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# Strengthening of Historical Masonry Buildings with Fiber Reinforced Polymers (FRP)

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**Abstract** The historical masonry buildings form widespread spectrum of existing buildings in IRAN. destruction on structures illustrate that historical masonry buildings have maximum damages due earthquake, in addition they don't actuate properly about seismic behavior (the main reason of this is lack of proper ductility). Shear of the masonry walls, is the only structural element of these type buildings, undertake gravity load and lateral load. This is the main reason that leads to researchers think over techniques about improvement and strengthening the walls, and also leads to experiencing real samples and scaled models.

In this essay, at the beginning was introduced a method about modeling finite elements unreinforced masonry (URM) wall by using of software (ANSYS).

In order to verifying the correctness of modeling, it's require to do experimental test on a sample of wall and then that wall should be modeled by illustrated method. Then correctness of modeling method and analyzing method should be verified by comparing the result of numerical modeling with the result of modeling experimental. The experimental model has been examined at Shiraz University. The result of numerical modeling and analyzing illustrate that lateral load-displacement curve is stiffer than experimental curve. And lateral load carrying capacity has precision about 99.28 percent, and lateral displacement has precision about 94.1 percent. also the numerical results agree reasonably well with the experimental results.

In the next stage the masonry walls are strengthened with Carbon Fiber Reinforced Polymer sheets (CFRPs). five different strengthening methods have been used with different thickness. The strengthened walls are affected by vertical loads and in-plane shear. It is found that the critical loads, the critical displacement, the ultimate loads, the ultimate displacements and the ductile coefficients of the masonry walls strengthened with CFRPs improve remarkably.

**Keywords:** Masonry walls, strengthening method, lateral load, Historical buildingsCFRPs

## Introduction

The masonry shear panels are the main vertical and lateral load-resisting elements in such buildings which transfer the loads to the foundation. The lack of proper connection joints at integrated elements such as masonry joints, panel connections and panel to floor connections are the main deficiencies of these buildings. The masonry buildings show rather good results under vertical loads though the absence of appropriate ductility during the earthquakes considers as the main deficiency (Moghadam 1998).

Different conventional retrofitting techniques are available to increase the strength and ductility of unreinforced masonry (URM) buildings which are seismically vulnerable such as surface treatment by shotcrete, grout and epoxy injection, confining URM using RC tie columns, post-tensioning and etc. These techniques include some advantages and disadvantages such as elongation in construction period, decrease in available space, disturbance for building residents, influence on aesthetic and etc. Moreover, the added mass to the building structure can cause an increase in seismic loads that result in retrofitting of building foundation (Gawady et al. 2004).

Using Fiber reinforced polymer (FRP) is one of the recently developed techniques for structural retrofitting that includes various kinds of fibers such as GFRP, CFRP and AFRP which are included in continuous polymer matrix. Using FRPs can increase the ratio of strength and stiffness to weight, enhance the durability at various situations and convenience in installation.

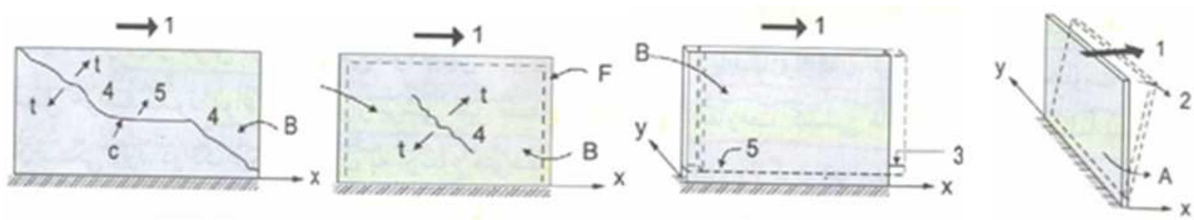
At the present study, the modeling methods and in plane behavior of an URM building reinforced by FRP are investigated under mutual effect of vertical and shear loads by pushover analysis using finite element software, ANSYS.

