In-plane Lateral Response of Brick Masonry Walls Retrofitted with Reinforced Concrete Layer

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ABSTRACT:

Seismic strengthening of brick masonry structures is in major priority because of their high vulnerability to earthquakes. An acceptable strengthening technique should provide both the stiffness and ductility for the structure. There are so many conventional techniques used to retrofit masonry structures in the world that more or less improve the performance of these structures, but still there is a need of much more investigation to clearly understand the influence of these methods on seismic behavior of masonry. One of the most popular strengthening methods for brick masonry buildings in Iran is coating the walls with reinforced concrete layers. This way of retrofitting provides good strength and ductility for the masonry structure and also controls the crack propagation in the walls, but because of the lack of experimental and analytical information on this method, retrofitting procedures are always done based on empirical recommendations. This research is an effort to study the seismic performance of the masonry structures retrofitted with this method. For this reason a novel approach is proposed to investigate the in-plane behavior of retrofitted masonry wall with RC concrete layer. The reliability of the numerical results is confirmed through a comparison between numerical and available experimental results.

KEYWORDS: Masonry, seismic strengthening, seismic performance

1.INTRODUCTION

Existing unreinforced masonry buildings constitute a significant portion of existing buildings around the world. This indicates the urgent need of retrofitting these buildings. For this reason, during the past decades different evaluation procedures have been proposed for seismic evaluations of masonry buildings. Also there are a large number of methods for retrofitting masonry structures that are intended to improve their in-plane and out-of-plane seismic performance. Some conventional methods are surface treatment (Ferrocement, FRP layer, Shotcrete layer [1]), grout and epoxy injection [2], external reinforcement [3] and confining masonry walls and post-tensioning.

Although a variety of techniques are used to for strengthening the masonry buildings, and many researches (e.g. [1]) have discussed the advantages and disadvantages of these techniques, there is little information and technical guidelines with which an engineer can judge the relative merits of these methods. Also there are no reliable analytical methods to evaluate the seismic resistance and performance of retrofitted masonry structures. In the past years many researchers have been tried to analytically investigate the seismic behavior of retrofitted masonry with different techniques of retrofitting. Among them we can say, Elgawady [4] proposed an analytical method to study the global behavior of retrofitted masonry with FRP layer, or Abrams [5] tried to experimentally and analytically study the behavior of retrofitted masonry with different retrofitting methods like shotcrete.

One of the most popular methods used in Iran for strengthening the masonry structures is coating the walls with reinforced concrete layers but because of the lack of experimental and analytical information on this method, rehabilitation procedures are being done based on empirical judgments. In this method a mesh of reinforcing bars is first placed in the face of the wall and then it is covered with a concrete layer. This procedure can be done for both or just a single side of the wall. Also the concrete layer and reinforcing bars would be anchored to the wall to assure the consistency of the deformations of the wall and concrete layer.

In this paper simple novel method is used to predict the behavior of masonry walls retrofitted with concrete layer. In this method the shear and flexural behavior of the wall are predicted separately and then they are coupled so that the shear displacement curve of the wall will be calculated with regard to the governing behavior.

2.ANALYSIS OF RETROFITTED WALL

In this section the procedure for analyzing the retrofitted wall with concrete layer is discussed. The aim of this analysis is to produce a simple method of calculating the shear-displacement curve of a retrofitted masonry wall under a constant axial force that is applied to the masonry part of the wall. As it is shown in Fig.1 deformation behavior of a wall under shear force is composed of two parts: flexural deformation and shear deformation. So for exact calculating the shear-displacement curve of a wall, we should compute the flexural and shear deformation parts of the wall. Then by coupling them in each step, the displacement of the wall is correctly estimated.

