ANALYTICAL AND EXPERIMENTAL SEISMIC EVALUATION OF UNREINFORCED MASONRY WALLS RETROFITTED BY SHOTCRETE AND CFRP STRIPS

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ABSTRACT

Masonry structures are widely used due to its available materials, low cost and construction easiness. Every year large casualties due to collapse of masonry buildings during earthquakes are reported. So many of the existing unreinforced masonry (URM) buildings are seismically vulnerable and need to be retrofitted.This paper presents experimental and analytical results of in-plane behaviour of URM walls retrofitted using shotcrete and carbon-fiber-reinforced polymer (CFRP).The experimental program consists of testing three URM walls. A traditional wall was tested as the reference. Another one was retrofitted by using a 50 mm thick layer of shotcrete on one side. The last wall was retrofitted by using CFRP composites, on one side. The traditional wall consists of a single–story clay brick panel confined by RC bond-beams and tie-columns. The RC members are assumed to be of the concrete with a compressive strength equal to 12 MPa. The lower RC bond–beam is restrained against horizontal and vertical displacements. However, the upper one transfers static monotonic lateral displacement load. In this study all of the samples are tested at an age of 28 days. Analytical studies are performed with macro modelling and tested walls are calibrated with the analytical model. The comparison of these retrofitting techniques in terms of capacity, implementation and cost showed the superiority of the shotcrete technique over the other alternative.

KEYWORDS: seismic retrofitting, unreinforced masonry, cyclic test, CFRP, shotcrete, macro model

INTRODUCTION

Iran is an earthquake-prone country with a history of more than 20 major earthquakes in the last 100 years, causing large-scale damage and human casualties. A high percentage of Iranian buildings are unreinforced masonry (URM) buildings. Construction of unreinforced masonry buildings in Iran dates back to more than 2000 years ago. The existing masonry buildings in Iran are mainly constructed in the past 50 years. Most of these buildings have not been designed for seismic loads. Recent earthquakes have shown that many such buildings are seismically vulnerable and should be retrofitted. The main structural elements that resist earthquake loads in these buildings are the traditional URM walls.

Buildings with masonry walls have suffered extensive damage during earthquakes due to in-plane shear actions, as observed in the 1985 Viña del Mar, Chile [1], the 1994 Northridge, USA, the 2003 Tecoman-Colima, Mexico [2], the 2002 Changureh-Avaj, Iran[3], the 2012 Ahar-

Varzeghan, Iran [4] earthquakes. Several conventional techniques are available to improve the seismic performance of existing URM walls. The objective of this study is to compare the seismic behaviour of traditional URM walls before and after retrofitting with CFRP composites and shotcrete.

EXPERIMENTAL PROGRAM

To compare the seismic behaviour of URM wall before and after retrofitting with CFRP composites and shotcrete, this study is made. Experimental program was performed in full scale specimens. The first reference wall consists of a single–story clay brick panel confined by 0.2m×0.2m RC bond-beams and tie-columns. The clay brick panel have 2.6m×2.6m×0.2 m dimensions. Because of poor workmanship of RC members, it is assumed that the concrete have a compressive strength equal to 12 MPa .The RC members have 4 longitudinal reinforcement bars with 12mm diameter and reinforcement ties with 8 mm diameter @ 150mm. The lower RC bond–beam is restrained against horizontal and vertical displacements. However, the upper one transfers static monotonic lateral displacement load. All of the samples are tested at an age of 28 days.

The walls were subjected to in-plane displacement controlled cyclic loading by means of hydraulic rams attached to the reaction frame with a simultaneous constant gravity load. Figure 1 shows the wall and positions of electrical transducers to measure the displacements of the walls. The displacement pattern used in the tests is shown in Figure 2. The loadings consisted of two loading cycles at each drift level for all the walls. The nominal vertical load was 10 KN, corresponding approximately to the load of a wall in a one story building with a light roof. The walls were fixed to the floor but free to laterally displace and rotate at the top.The horizontal displacement was measured at the top transfer beam with a horizontal transducer.