## Failure Mechanism of Single Panels under Seismic Loads

Typical damages at masonry panels are illustrated in fig. 1 (a). The seismic load is applied through vertical plane to the panel and the applied load to the panel mass can result in overturning of the panel.

The panel is constrained on the ground (See Fig. 1 (b)) and the seismic load is applied through panel plane. Whereas the panel shows greater resistance due to smaller aspect ratio (length to height), in plane slippage is occurred and performs as a shear panel. Typical damages applied to the URM panels are dependant to their aspect ratio. Diagonal cracking occurs in a confined panel with mean aspect ratio which is mainly in consequence of shear forces. (See Fig. 1 (c))

Diagonal and horizontal cracks occur at both sides of the panel mainly due to tensile forces and at mid span of the panel with high aspect ratio, respectively. (See Fig. 1 (d))




*(d) Panel with great aspect ratio* *(c) Panel with mean aspect ratio* *(b) Panel with small aspect ratio* *(a) Overturning of the panel due to vertical loads*

*Figure 1: Cracking patterns at the panels*

## In Plane Shear Test on URM Panel

It is required to empirically test a typical panel and to be modeled by presented method and then to be validated by comparing corresponding results. Therefore, the results of experimental tests conducted by Dr. M.R Maheri et.al at University of Shiraz are investigated (Maheri 2008).

Consider a typical 160×140 $cm^2$ panel with thickness of a brick while the bricks are used saturated with dry surface and are cured during 28 days after the panel constructed. It shall be noted that fine aggregate within ASTM standard is used in mortar. Thus, the mortar can carry the loads sufficiently due to proper cohesion with adjacent bricks.

The main elements are reaction frame, strong floor, 30 ton vertical and horizontal hydraulic loading system.

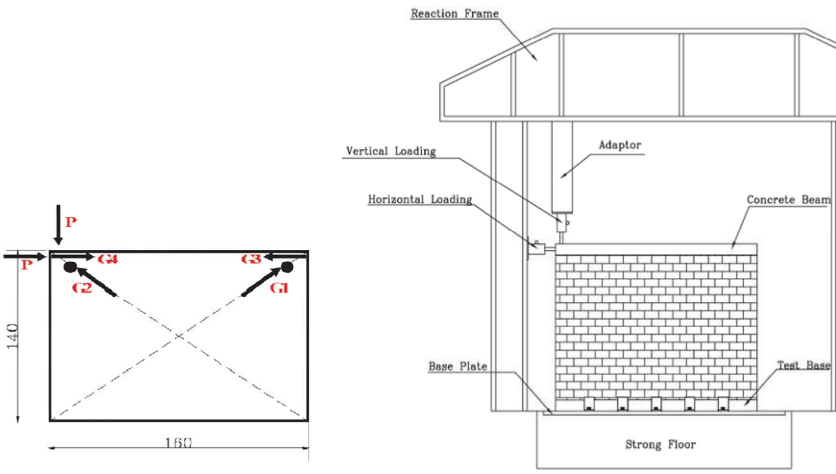



*Figure 2: In plane shear test and displacement meter layout* (Maheri 2008)

The loadings are applied by two horizontal and vertical hydraulic loading systems. In fact, in plane lateral forces are applied by horizontal loading system and also the vertical loading system which simultaneously applied causes shear performance through the panel. Pushover static test with approximately 3 KN loading stages are carried out. Moreover, the displacement of the specimens is recorded by four displacement transducers installed on the panel.  The loading continues until the specimens fail and thereafter the Load-displacement curves are derived.

*Figure 3: Loading conditions and failure of the masonry shear panel*

*Figure 4: Shear failure pattern as diagonal cracks*

Shear failure pattern as diagonal cracks on the specimen is illustrated in Fig. 4. As it is shown, the diagonal cracks crossed the brick and mortar interface with no slippage. Accordingly, the results of this test are used to calibrate and validate the models (Maheri 2008).