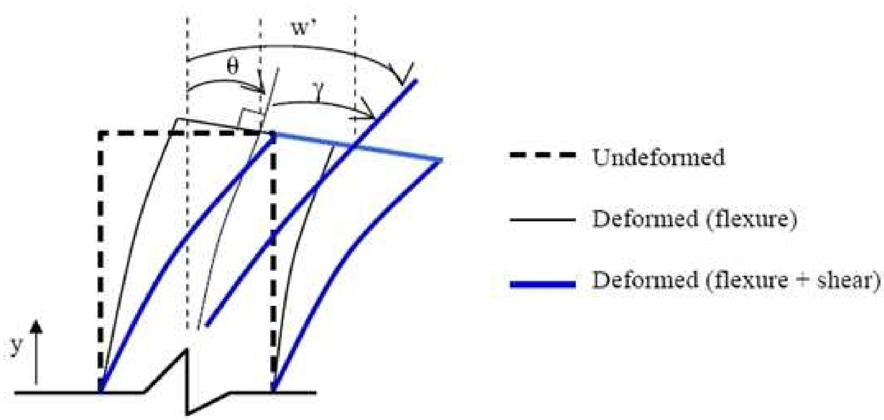

Figure 1 Load versus axial strain curves

Firstly, a moment-curvature analysis is done to obtain the moment-curvature curve of the retrofitted wall (Fig.2). The method of calculating moment-curvature relation of the wall is discussed in the following section (sec. 3). After calculating the moment-curvature diagram, the shear displacement curve of the wall with regard to flexural deformations can be computed.

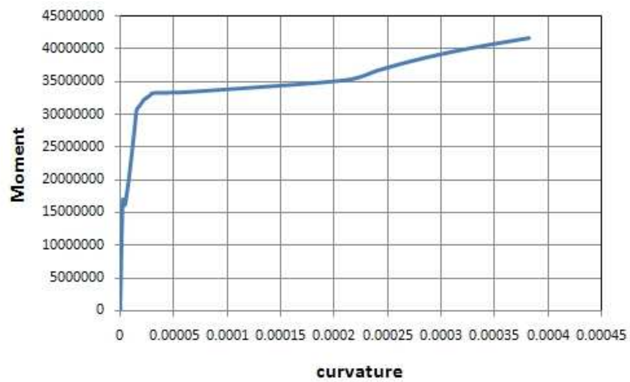

Figure 2 Moment-curvature curve of a sample retrofitted wall

In each step the shear can be calculated according to the Eqn.2.1 from the value of moment in that step.

$$V = \frac{M}{h} \tag{2.1}$$

where V is shear, M is moment and h is the height of the wall.
For calculating the displacement, we should first calculate the rotation of the wall, which can be done based on the general relation between the rotation and curvature as:

$$\theta = \int_0^h \frac{\kappa . x}{h} dx \tag{2.2}$$

where θ is the rotation of the wall, κ is the curvature of the wall in each step, x is shown if Fig.3 and h as previously defined is the height of the wall. So the shear-displacement curve of the wall with regard to flexural deformations can be extracted from moment-curvature curve of the wall.

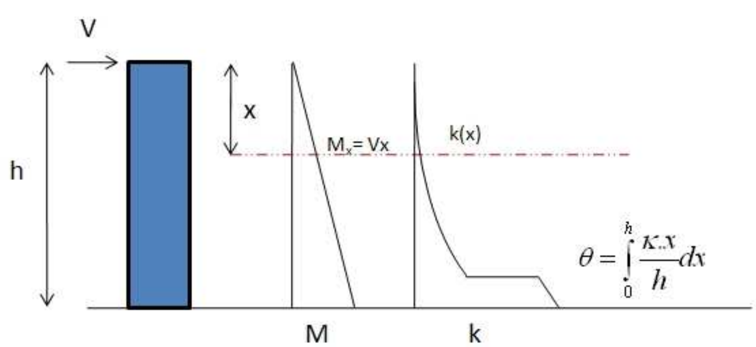

Figure 3 Determination of the wall rotation

Secondly, the shear-displacement curve of the wall under pure shear loading is calculated. The adopted procedure for analysis of retrofitted masonry panels under pure shear loading is discussed in sec. 4. Having calculated the shear-displacement curves of the wall according to flexural and shear behavior separately, these two curves will be coupled as shown in Fig.4.