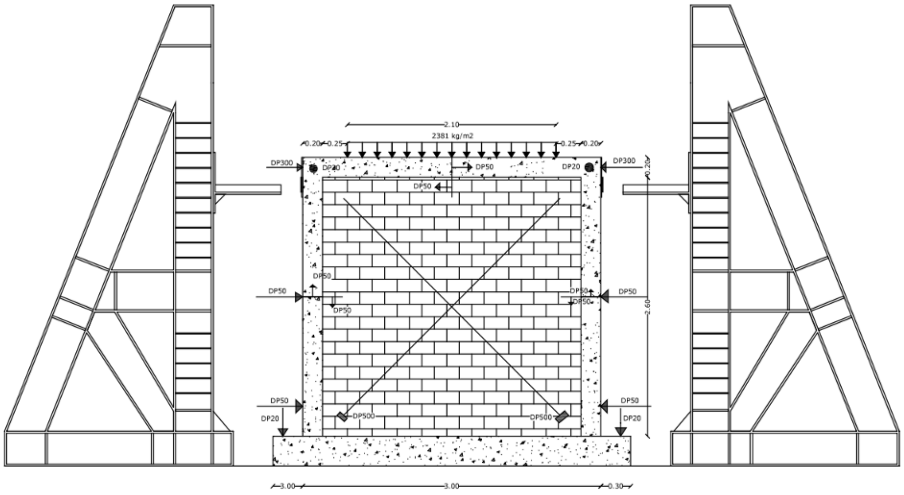

Figure 1: Elevation View of Tested Wall and Positions of Electrical Transducers

MATERIAL PROPERTIES OF MASONRY UNITS

Masonry is a highly orthotropic material due to the presence of the mortar joints acting as planes of weakness. In macro modeling, masonry is considered as a homogenized body using the material properties of masonry assemblage.

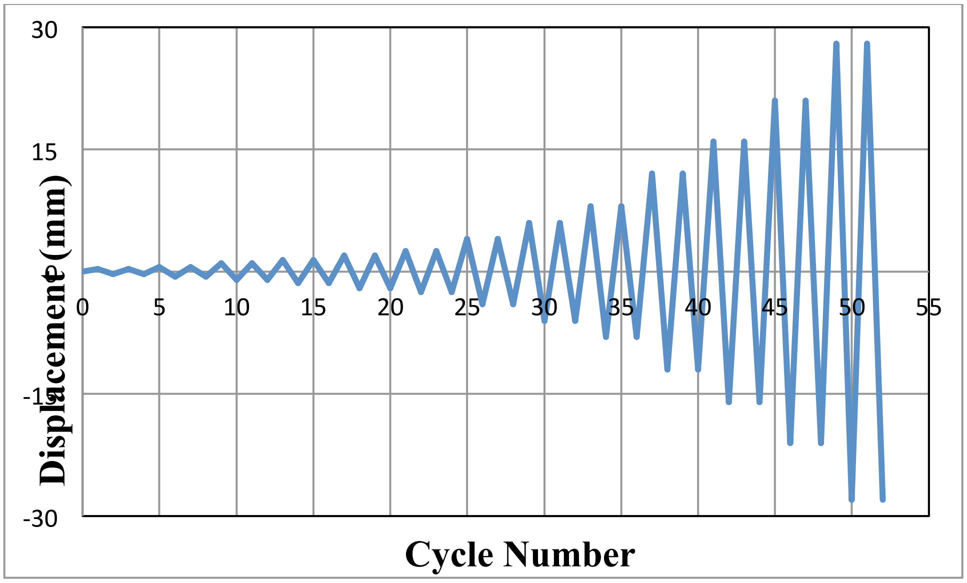

Figure 2: Displacement History for Cyclic Loading Tests

The material properties used in macro modeling of masonry walls is evaluated based on experimental studies. In this study, a macro–modeling in which isotropic elasticity is combined with orthotropic inelastic behaviour is used for modeling of masonry wall of the confined masonry wall. By using this modeling, it is anticipated that the resulted concrete damage plasticity within the wall is well distributed and also a good agreement between experimental and numerical results would occur. To determine the modulus of elasticity and compressive strength of masonry three specimens were built with clay bricks of dimensions 0.21 m × 0.105 m × 0.05 m. The isotropic material properties of masonry wall, in linear elastic and inelastic range, are shown in Table 1. The modulus of elasticity is defined as a secant modulus at service load conditions in compression tests, i.e. at 1/3 of maximum vertical load [5]. The cracking and failure pattern of the specimen and elastic and inelastic properties of masonry wall are shown in Figure 3 and Table 1, respectively. The modulus of elasticity is obtained from the specimens and the other parameters are taken from the reference by [6]. Some parameters are needed to define the concrete damaged plasticity model. As shown in table 1, eccentricity is a small positive number that defines the rate at which the hyperbolic flow potential approaches its asymptote. fb0/fc0 is the ratio of initial equi-biaxial compressive yield stress to initial uni-axial compressive yield stress. K must satisfy the yield condition and Viscosity Parameter is used for the visco-plastic regularization on the constitutive equation.

