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Strength and Ductility in unreinforced masonry walls with two openings retrofitted by Carbon Fiber Reinforced Polymers

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Abstract - *In almost all masonry structures, walls are among the most vulnerable organs because of their low capability in ductility and lack of strength. Composite materials are one of the retrofitting techniques which increase the essential factors: loading capacity and the wall ductility. A nonlinear finite element model has been developed for Unreinforced Masonry (URM) wall with two openings, retrofitted using Carbon Fiber Reinforced Polymers (CFRPs) by ANSYS software. Then the behaviour of unreinforced masonry (URM) walls with openings strengthened by CFRP in different arrangements, affected by in-plane cyclic and gravity loads have been analysed.*

***Key Words*: Unreinforced masonry walls, openings, cyclic loading, retrofitting, carbon fiber reinforced polymers**

1. INTRODUCTION

Before the advent of concrete and steel, masonry helped build civilizations. From Egypt in Africa, Rome in Europe, Maya in the America to China in Asia, masonry was exploited to construct the most significant, magnificent and long lasting structures on the Earth. Looking at the Egyptian pyramids, Mayan temples, Roman coliseum and Chinese Great Wall, one cannot stop wondering about the significance and popularity that masonry has had throughout history.

Masonry structures are very reliable if they carry only gravity loads, but do not exhibit a good performance when subjected to lateral forces such as earthquake loadings. Moderate to strong earthquakes can devastate complete cities or villages resulting in massive death toll and cause extensive losses. Hence retrofitting of these structures and improving their strength is significant and vital. Numerous techniques have been developed and applied to improve the seismic behaviour of these structures.

There are many methods for seismic retrofitting of un-reinforced masonry wall, such as Ferro cement, Post tensioning, Shotcrete, Grout and Epoxy injection and so on. Each of these methods has advantages and defects. Using composite fiber is one of the new methods of rehabilitation that has gained some popularity. Because of in-plane and out-plane stresses due to earthquake and wind loads, composite materials are a suitable solution for retrofitting of masonry walls. Based on the fiber formation, FRP is generally divided in several groups. The three mostly used FRPs are carbon (CFRP), glass (GFRP) and aramid (AFRP).

A nonlinear finite element model has been developed for Unreinforced Masonry (URM) walls with openings, retrofitted using Fiber Reinforced Polymers (FRPs) by ANSYS software. Kalali et.al had conducted experiments on URM walls with openings retrofitted by GFRPs. The test results of experiment have been used for validation of model. The present study examines the in plane behaviour of URM wall with two openings and walls strengthened with CFRP subjected to lateral loading.

1.1 Unreinforced masonry Buildings

Unreinforced masonry (URM) buildings represent a large portion of the buildings around the world. As we know large numbers of these structures have not been designed for seismic loads and structural walls of these buildings were principally designed to resist gravity loads. Therefore moderate to strong earthquakes can devastate complete cities or villages resulting in massive death toll and cause extensive losses. Hence retrofitting of these structures and improving their strength is significant and vital. Numerous techniques have been developed and applied to improve the seismic behaviour of these structures. Since the majority of human deaths in such building as a result of earthquake are caused because of the out-of-plane corruption of the unreinforced masonry walls, the methods with high potential to improve out-of-plane behaviour was considered.

Two types of failure are commonly observed in load bearing URM walls subjected to seismic loads. These are in-plane failure characterized by a diagonal tensile crack pattern, and out-of-plane failure, where cracks are primarily along the mortar bed joints. The aim of seismic retrofitting is to enhance the ultimate strength of the building by improving the structures ability to absorb inelastic deformation. This can be achieved by changing the structural system such that the energy is transferred along alternative load paths, or alternatively, increasing the ductility in the individual elements that make up the structural system

1.2 Retrofitting methods for URM walls

There are various methods of retrofitting URM structures in different categories, and some of them are under research and being experimented. Application of these methods to URM structures is expected to increase strength and ductility of the structure. However, sometimes the cost of retrofitting is not reasonable, or advanced technology is needed and therefore isn't suitable for developing countries (that need to retrofit buildings), especially in rural regions. The disadvantages of these techniques can be listed as: time consuming to apply, available space reduction, occupancy disturbance, building operation disruption, and affecting aesthetics of existing walls. In addition, the added mass can also increase the earthquake induced inertial forces, and may also require the strengthening of the foundations. Most of these problems may be overcome using FRP for retrofitting.