As it is shown in Fig.4 the total displacement of the wall, *dt*, in each step is calculated by adding the flexural displacement, *df*, to the shear displacement, *ds*, of the wall in that step. This procedure is continued unless the peak point of the lower curve is reached (*dp*). From this point forward the shear displacement of the wall will be the same as the governing behavior curve (lower curve) in which the displacement will be increased by the value of *dfp*.

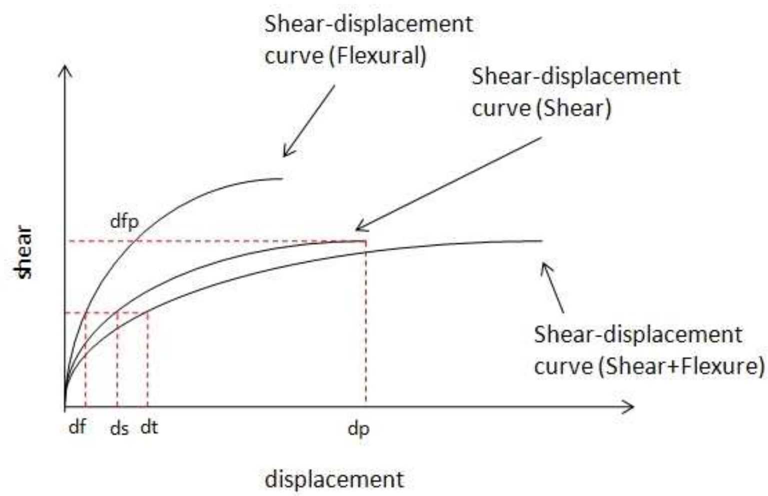

Figure 4 calculating the total shear-displacement curve

The aforementioned procedure has been included in a Fortran code. This software code, MPV, can be used to predict the shear-displacement curve (pushover curve) of bare masonry wall, RC wall and retrofitted masonry wall with concrete layer (rectangular or I shape walls) with any governing behavior (shear or flexure) and considering all probable failure modes in masonry and concrete (bed joint sliding, diagonal tension, toe crushing, rocking).

3.Calculating the Moment-Curvature diagram of retrofitted masonry wall

For the creation of the inelastic moment-curvature curves of the retrofitted wall there will be two main steps. First defining the wall geometry and material properties and second is the moment-curvature analysis. In the first step the geometry of the wall is defined and then it is divided into some cells (fibers), as shown in Fig. 5, and then the appropriate material properties are assigned to each cell. Also we need the nonlinear stress-strain behavior of each material (concrete and masonry) in compression and tension.

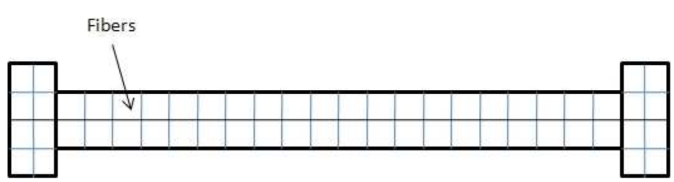

Figure 5 Section and fibers defining

In the second step, by knowing the constant axial force, we should assume a strain distribution (Fig. 6) over the wall section that the resulting stresses in fibers will satisfy the equilibrium equations in the section. The equilibrium equation that should be satisfied is Eqn.3.1.

$$\sum \sigma_i A_i = N \tag{3.1}$$

where σ_i is the stress in each fiber, A_i is the area of each fiber and *N* is the constant axial force applied to the wall. This procedure should be done with an iterative method to obtain the appropriate strain distribution over the wall section that satisfies the Eqn.3.1. Then the moment can be calculated according to Eqn.3.2.

$$\sum \sigma_i A_i y_i = M \tag{3.2}$$

where y_i is the fiber distance to the neutral axis of the section. The curvature of the section is also computed with Eqn.3.3.

$$\kappa = \frac{\varepsilon_t + \varepsilon_c}{l} \tag{3.3}$$

where κ is the curvature of the section, ε_t is the first layer strain, ε_c is the last layer strain and *l* is the length of the section. This procedure shall be done for different strain distributions and then the moment-curvature diagram of the wall will be obtained.