Figure 3: Cracking and Failure Pattern of the Specimen in Compression Strength Test

Table 1: Elastic and Inelastic Properties of URM Walls

E (N/mm^2)	Poisson's ratio	eccentricity	fb0/fc0	k	Viscosity	compression strength (N/mm^2)	tension strength (N/mm^2)
10000	0.15	0.1	1	0.67	0	9.5	0.5

MODELLING CONCRETE AND STEEL

The model which used for RC members in this study is Concrete Damaged Plasticity (CDP) that developed by Rabotnov & Kachanov [7, 8, and 9]. The model is a plasticity-based, continuum damage model for concrete. It is assumed that the main two failure mechanisms are tensile cracking and compressive crushing of the concrete material. The evolution of the yield (or failure) surface is controlled by two hardening variables, linked to failure mechanisms under tension and compression loading, respectively. The model assumed that the uniaxial tensile and compressive response of concrete is characterized by damaged plasticity, as shown in Figure 4.

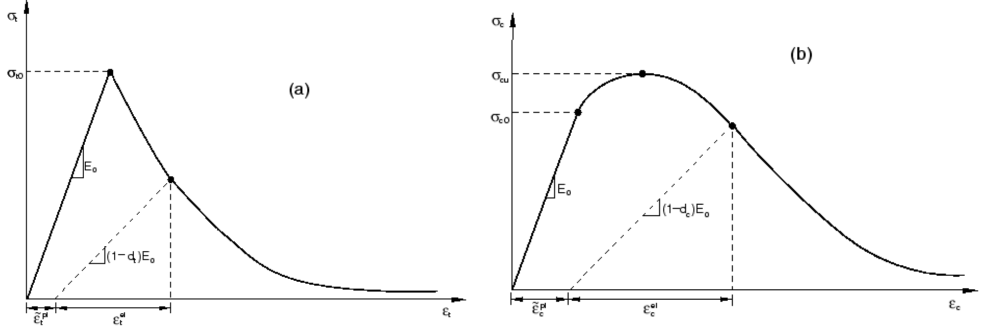

Figure 4: Stress-Strain of Concrete to Uniaxial Loading: a) Tension; b) Compression

Also, by the tension test, the stress-strain behaviour of the steel bars is obtained. In this study, the Mander model for compression behaviour of concrete is used. Figure 5 shows the stress-strain curves [10].

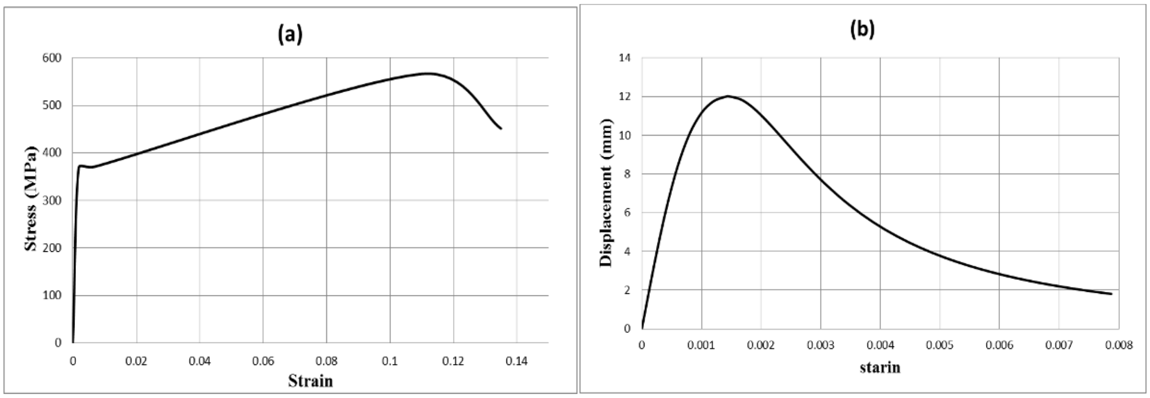

Figure 5: a) Stress-Strain Model for Steel; b) Mander Stress-Strain Model for Concrete

EXPERIMENTAL RESULTS OF THE REFERENCE WALL

The crack pattern and the hysteretic response of the traditional wall are shown in Figure 6 and Figure 7 respectively. The wall had an almost linear behaviour up to approximately 90 KN, at a lateral displacement of 1 mm. In larger drifts the lateral resistance of the wall increased up to 148KN at a displacement of 5.16 mm. Failure mode occurred at a lateral displacement of 21 mm. As it can be seen from the figure the failure mode is the sliding bed joints.