1.3 FRP system as retrofitting method

Fiber-reinforced polymers/plastics (FRP) is a recently developed material for strengthening of concrete and masonry structure. This is an advanced material and most of the development in its application in structural retrofitting has taken place in the last two decades. The main advantage of FRP is its high strength to weight ratio and high corrosion resistance. FRP plates can be 2 to 10 times stronger than steel plates, while their weight is just 20% of that of steel. However, at present, their cost is high. FRP composites are formed by embedding a continuous fiber matrix in a resin matrix. The resin matrix binds the fiber together and also provides bond between concrete and FRP. The commonly used fibers are Carbon fibers, Glass fibers and Aramid fibers and the commonly used resins are polyester, vinyl ester and epoxy. FRP is named after the fiber used, e.g. Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), and Aramid Fiber Reinforced Polymer (AFRP).

Fiber Reinforced Polymers (FRP) system enhance the in-plane performance of masonry walls under monotonic, cyclic or seismic loading. Large increases in both load and displacement capacity were observed, with the amounts depending on the quantity and type of the FRP used.

1.4 Modelling strategies of masonry wall

Masonry is a composite material that consists of units and mortar joints. Numerical modelling of the bricks walls are generally categorized in micro-modelling and macro-modelling. In general, the approach towards its numerical representation can focus on the micro-modelling of masonry as a component, such as unit (brick, block, etc.) and mortar, or the macro-modelling of masonry as a composite. Depending on the level of accuracy and the simplicity desired, it is possible to use the following modelling strategies.

- Detailed micro-modelling – units and mortar in the joints are represented by continuum elements whereas the unit-mortar interface is represented by discontinuous elements.
- Simplified micro-modelling - expanded units are represented by continuum elements whereas the behaviour of the mortar joints and unit-mortar interface is lumped in discontinuous elements.
- Macro-modelling – unit, mortar and unit-mortar interface are smeared out in the continuum.

The macro-modelling is more practice oriented due to the reduced time and memory requirements as well as a user-friendly mesh generation. This type of modelling is most valuable when a compromise between accuracy and efficiency is needed. The macro-modelling does not make a distinction between individual units and joints but treats masonry as a homogeneous anisotropic continuum. Masonry can be assumed to be a homogeneous material if a relation between average stresses and strains in the composite material is established.

2. FINITE ELEMENT MODELLING

Modelling is one of the most important aspects in Finite Element analysis. Accuracy in the modelling of element type and size, geometry, material properties, boundary conditions and loads are of absolute necessary for numerical idealization of the actual member. Creative thinking in idealizing and meshing the structure helps not only in considerable reduction of time but also in less memory usage of the system.

2.1 Finite element modelling of URM wall

Macro- modelling is adopted to model the unreinforced masonry (URM) wall with openings. Masonry is a composite material, consists of bricks and mortar joints. The macro-modelling does not make a distinction between individual units and joints but treats masonry as a homogeneous and uniform material with equivalent mechanical properties.

Finite Element Modelling consists of following three phases:

- Selection of element type
- Assigning material properties
- Modelling and meshing the geometry

Selection of proper element type is important criterion in finite element analysis. ANSYS provides a dedicated three dimensional eight noded solid isoparametric element, SOLID65, to model the nonlinear response of brittle material. SOLID65 element can simulate the behaviour of URM walls. This element is capable of cracking in tension and crushing in compression.

Development of a model for the behaviour of masonry is a challenging task. Masonry is a quasibrittle material and has different behaviour in compression and tension. There are two major aspects to develop an accurate analytical model. One is to understand the behaviour of masonry which is the constitutive relations of the material. And the other is the failure criteria of the masonry. ANSYS non-linear masonry model is based on William- Warnke failure criteria. As per William – Warnke failure criteria, at least two strength parameters, ultimate uniaxial tensile and compressive strengths are needed to define a failure surface for the masonry. Both cracking and crushing failure modes are accounted for masonry materials. In masonry, cracking occurs when the principal tensile stress in any direction lies outside the failure surface. After cracking, the elastic modulus of the masonry element is set to zero in the direction parallel to the principal tensile stress direction. Crushing occurs when all principal stresses are compressive and lies outside the failure surface; subsequently, the elastic modulus is set to zero in all directions.