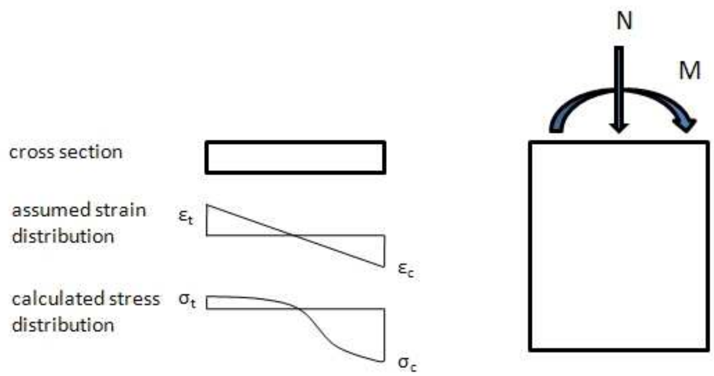

Figure 6 assumed strain distribution in the wall section

4.Shear behavior analysis of the retrofitted masonry wall

For analysis of the retrofitted wall under shear, it is assumed that the masonry and concrete layer are tied together and their deformations are the same. By taking into account the mentioned assumption, the problem is to calculate the shear stress for the increasing values of shear strain in each step by satisfying the equilibrium equations:

$$\sigma_{xc} + \sigma_{xm} = 0 \tag{4.1}$$

$$\sigma_{yc} + \sigma_{ym} - \sigma_{yi} = 0 \tag{4.2}$$

$$\varepsilon_{xc} = \varepsilon_{xm} \tag{4.3}$$

$$\varepsilon_{yc} = \varepsilon_{ym} \tag{4.4}$$

Here an iterative procedure (modified Newton's method) is employed to iterate on the unknown quantities, $\varepsilon_x, \varepsilon_y$, and satisfy the equilibrium equations, Eqn.4.1 and Eqn.4.2, for a given shear strain. Two different approaches are used to compute the stresses of masonry and concrete layers as discussed in the section 4.1 and 4.2.

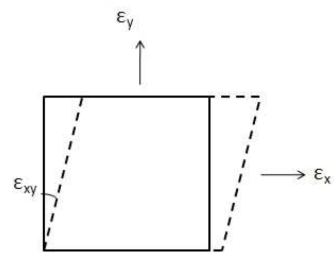

Figure 7 Definition of the strains in retrofitted element

4.1.shear analysis of masonry

In the proposed method for the analysis of the masonry part of the wall, the strains are translated to the principle planes, assuming the stress and strain principle planes are same, and then the stresses in the principle planes will be computed according to biaxial behavior models of masonry and then it will be translated again to the local planes. The appropriate failure criteria and biaxial stress-strain relations are considered for masonry here. In compression-compression range the stress-strain relation and failure criteria proposed by Zhuge [6] is used, in compression-tension and tension-tension ranges the Maekawa concrete model[7] is used and in shear the Mohr-Coloumb criteria is used to determine the shear cracking. For the post cracking behavior of masonry in shear the Li's contact density model [7] is used. As the Li's contact density model has originally been developed for concrete, it was modified for masonry.

The proposed method of analysis of masonry walls is able to predict all kinds of probable failures in masonry like toe crushing, rocking, bed joint sliding, diagonal tension and also stair-stepped bed joint sliding. A comparison between analysis result and Atkinson experimental result [8] is shown in Fig. 8.

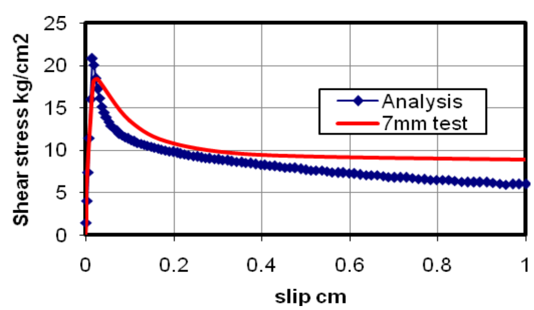

Figure 8 comparison of the analysis with experimental result

4.2.shear analysis of reinforced concrete

The procedure used for nonlinear analysis of reinforced concrete is based on fixed smeared crack approach and the nonlinear models of concrete in compression, tension and shear for reinforced concrete elements under biaxial stress states proposed by Okamura [7].