Also the Load-displacement curve resulted from different displacement transducers mounted laterally and diagonally on the specimen are shown in Fig. 5.

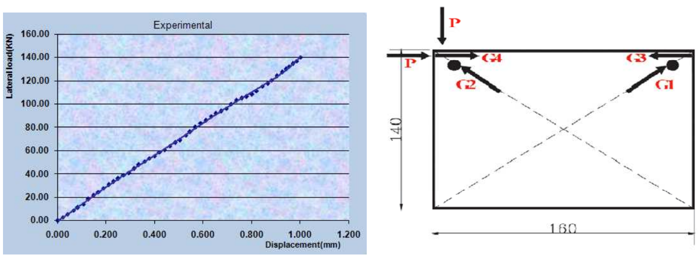



*Figure 5: Load-Displacement curve for G3 lateral displacement transducer*

The behavioral and strength parameters of the materials of the tested specimens which are in accordance with ASTM E519-81 (1999) are tabulated in Table 1.

*Table 1: Behavioral and strength parameters of the materials of the tested specimens*

| *Parameters* | *Values (MPa)* |
|---|---|
| Compressive strength of the brick | 11 |
| Tensile strength of the brick | 1.1 |
| Compressive strength of the mortar | 34 |
| Tensile strength of the mortar | 4.4 |
| Elasticity modulus of the brick | 7500 |
| Elasticity modulus of the mortar | 12000 |

**Finite Element Modeling**

The numerical modeling of the masonry panels are generally divided to Micro and Macro modeling. A typical masonry panel is integrated of three main elements: brick, mortar and their interfaces. Each of the masonry panel elements are separately modeled in Micro modeling. (See Fig. 6) Although the models are more precise in micro modeling, the calculation and modeling method is rather complicated and is not applicable for greater models. The masonry panel is considered as homogenous materials with equivalent mechanical characteristics in Macro modeling. (See Fig. 7) The Macro modeling is more convenient and easier than Micro modeling and also has rather less calculation process.

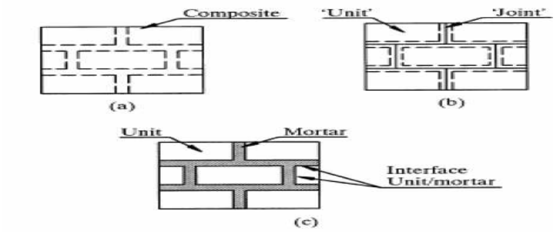



*Figure 7: Macro modeling of the masonry panel*

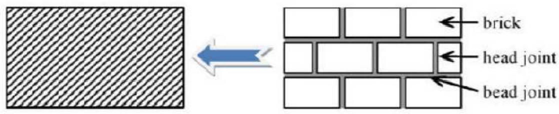



*Figure 6: Micro modeling of the masonry panel*

At the present study, the Macro modeling is used which has been presented by Lourenco et. al (1997) at Minho university. Also some other researchers such as Kappos et. al and Giordano et. al (2002) have created Macro models on masonry buildings in greater dimensions by ANSYS and ABAQUS software which bricks, mortar and their interfaces are assumed as homogenous materials (Betti and Vignoli 2007).

A three dimensional isoparametric element, Solid 65, is used to model URM panel. SOLID 65 is a three dimensional 8-node element and it has six corner nodes, and each node has three translational degrees of freedom. The materials are able to crack at tensile stresses and fail under compressive stresses at three perpendicular directions and also creep and plastic deformations. It is possible for the user to add reinforcements at each direction with steel or other materials. (See Fig. 8) The panel is modeled by isotropic materials with equivalent properties which have general elastic characteristics of masonry panel (ANSYS user Manual 2005).