As an initial step, finite element analysis requires meshing of the model. In other words, model is divided into a number of small elements and after loading, stress and strain at integration points of these small elements is calculated. An important step in finite element modelling is the selection of mesh density. A convergence of results is obtained when an adequate number of elements are used in a model. This is practically achieved when an increase in mesh density has negligible effect on the results.

2.2 Finite element modelling of FRP retrofitted walls

FRP composites are materials that consist of two constituents. The constituents are combined at a macroscopic level and are not soluble in each other. One constituent is the reinforcement, which is embedded in the second constituent, a continuous polymer called the matrix. The reinforcing materials are in the form of fibres.

For modelling FRP layers, non-linear structural element SHELL 181 is used, which is a 4-nodal three dimensional crust element having six degrees of freedom in each node. The bond strength between the masonry and FRP material should be considered. In this study perfect bond between the materials is assumed. The high strength of epoxy used to attach FRP sheets to the masonry walls supported the assumption.

3. VALIDATION

The cyclic behaviour of three one-half scale perforated unreinforced brick shear walls before and after strengthening using glass fiber reinforced polymers (GFRPs) was investigated in the experimental work of Kalali et.al. [5].This laboratory study was conducted on the existing unreinforced brick shear walls representative of conditions existing in Iran. These walls were constructed using one-half scale solid clay bricks and cement mortar. The original full scale solid clay brick is 210 mm×100 mm×56 mm; this resulted in a ½-scale brick nominally measuring 105 mm×50 mm×28 mm. In addition, during construction the head and bed joints were approximately 6 and 10 mm thick respectively, to be consistent with the half-scale bricks. The mortar had a composition of 1part cement to 5 parts sand, by volume. The masonry material properties are summarized in Table -1.

Table -1: Masonry properties in the experiment

Item	Property	Value
Brick	Compressive strength	11.7 MPa
Mortar	Compressive strength	5.2 MPa
Brick/mortar interface	Tensile bond strength Shear bond strength Coefficient of friction	0.062 MPa 0.2 MPa 0.58
Masonry prism	Compressive strength Elastic modulus	3.89 MPa 843 MPa
Mortar	Compressive strength	5.2 MPa

Glass fiber reinforced polymers were used to retrofit the brick walls. One brick wall was unreinforced and considered as a reference specimen. Two walls were directly upgraded after construction using one layer of GFRP. Each wall was retrofitted on the surface of both sides. Application of the GFRP took place after curing of the brick walls for at least 28 days in laboratory conditions. The application of the wrap material was a simple and rapid operation. The application method was dry lay-up. An epoxy resin based adhesive (two component epoxy Sikadur 330) was used for bonding the glass fiber sheet.

The length, height and thickness of the walls were 194, 143, and 16 cm, respectively. Thus, the aspect ratio of the test walls was about 0.74. The test walls were constructed on a strong reinforced concrete footing. After allowing the wall to cure (for at least 7 days), a strong reinforced concrete loading beam was built on the top of the brick wall. The foundation and loading beam dimensions were 240 cm×20 cm×24 cm and 194 cm×20cm×16 cm, respectively. These test walls had a window opening in their centre. The length and height of this window were 52 and 47 cm, respectively. The unreinforced and GFRP strengthened walls are illustrated in Fig -1 and Fig -2.

Fig -1: Unreinforced masonry wall

Fig -2 : GFRP strengthened wall

In this experimental study, a gravity load of 41.2 kN was applied along the top of the wall by a loading beam in a manner consistent with the floor or roof loading. For this purpose, a steel loading basket was constructed. This steel loading basket was filled with 210 lead weights and was subsequently placed on the loading beam. The loading beam distributed this vertical load uniformly on the top of the wall. Thus, this axial load acting on the wall was constant during cyclic loading as seen in the walls in real buildings under seismic loading. Horizontal cyclic load was applied manually in the plane of the wall to the loading beam (via steel plates which were connected to the loading beam during the construction) using two hydraulic jacks and hand pumps. These jacks could only produce compressive load and were mounted on rigid reaction frames. The loading beam distributed this concentrated load uniformly along the top of the wall to simulate floor or roof loads used in the actual masonry building construction. The test wall assembly was laterally supported along its top so as to restrict the out-of-plane displacement of the assembly. The test setup was similar for all of the test walls. For example, it is illustrated in Fig -3. And Fig -4 for specimen RBW-X-S1.