In this method the response of RC elements is computed based on the relation between the average strains and the average stresses mobilized in RC domain, due to the interaction of concrete-reinforcing bars and stress transfer across cracks i.e. aggregate interlock (Fig. 9).

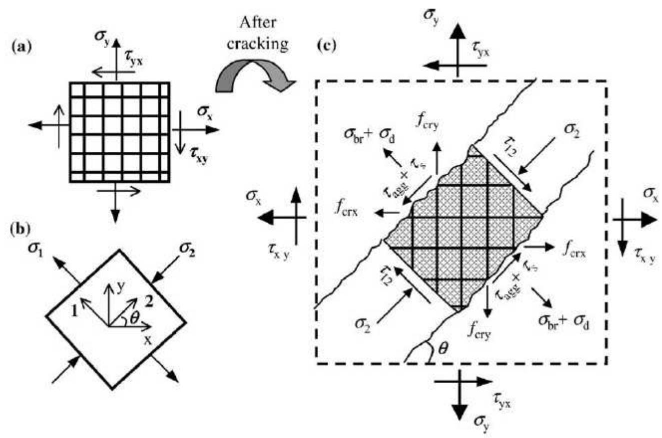

Figure 9 local and principle stresses in concrete element planes and crack surface [9]

The results obtained by this method show very good agreement with experimental results with well predicting the post cracking behavior of the RC elements.

5.STRUCTURAL COMPARISONS

In this section, the results of the produced software are compared with the experimental results, to confirm the reliability of the proposed method for analysis of masonry and concrete walls and also masonry wall retrofitted with concrete overlay. Firstly Ganz W4 masonry wall [10] and Vecchio B2 reinforced concrete wall [11] are analyzed. The comparison of the results with experimental results is shown in Fig. 10, and the good agreement between them is obvious.

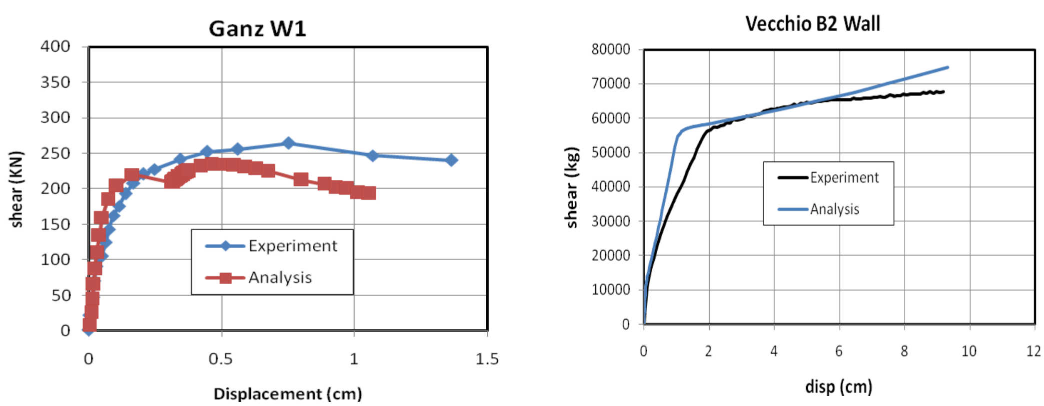

Figure 10 Ganz W1 masonry wall and Vecchio RC Wall verification

Abrams [5] tested a masonry pier retrofitted with different techniques. One of the retrofitting techniques used in his study is RC concrete layer (Fig. 11). The pier 1F is bare pier without any retrofitting and pier 4F is that has been retrofitted with reinforced concrete layer. These two piers have been analyzed with the prepared software, MPV, and the results are shown in Fig.12.