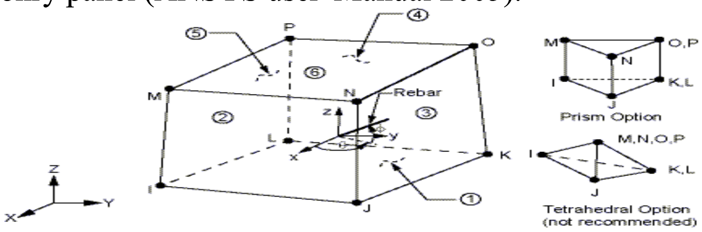



*Figure 8: SOLID 65 element*

Concrete is used for plastic parameters. Whereas ANSYS is able to model brittle materials, Concrete is defined and used in this software which performs based on Willam-Warnke yield criterion. So, if the tensile stress exceeds tensile resisting capacity of the materials, the cracking will occur and if the combination of the available stresses exceeds the compressive strength of the materials, the crashing at three perpendicular directions and also creep and plastic deformation will occur. The nonlinear behavior includes cracking, failure and decrease in stiffness due to cracks, creep and plasticity (ANSYS user' Manual 2005) (See Fig. 9).

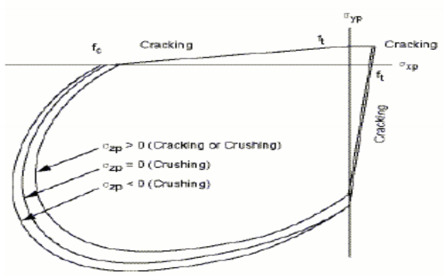



*Figure 9: Willam-Warnke yield criterion at Concrete material in ANSYS*

Nonlinear structural-layered element SHELL181 (Shell with limited strain) is used to model FRP shells which is a three dimensional 4-node shell element and each node has six degrees of freedom. This element is able to apply all nonlinear properties and also bounded strains. The modeling is allowed up to 255 layers in this element. (See Fig. 10) The layers related data are entered by shell cross section instead of constant values (Motlagh et al. 2003). Also Tsai-Wu failure criterion is considered for FRP composites. Therefore, only SHELL181 element which is a 4-node element is used to model composites and has the capability to transfer forces at panel and FRP interfaces. Since the required force to separate the panel and FRP is rather high, the cohesion at panel and FRP shell interface assumes ideally perfect (Gabor 2006).

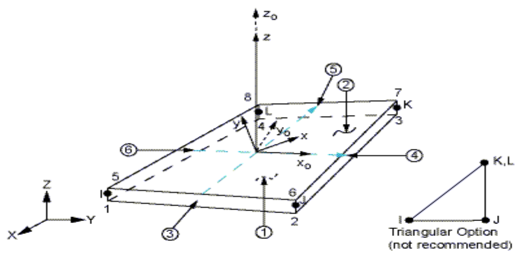



*Figure 10: SHELL181 element*

According to Fig. 11, the size of the element is 5 cm and the total number of the elements and also the nodes are 2080 and 4092, respectively. An equivalent compressive load equal to 0.7 MPa is applied on 132 nodes above the panel at rather short duration (i.e. 0.01 s) and the lateral loads on those nodes above the panel are gradually increased in order the problem to be converged. The bottom of the panel is well constrained which is in good accordance with the condition of the strong floor at the laboratory.

As it is shown in Table 2 and Fig. 12, the numerical curve shows stiffer condition than experimental curve and the load bearing capacity revealed 0.72 and 99.28 percent error and precision, respectively and also percentage of the error and precision at ultimate displacement are equal to 5.9 and 94.1, respectively; Consequently, the curves show good accordance in numerical and experimental results and it can be stated that the models are well calibrated.