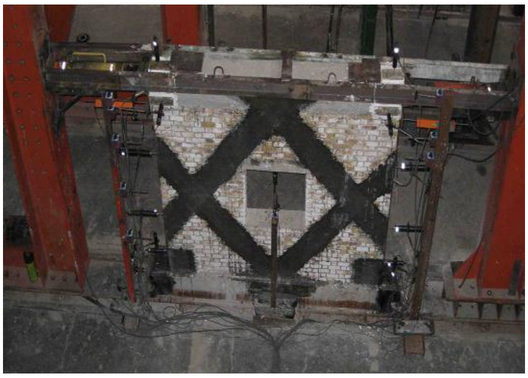


Fig -3: Cyclic load test setup

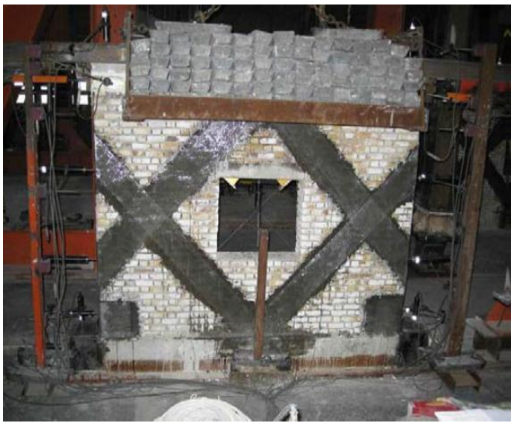


Fig -4 : Vertical load test setup

All walls are tested under constant gravity load and incrementally increasing in plane loading cycles as shown in Fig -5. The selected loading procedure can simulate the earthquake actions and their effects on the walls. During the test, each wall was allowed to displace in its own plane. The force required to push the wall and the corresponding displacement at each load interval are measured. The observed hysteresis response curve for each tested wall specimen is shown in Chart-1.

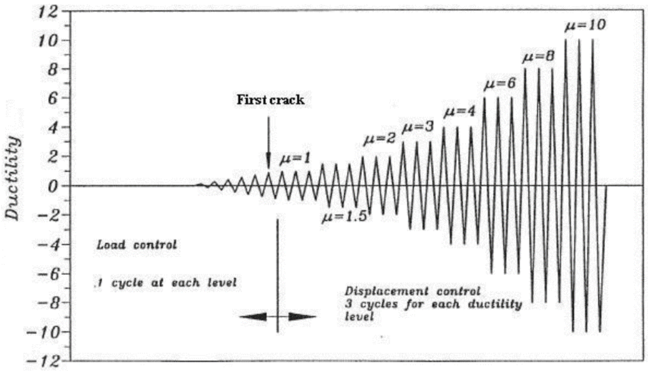


Fig -5: Cyclic loading history

The computer models used to predict the behaviour of unreinforced masonry wall are presented in fig -6.

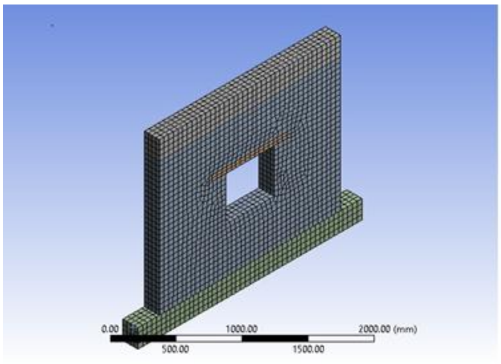


Fig -6: Finite element model of wall

Charts 1-2 show the load deflection plots from the finite element analyses and the experimental results for the URM wall.