Figure 6: Crack Pattern of Traditional URM Wall under Cyclic Loading

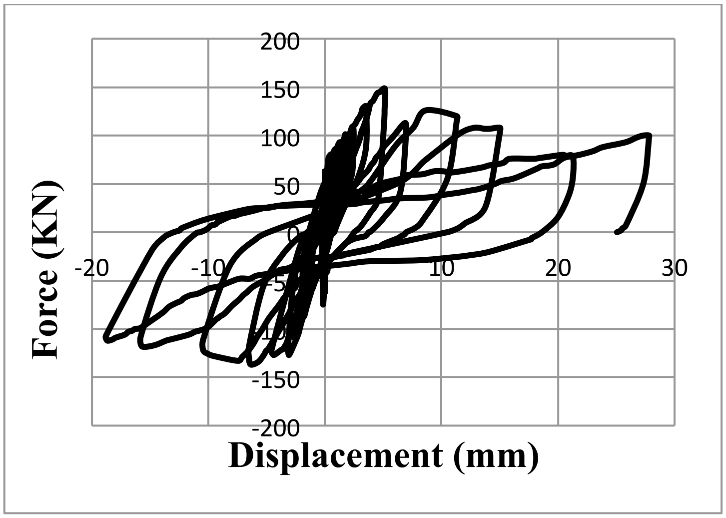

Figure 7: Hysteretic Response of URM Wall under Cyclic Loading

EXPERIMENTAL RESULTS OF THE RETROFITTED WALL WITH CFRP

The retrofitting technique consists of the CFRP composites to one side of the wall. Before bonding the strips the surfaces of the wall were grinded with a common hand held sanding machine and levelled with putty placed in the mortar joints. The configuration of CFRP reinforcement was considered as vertical and horizontal strips, as shown in Figure 8.

The failure mode of the wall changed from the bed joint sliding to the diagonal cracking. The results showed the efficiency of the retrofitting and repairing technique using CFRP composites. The cracks were first generated in wall and then the CFRP composites were ripped. The maximum force in the hysteretic behaviour of wall increased up to 202 KN. Figures 9 and 10 show the crack pattern and hysteretic curve of the retrofitted wall with CFRP, respectively.

Figure 8: Configuration of CFRP Reinforcement

Figure 9: Crack Pattern of the Retrofitted Wall with CFRP

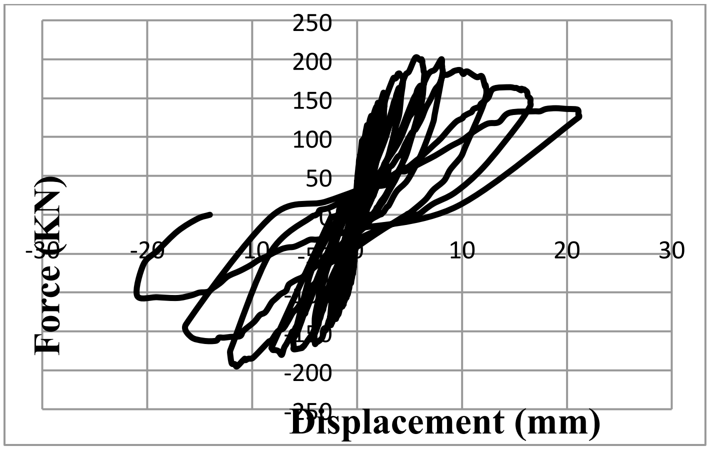

Figure 10: Hysteretic Response of the Retrofitted Wall with CFRP

EXPERIMENTAL RESULTS OF THE RETROFITTED WALL WITH SHOTCRETE

The wall was retrofitted on a single-side using a 50 mm thick layer of shotcrete. One layer of 6-mm diameter steel bars mesh @ 150 mm was fixed to one side of the wall. The mesh bars were fixed by epoxy resin on the RC bond-beams and tie-columns. Then, the wall surface was wetted and the shotcrete was applied on a single side of the wall as shown in Figure 11.