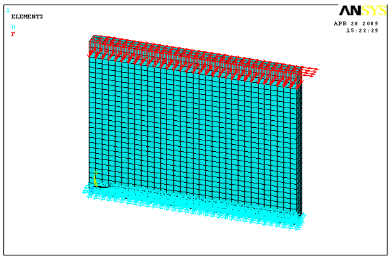


*Figure 11: Finite element model of masonry panel and loading conditions*

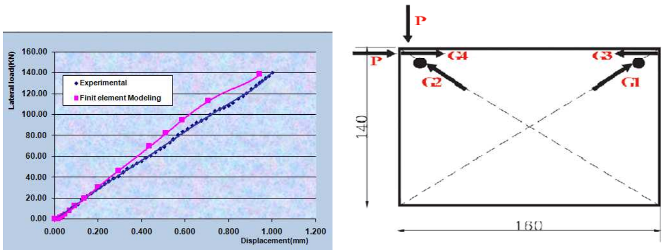


*Figure 12: Lateral load- displacement at G3 direction*

*Table 2: Comparing numerical and experimental results for lateral load-displacement of G3*

| *Ultimate Load (KN)* | *Ultimate Load(KN)* | *Ultimate Displacement(mm)* | *Ultimate Displacement(mm)* |
|---|---|---|---|
| Experimental | Numerical | Experimental | Numerical |
| 140 | 139 | 1.000 | 0.941 |

## Properties of Composite Materials

The properties of composite materials of CFRP applied in modeling of masonry specimens reinforced by FRP are presented in Table 3.

*Table 3: Mechanical properties of FRP shells (Jones 1999)*

| *Materials* | $E_x$ (GPa) | $E_y$ (GPa) | $v_{xy}$ | $v_{yz}$ | $G_{xy}$ (GPa) | $X_t$ (GPa) | $Y_t$ (GPa) | $S_{xy}$ (GPa) | *Ultimate strain* | *Thickness (mm)* |
|---|---|---|---|---|---|---|---|---|---|---|
| CFRP shell | 373 | 2.35 | 0.25 | 0.35 | 1.56 | 2940 | 55.9 | 70 | 0.8 | 0.165 |

## Reinforcing Patterns of Masonry Panel

Different reinforcing patterns of URM panels with FRP based on failure modes are presented in Fig. 13 which can be applied to counter such types of failure. It shall be noted that 2 mm FRP sheets with carbon fiber angle of 0 and 90 degrees are used on both sides and the width of FRP sheets are considered 20 cm at reinforcing pattern of vertical, horizontal, wrapping and diagonal sheets.

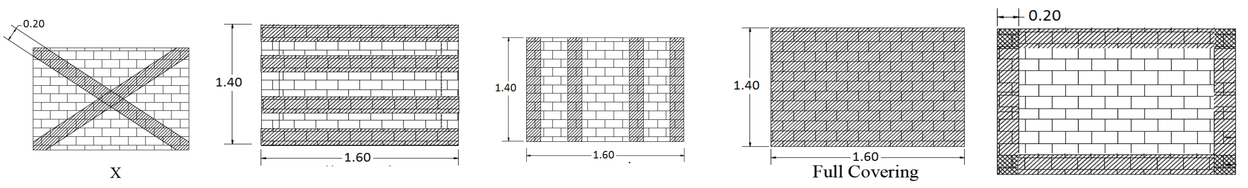



*Figure 13: Different reinforcing patterns of the panel by FRP sheets*

The Load-displacement curves and comparing results of different reinforcing methods of URM panels are presented in Fig. 14 and Table 4.