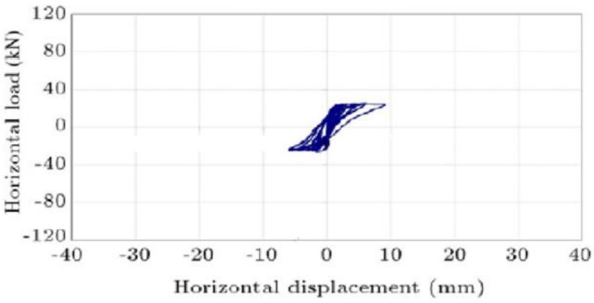


Chart -1: Load displacement curve of URM wall from the experiment

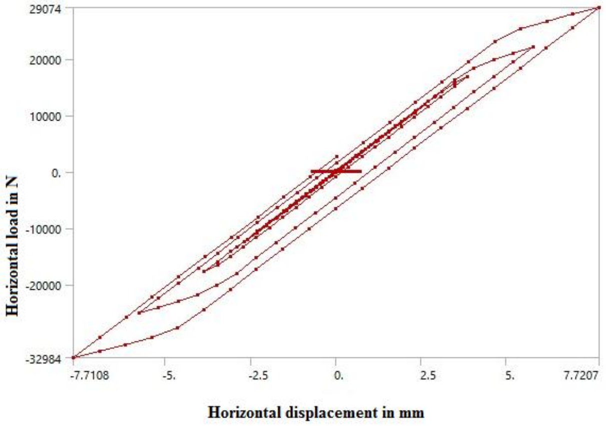


Chart -2: Load displacement curve of URM wall from numerical analysis

Charts 1-2 show that the load- deflection plots from the finite element analysis agrees well with the experimental data for the tested wall. The average load carrying capacity for URM wall from the finite element analysis is higher than from the experimental result by 11.39%.

4. SPECIMEN SELECTION

The masonry wall with two openings is selected for the study. To show the influence of CFRP patterns on the load carrying capacity of URM wall, different strengthening configurations are considered.

4.1 Geometry

The wall model used for the parametric study are shown in Fig-7. The length, height and thickness of the wall are 6m, 3m and 0.23m respectively. The dimensions of loading beam and foundation beam are 6m, 0.3m and 0.23m. The two openings, door and window found in the model. The distance of opening edge of door from the beginning of wall is 0.75m. The distance of opening edge of window from the end of wall is 1.25m. The dimensions of door opening are 1.2m and 2.1m. The length and height of window opening are 1.8m and 1.35m respectively.

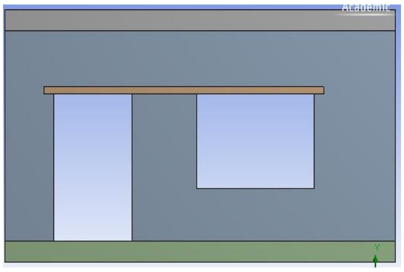


Fig -7: Model used for the study

4.2 Material properties

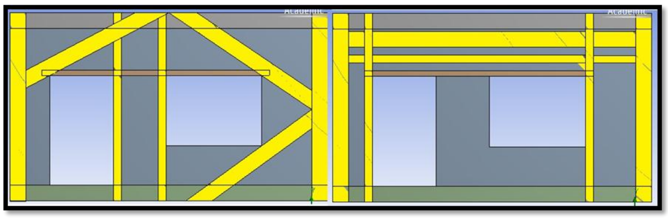
The material properties of the models are same as those used in the experimental study as mentioned in the previous section. CFRP properties used in this study are given in Table 2.

Table -2: FRP properties

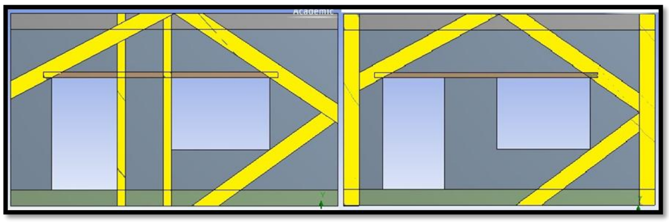
Density (kg/m³)	1650
E_x (Gpa)	207
E_y (Gpa)	5
Poisson's ratio	0.25
G_{XY} (Mpa)	2600
Tensile strength X (Mpa)	1035
Tensile strength Y (Mpa)	41
Compressive strength X (Mpa)	689
Compressive strength Y (Mpa)	117
Shear strength (Mpa)	69

