonry walls and enabling making openings in the loaded walls.
- Numerical results showed agreement with the experimental results regarding maximum load, deformation, crack pattern and failure mechanism for most cases. The numerical ultimate loads of the strengthened walls are slightly over-estimated by about 9%, while the maximum displacements are considerably under estimated, due to the assumed homogeneity of material.
- Agreement between numerical and experimental results demonstrates the validity of the proposed numerical model, and its accuracy in simulating the structural behaviour of masonry walls with openings and estimating the failure loads and safety level.
- The proposed numerical modeling approach assumes full bond between masonry and the strengthening materials; ongoing research is taking into consideration the bond and transfer of tangential stresses between masonry and the strengthening elements.
- The numerical case study demonstrated the applicability of the adopted numerical modeling for analysis and design of strengthening schemes for masonry walls in existing structures while loaded with the service loads.

REFERENCES

[1] M. Shariq, H. Abbas, H. Irtaza, and M. Qamaruddin, "Influence of openings on seismic performance of masonry building walls", *Building and Environment*, 43(7), pp. 1232–1240, 2008.

[2] A.Moussa, and M. Aly, "Repair and Strengthening of Masonry Walls with Openings Using FRP Laminates," *Proc. 26th Conf. Our World in Concrete and Structures*, Singapore, pp. 473-482, 27 - 28 August 2001.

[3] T. Bahaa, A. Abd El-Khalik, and M. Ghoneim, "Behaviour of Unreinforced Masonry Walls Strengthened Using GFRP Laminates," *Proc.*

Fifth Int. Conf. Nanotechnology in Construction (NTC 2013) , Cairo, Egypt, 23-25 March 2013.

[4] E. Etman , T. El-Shafey, and S.A. Bayoumi, "Experimental Investigation of Masonry Walls Under Different Cases," *Proc. Int. Conf. Advances in Structural and Geotechnical Engineering ICASGE'15*, Hurghada, Egypt, 6-9 April 2015.

[5] C. Wang, V. Sarhosis, and N.Nikitas, "Strengthening/Retrofitting Techniques on Unreinforced Masonry Structure/Element Subjected to Seismic Loads: a Literature Review," *Open Construction and Building Technology J.*, vol.12, pp. 251-268, 2018.

[6] K.M. Amanat, M.M. Maksudul Alam, and M. Shahria Alam, "Experimental Investigation of the Use of Ferrocement Laminates for Repairing Masonry Infilled RC Frames,"*J. Civil Engineering (IEB)*, 35 (2), pp. 71-80, 2007.

[7] Y. Yardim, and O. Lalaj, "Shear Strengthening of Unreinforced Masonry Wall with Different Fiber Reinforced Mortar Jacketing," *Construction and Building Materials*, vol. 102, pp.149–154, 2016.

[8] S.B. Kadam, Y. Singh, and B. Li, "Out-of-plane Behaviour of Unreinforced Masonry Strengthened Using Ferrocement Overlay, " *Materials and Structures*, vol. 48, no. 10, pp. 3187–3203, 2015.

[9] C. Shermi, and R.N. Dubey, "Study on Out-of-Plane Behaviour of Unreinforced Masonry Strengthened with Welded Wire Mesh and Mortar," *Construction and Building Materials*, vol. 143, pp. 104–120, 2017.

[10] S. Banerjee, S.Nayak, and S. Das, "Enhancing the Flexural Behaviour of Masonry Wallet Using PP Band and Steel Wire Mesh," *Construction and Building Materials*, vol. 194, pp. 179–191, 2019.

[11] A. Mosallam, and A.Banerjee, "Enhancement in In-plane Shear Capacity of Unreinforced Masonry (URM) Walls Strengthened with Fiber Reinforced Polymer Composites, "*Composites Part B: Engineering*, vol. 42, no. 6, pp. 1657–1670, 2011.

[12] E. Bernat-Maso, L. Gil, and C. Escrig, "Analysis of Brick Masonry Walls Strengthened with Fibre Reinforced Polymers and Subjected to Eccentric Compressive Loads," *Construction and Building Materials*, vol. 84, pp. 169–183, 2015.

[13] J. Velazques , B. Quinonez, J. Castorena, A. Reyes , and J. Gonzalez, "In-plane Behavior of Confined Masonry Walls with Holes Retrofitted with GFRP and Subjected to Lateral Cyclic Loading", *Proc. 15th World Conference on Earthquake Engineering*, Portugal, 2012.

[14] A. Kalali, and M.Z. Kabir, "Cyclic Behavior of Perforated Masonry Walls Strengthened with Glass Fiber Reinforced Polymers, " Scientia *Iranica Transactions A. Civil Engineering, Sharif University of Technology*, vol. 19, no. 2, pp. 151–165, 2012.

[15] A.A.Nasser, "Optimization of Retrofitting Schemes of Clay Brick Masonry with Openings," *International Journal of Multidisciplinary and Current Research*, pp. 180-187, Nov.-Dec.2013, 2013.