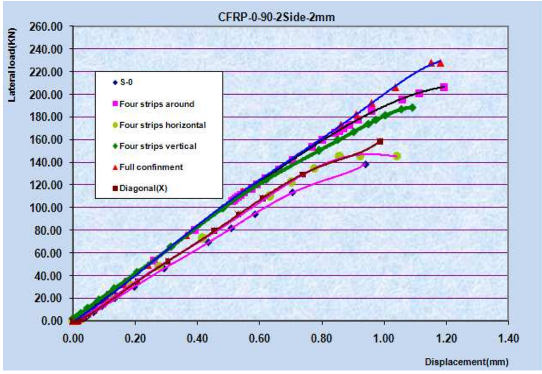



*Figure 14: Lateral load-displacement of G3 with five FRP reinforcing method having fiber angle of 0-90 and thickness of 2 mm*

*Table 4: Numerical results of different reinforcing methods by CFRP composites with thickness of 2 mm*

| | *Ultimate Load* | | *Ultimate displacement* | |
|---|---|---|---|---|
| Numerical object | Numerical result (KN) | Improvement (%) | Numerical result (mm) | Improvement (%) |
| S0 | 139 | --------------- | 0.941 | ----------------- |
| Four strips horizontal | 145 | 4.31% | 1.04 | 9.9% |
| Four strips vertical | 189 | 35.97% | 1.092 | 16.04% |
| Four strips around | 211 | 51.79% | 1.36 | 42.4% |
| Full | 227.72 | 63.8% | 1.181 | 25.5% |
| Diagonal | 158 | 13.66% | 0 .988 | 4.99% |

As it is shown in Fig. 14 and Table 4, the application of CFRP can improve and increase the ductility and lateral bearing capacity. Reinforcing URM panels with 20 cm wide horizontal CFRP sheets have increased the ultimate lateral load about 4.31 percent and also the displacement of the panel has been increased to some extent which in fact causes an increase in ductility amounted to 9.9 percent. The vertical CFRP sheets with thickness of 2 mm and width of 20 cm covered on both sides of the panel have caused 35.97 and 16.09 percent increase in ultimate lateral load and ductility, respectively. The wrapping CFRP sheets with thickness of 2 mm and width of 20 cm covered on both sides of the panel have caused an increase in ultimate lateral load and ductility about 51.79 and 42.4 percent, respectively. The diagonal CFRP sheets with thickness of 2 mm and width of 20 cm covered on both sides of the panel have resulted in 13.66 and 4.99 percent increase in ultimate lateral load and ductility, respectively. Fully covering of CFRP sheets with thickness of 2 mm and width of 20 cm on both sides of the panel have caused 63.8 percent increase in ultimate bearing capacity and also the ductility is increased 25.5 percent. In fact, all of the reinforcing methods have enhanced the stiffness and ductility of the URM panel though the most proper method is fully covering of CFRP on masonry panels which showed 63.8 percent increase in lateral bearing capacity and on the other hand the weakest performance was belonging to horizontal CFRP sheets which only showed 4.31 percent increase in lateral bearing capacity. Whereas the wrapping CFRP sheet forms a Frame, showed nearly the same performance as fully covering of CFRP on both sides of the panel showed and also consume less materials; therefore, it is the most optimum method among other reinforcing methods.

## Conclusion

The numerical modeling curve shows more stiffness than experimental curves and the bearing capacity revealed 0.72 and 99.28 percent error and precision, respectively due to calibration of the finite element model using ANSYS comparing to experimental results from Dr.Maheri et.al at University of Shiraz and also percentage of the error and precision at ultimate displacement are equal to 5.9 and 94.1, respectively which shows good accordance in numerical and experimental results. Comparing both analytical and experimental curves revealed that ultimate load of experimental specimen is equal to 140 KN while the ultimate load at analytical model is equal to 139 KN and also the ultimate displacement of the experimental specimen is equal to 1 mm though the analytical value is amounted to 0.941 mm which shows more stiffness in analytical model than experimental one.

The ductility and energy dissipation of the panel increases by using fibers with high failure strain capacity which can postpone the whole failure modes of the masonry panels.

The wrapping sheet system has the most optimum performance among all of the introduced patterns; since it develops a *Frame* for URM panel and resist against all three failure mechanisms and also consumes less materials.

The diagonal and horizontal CFRP sheets had the weakest performance than other reinforcing methods.

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