Figure 11: The Retrofitted Wall with Shotcrete Layer

Figure 12 shows that the failure mode of the retrofitted wall with shotcrete compare to the traditional wall was changed to the rocking mode. In load of 203 KN, the main crack is observed with continuing the test, steel bars lied under tension, so the shotcrete layer separated from wall and Steel bars were pulled out of the shotcrete in ultimate load. The hysteretic curve of the tested wall is presented in Figure 13. From this figure, the effect of retrofitting on deformation capacity and ultimate lateral strength is readily seen. The maximum load in hysteretic behaviour approached to 268 KN.

Figure 12: Rocking Failure Mode of Retrofitted Wall with Shotcrete Layer

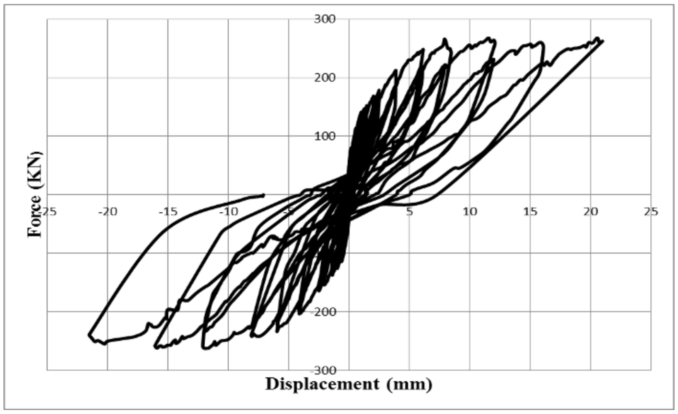

Figure 13: Hysteretic Response of Shotcrete Wall

NONLINEAR ANALYSIS

A pushover analysis is performed to obtain the crack pattern, distribution of the maximum and minimum principal stresses and the force–deformation curve (i.e. capacity curve). The analysis type is physically nonlinear. For pushover analysis of a confined masonry wall, a monotonic lateral load should apply on the top of the model based on the ATC-40 requirements. This guideline does not recommend any other load pattern to apply on one story buildings. The Newton–Raphson iteration method is used. The augmented lateral displacement load is applied at the upper RC bond–beam from left to right after the gravity load analysis is performed.

CRACK FORMATION AND DAMAGE DISTRIBUTION

As it can be seen from Figure 14, the sliding failure of the traditional wall is calibrated by the analysis. The failure mode of the retrofitted wall with CFRP in analysis was diagonal cracking which confirm with the experimental findings. Also, Analysis on the retrofitted wall with shotcrete layer was showed to be rocking mode of failure similar to the results of the experiment. All the walls calibrated by the FEM model analysis on ABAQUS software. Cracking pattern of analysis and force-displacement curves of the analytical and experimental for the walls are shown in Figures 14, 15 and 16.

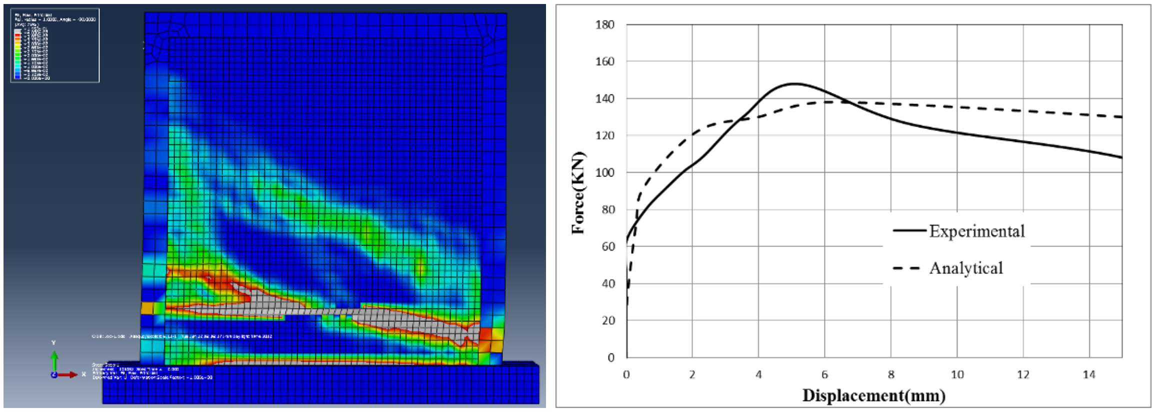

Figure 14: Traditional Wall: a) Crack Pattern in Analysis; b) Analytical and Experimental Pushover Curves