[16] M. El-Diasity, H. Okail, , O. Kamal, and M.Said, "Structural Performance of Confined Masonry Walls Retrofitted using Ferrocement and GFRP under In-plane Cyclic Loading", Engineering Structures, 94, 54–69, 2015.

[17] ANSYS v.12, *ANSYS® Nonlinear Analysis Computer Program, Release 12.0, Theory Reference Manual*, ANSYS Inc., Canonsburg, PA, USA, 2012.

[18] ESS 1524/1993. *Egyptian Standards Specifications: 1524/1993: Building Brick Solid Masonry Units Made From Clay or Shale*, Egyptian Organization for Standards and Quality, Cairo, Egypt, 1993.

[19] ECP 204-2005, *Egyptian Code for Design and Construction of Masonry Structures*, Ministry of Housing and Urban Communities, Housing and Building Research Center, Cairo, Egypt, 2005.

[20] P.B. Lourenço, G. Milani, A. Tralli, and A. Zucchini, "Analysis of Masonry Structures: Review of and Recent Trends of Homogenisation Techniques," *Canadian J. Civil Eng*., vol. 34, pp.1443–1457, 2007.

[21] [21] A.A. Costa, B. Silva, A. Arêde, J. Guedes, and A. Costa, "Experimental Assessment, Numerical Modelling and Strengthening of a Stone Masonry Wall," *Bulletin of Earthquake Engineering*, vol. 10, no. 1, pp. 135–159, 2012.

[22] [22] P.B. Lourenço, and J.G. Rots, "A Multi-surface Interface Model for the Analysis of Masonry Structures," *J. Engineering Mechanics, ASCE*, vol. 123, no.7, p. 660–668, 1997.

[23] P.B. Lourenço, "Computations on Historic Masonry Structures," *Progress in Structures and Materials Engineering*, vol. 4, no. 3, pp. 301–319, 2002.

[24] L. Pelá, A. Aprile, and A. Benedetti, "Seismic Assessment of Masonry Arch Bridges," *Engineering Structures*, vol. 31, no. 8, pp. 1777–1788, 2009.

[25] B. Silva, J. Guedes,, A. Arêde, and A. Costa, "Calibration and Application of a Continuum Damage Model on the Simulation of Stone Masonry Structures: Gondar Church as a Case Study," *Bulletin of Earthquake Engineering*, vol. 10, no. 1, pp. 211–234, 2012.

[26] A. Kalali, and M.Z. Kabir, M.Z., "Modeling of Unreinforced Brick Walls under Inplane Shear and Compression Loading", *Structural Engineering and Mechanics, An International Journal*, vol. 36, no. 3, pp. 247–278, 2010.

[27] V. Gattulli, G. Lampis, G. Marcari, and A. Paolone, "Simulations of FRP Reinforcement in Masonry Panels and Application to a Historic Façade," *Engineering Structures*, vol. 75, pp. 604–618, 2014.

[28] E. Grande, M. Imbimbo, and E. Sacco, "Finite Element Analysis of Masonry Panels Strengthened with FRPs," *Composites Part B: Engineering*, vol. 1, pp. 1296–1309, 2013.

[29] A. Gabor, A. Benanni, E. Jacquelin, and F. Lebon, "Modelling Approaches of the In-plane Shear Behaviour of Unreinforced and FRP Strengthened Masonry Panels," *Composite Structures*, vol. 74, pp. 277–88, 2006.

[30] M.Z. Kabir, and A. Kalali, "In-plane Numerical Modeling of Strengthened Perforated Masonry Walls Using FRP under Cyclic Loading," *Asian Journal of Civil Engineering (BHRC)*, vol. 14 no. 1, pp. 161-179, 2013.

[31] K.J. Willam and E.P. Warnke, "Constitutive Model for the Triaxial Behavior of Concrete," *Proceedings of the International Association for Bridge and Structural Engineering (ISMES)*, Bergamo, Italy, 1975.

[32] M.V. Sandeep, S. Renukadevi, and M. Somanath, "Influence of Reinforcement on the Behavior of Hollow Concrete Blocks Masonry Prism under Compression – an Experimental and Analytical Approach," *Int. J. Research in Engineering and Technology*, pp.106-110, 2013.

[33] H.B. Kaushik, D.C. Rai, and S.K. Jain, "Stress-Strain Characteristics of Clay Brick Masonry under Uniaxial Compression," *Journal of Materials in Civil Engineering, ASCE*, vol. 19, no. 9, pp. 728–739, 2007.

[34] G.A. Hamdy, O.A. Kamal, O.R. Al-Hariri, and T.S. El-Salakawy, "Plane and Vaulted Masonry Elements Strengthened by Different Techniques – Testing, Numerical Modeling and Nonlinear Analysis", *Journal of Building Engineering* 15, 203-217, 2018.

[35] ECP 201-2012, *Code of Practice for Loads on Buildings and Structures*, Ministry of Housing and Urban Communities, Housing and Building Research Center, Cairo, Egypt, 2012.

[36] SAP2000.V19, *CSI Analysis Reference Manual*, Computer and Structures, Berkeley, USA, 2017.