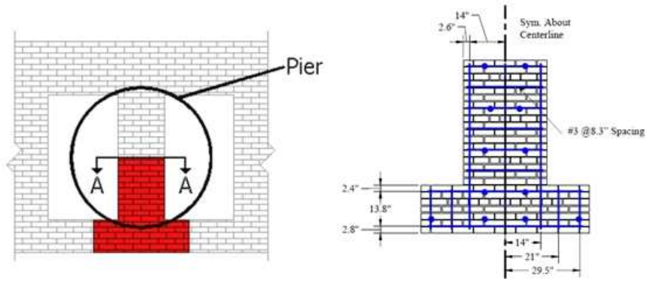

Figure 11 Masonry pier tested by Abrams[5]

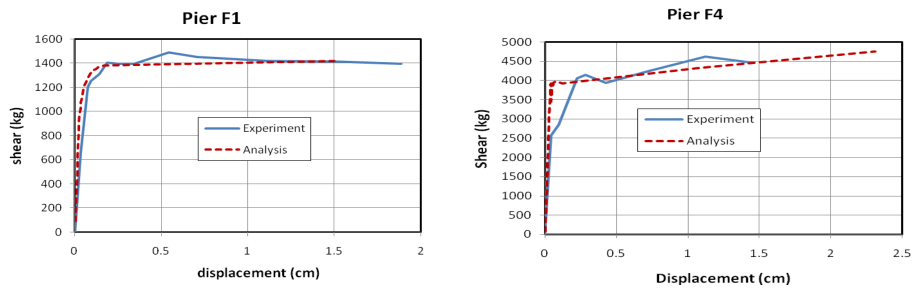

Figure 12 Comparison of analysis results and experimental results

6.CONCLUSIONS

In this paper a novel analytical model has been presented for studying the response of retrofitted masonry walls with RC concrete layer. This analytical method uses an iterative procedure to satisfy the equilibrium equations. For the masonry the biaxial stress-strain relations and failure criteria is used and all the possible failure modes are taken into account. For the RC part of the wall the fixed smeared crack approach is used. The analytical model was validated by comparing the results with existing experimental results.

REFERENCES

1. Elgawady, M., Letuzzi, P., Badoux, M., (2004), *A review of conventional seismic retrofitting techniques for URM*, in *13ht international brick and block masonry conference*. 2004: Amsterdam.
2. Calvi G., M.G.,(1994), *Experimental results on unreinforced masonry shear walls damaged and repaired*, in *10th international brick and block masonry conference*. 1994: Calgary, USA.
3. Chaung S. , e.al., (2004), *Seismic retrofitting of unreinforced masonry by cable system*, in *13th WCEE*. 2004: Vancour.
4. Elgawady, M., Letuzzi, P., Badoux, M., (2006), *Analytical model for the in-plane shear behavior of URM walls retrofitted with FRP* ,Composites Science and Technology, **66**: p. 459-474.
5. Abrams, D., Smith, T., Lynch, J., Franklin, S., (2007), *Effectiveness of Rehabilitation on Seismic Behavior of Masonry Piers.* Journal of Structural Engineering, **133**(1): p. 32-43.
6. zhuge, y., et.al, (1998), *Nonlinear dynamic analysis of unreinforced masonry.* Journal of Structural Engineering, **124**(3).
7. Okamura,H.,Maekawa, K., (1990) *Nonlinear Analysis and Constitutive Models of Reinforced Concrete*.
8. Atkinson, R. H., et.al, (1989) *Response of Masonry Bed Joints In Direct Shear.* Journal of Structural Engineering, **115**(9).
9. Soltani M., X.A., Maekawa K., *Cracking response and local stress characteristics of RC membrane elements reinforced with welded wire mesh*. Cement and concrete Composites, 2004. **26**: p. 389-404.
10. Lourenco, P., (1996), *Computational strategies for masonry structures*, Delft University.
11. Palermo D., V.F., (2004), *Compression Field Modeling of Reinforced Concrete Subjected to Reversed Loading: Verification*. ACI Journal, **101**(2): p. 155-164.