4.2 Material properties

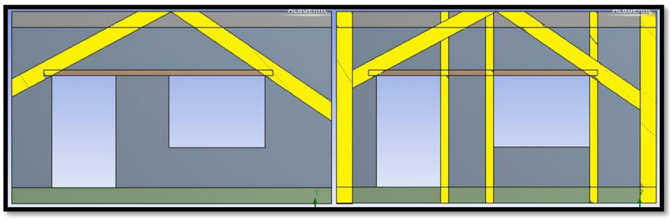
The strengthening configurations for the wall model are shown in Fig -8. The walls are reinforced with one layer of CFRP material of 5mm thickness. The width of the vertical and diagonal FRP strips is 0.3m. The width of narrow vertical strip is 0.15m.



(a) (b)



(c) (d)



(e) (f)

Fig -8: Reinforcing schemes of wall model (a) model E1 (b) model E2 (c) model E3 (d) model E4 (e) model E5 (f) model E6

5. NUMERICAL RESULTS

All the finite element models are analyzed under constant gravity load and incrementally increasing in-plane loading cycles as shown in fig -5. The gravity load is considered to create a more realistic loading condition.

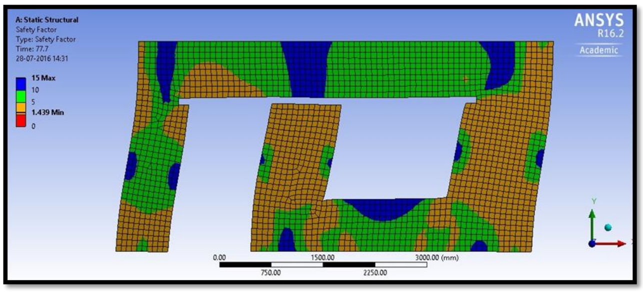


Fig -9 : Tensile stress pattern of wall model

The Fig -9 shows the tensile stress patterns of unreinforced wall. Load displacement curves of unreinforced and CFRP strengthened walls under cyclic loading are shown in chart-3. Also, the average maximum load and failure displacement are compared in two cases of unreinforced and strengthened with CFRP in Table -3.

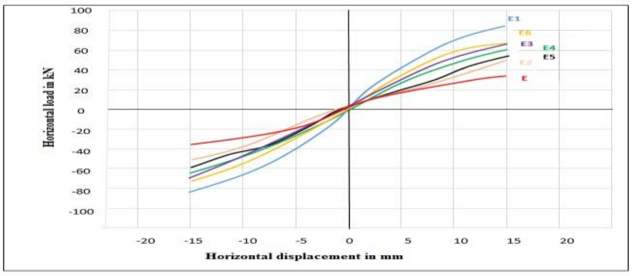


Chart -3: Comparison of load displacement curves for the wall model

Table -3 : Performance parameters of wall model

Wall model		Average maximum load in kN	Failure displacement in cm
E	Average	57.71	4.26
E1	Average	342.68	11.1
	Ratio	5.9	2.62
E2	Average	102	5.5
	Ratio	1.77	1.29
E3	Average	229.81	9.5
	Ratio	3.98	2.23
E4	Average	149.45	7.3
	Ratio	2.6	1.71
E5	Average	108.38	6.7
	Ratio	1.88	1.57
E6	Average	264.58	9.9
	Ratio	4.6	2.32

6. CONCLUSIONS

Finite element models are developed to predict the behaviour of URM wall using the software ANSYS .The experimental results of URM wall obtained from the study of Kalali et.al are compared with those obtained from analytical solutions. The proposed finite element model has the ability to track the behaviour of URM wall. The load displacement plots obtained from these models show good agreement with the experimental data.

It can be seen that the increase in performance parameters is depending on the quantity and layout arrangement of the implemented CFRP fabrics. CFRP coating which had been used as four vertical plus three diametric CFRP strips (E1 model), had the most optimized behaviour, which significantly, increased lateral resistance and ductility. The load-bearing capacity of the CFRP retrofitted masonry walls is between 1.77 and 5.9 times that of the reference unreinforced masonry walls. Also, the CFRP increased the failure displacement by a factor ranging from 1.29 to 2.62.

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