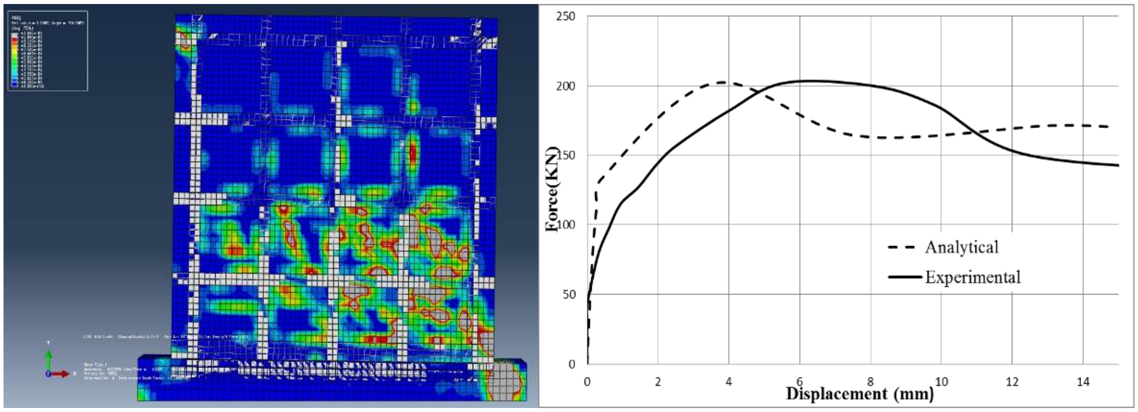

Figure 15: Retrofitted Wall with CFRP: a) Crack Pattern in Analysis; b) Analytical and Experimental Pushover Curves

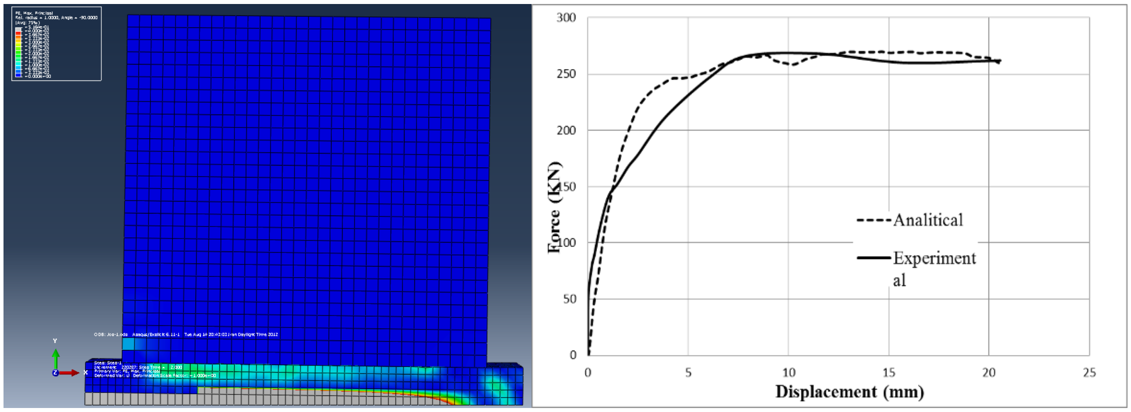

Figure 16: Retrofitted Wall with Shotcrete Layer: a) Crack Pattern in Analysis; b) Analytical and Experimental Pushover Curves

CONCLUSIONS

This paper presents the results of the experimental and analytical of the in-plane behaviour of URM walls before and after retrofit using CFRP and shotcrete layer in full scale. A traditional wall was tested as a reference wall. The other two traditional walls were retrofitted on one side of wall by horizontal and vertical layer of CFRP and a 50 mm thick layer of shotcrete. Also, In order to evaluate the crack pattern; maximum and minimum principal stress contours and capacity curves for full scale confined traditional masonry wall and retrofitted by CFRP and shotcrete layer a macro model analyses were carried out. The following conclusions can be drawn from the present study:

1. The elastic stiffness of the retrofitted wall with shotcrete is more than the retrofitted wall with CFRP. The ultimate loads of the retrofitted wall with shotcrete and the retrofitted wall with CFRP are about 80% and 40% more than the reference wall, respectively. However, the ductility and the energy dissipation of the retrofitted wall with CFRP are more than the retrofitted wall with shotcrete layer.
2. The pushover analyses on the macro models of the walls are well estimate on maximum and minimum principal stress contours as well as the first cycle of the capacity curves. The modes of failure are well matched with the mode of failure obtained from the experimental

models. However, a micro model of the wall can give more accurate results compared to the macro model which requires further research.

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