Seismic Strengthening of brick masonry with reinforced concrete layer on the basis of homogenization theories

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ABSTRACT :

Vulnerability of masonry structures to seismic actions has been proved with the experience of last earthquakes. A great number of these structures in Iran are residential buildings, hospitals and schools and their damaging will cause death of so many people. So, today seismic evaluation and strengthening of masonry structures are very crucial. Coating the walls with reinforced concrete layer is a common technique of retrofitting the masonry buildings in Iran but there is not any design guideline for that. In this study, firstly the elastic properties of bare and retrofitted masonry wall that are used in linear evaluation procedures are derived through a developed homogenization method. This approximate homogenization method is very simple to use for any kind of bond pattern and the solution will be in close-form, and also shows very good results in agreement with the homogenization procedures the other authors used. Secondly, the continuum yield surfaces of bare and retrofitted masonry are derived that are used for computing the strength of continuum media in any direction.

KEYWORDS: homogenization, masonry structures, seismic retrofitting, seismic evaluation

1.INTRODUCTION

More than 70 percent of the structures in Iran are masonry structures and most of them are residential buildings, hospitals and schools and occupy so many people and children. The experience of past earthquakes has shown that a great number of masonry structures are vulnerable to seismic actions so that moderate to strong earthquakes can devastate them resulting in massive death of people and extensive losses. This vulnerability is mostly because of the following reasons: 1-Some of these structures were constructed in a time that there was not any seismic code available, 2-Some were constructed when the seismic codes had been published but they were not designed and constructed according to the code, and 3-Some of the structures were designed and constructed according to the seismic code, but because of the complexity and lack of information on the behavior of the masonry structures, the code's regulations were not accurate enough. In General, high seismic vulnerability of these structures can be associated with both the particular configuration of this type of structures and the mechanical properties of the masonry.

There are a large number of methods of retrofitting masonry structures that are intended to improve their in-plane and out-of-plane performance. Some conventional methods are surface treatment (Ferrocement [1], FRP layer, Shotcrete layer [2]), grout and epoxy injection [3], external reinforcement [4] and confining masonry walls and post-tensioning [5]. 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.

Seismic evaluation and strengthening masonry structures firstly need modeling them with an analytical computer software. Modeling of masonry structures can be done in macro or micro phase. Micro modeling represents brick, mortar and brick-mortar interface separately and the Young modulus, the Poisson coefficient and if the analysis is nonlinear, the inelastic properties are taken into account. In fact this is a difficult task because the model should include the behavior of brick and mortar correctly and also micro-modeling process and analysis of the analytical model in a micro phase, takes a lot of time that make this approach not usable for a complete structure. Although this method is more accurate than the other methods, it is much more expensive in terms of computational costs and the corresponding high number of degrees of freedom limits the applicability. Therefore, micro modeling is necessary to better understanding the local behavior of masonry structures. A large number of micro-models were developed by researches such as Page [6] and Lourenco [7]. Another modeling approach is macro-modeling. In macro modeling there is not any distinction between brick, mortar and brick-mortar interface and masonry is modeled as an isotropic or anisotropic homogenous continuum medium. It doesn't take a lot of time for modeling and analyzing such models and is an acceptable approach for modeling complete structures; see e.g. Kappos et al. [8], Mistler et al. [9].

For numerical modeling of masonry components, as a continuum medium in the elastic range, the mechanical continuum elastic properties are needed. These properties can be achieved through homogenization techniques. The homogenization theory for periodic media allows derivation of global behavior of masonry from the behavior of the constituent materials (brick and mortar). In other words homogenization is the technique of describing the composite behavior of masonry in terms of average stresses and strains. Homogenization techniques can be approached from two main directions called experimental homogenization and analytical homogenization. Experimental homogenization needs so many costly tests and the obtained results are limited to the tests conditions [10]. Analytical homogenizations have been used by many authors in different frame works (elastic, plastic, limit states and …) and with a variety of methods like single step homogenization [11], two-step homogenization and engineering methods [12] and in most cases only in-plane behavior in a two dimensional framework is considered.

This paper presents a new three dimensional homogenization method based on energy concepts. The advantages of this method are simplicity to use, a few number of calculations and close-form solution that can be used in the modeling of masonry walls for linear elastic analysis. The proposed method shows very good results in agreement with other homogenization methods.

2.HOMOGENIZATION OF UNREINFORCED MAONRY

Masonry is a composite material consisting brick and mortar and usually its components are arranged in a periodic way. In this section a basic cell that has a periodic pattern in the whole wall is selected, Fig.1, and the average stresses and strains will be computed from the basic cell and will be extended to the whole masonry wall. The developed homogenization technique in this paper is based on the strain energy of the hyper elastic materials. In hyper elastic materials there is a relation between total energy and stress and strain tensors:

$$\sigma_{ij} = \frac{\partial u}{\partial e_{ij}} \tag{2.1}$$

where σ_{ij} is the stress in the i-th plane and to the j-th direction of the basic cell, u is the total volumetric strain energy of the basic cell and e_{ij} is the strain in the i-th plane and to the j-th direction of the basic cell. In this method of homogenization it is correctly assumed that the components of masonry are hyper elastic. According to equation (2.1), if we compute the total strain energy of the basic cell in terms of average stresses and strains and then substitute it in equation (2.1), the average stresses of the cell in terms of the average strains will be obtained and then the elasticity tensor can be obtained.

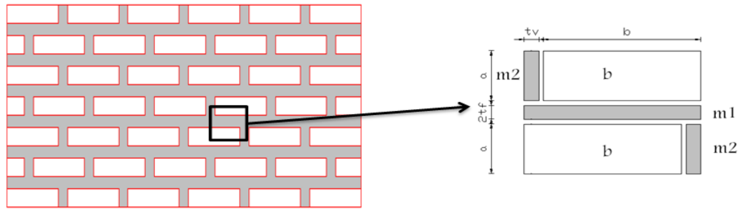

Figure 1 Selecting the Basic Cell

Volumetric energy can be calculated by the summation of the volumetric energy of each constituent as follows:

$$U^E \times V^E = U^b \times V^b + U^{m1} \times V^{m1} + U^{m2} \times V^{m2} \tag{2.2}$$

where U^m is the total volumetric strain energy, V^m is the total volume of the basic cell, U^b is the total strain energy of bricks, V^b is the total bricks volume, U^{m1} is the total strain energy of horizontal mortar, V^{m1} is the horizontal mortar volume, U^{m2} is the total strain energy of vertical mortar and V^{m2} is the volume of vertical mortar joint.

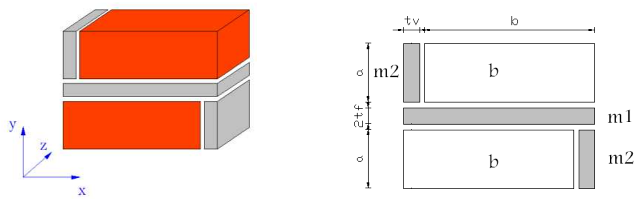

Figure 2 The dimensions of the basic cell's constituents

The strain energy in hyper elastic materials can be calculated as follows:

$$u_{ij} = \frac{1}{2}\sigma_{ij} e_{ij} \tag{2.3}$$

where: $\sigma_{ij} = C_{ijkl} e_{ij}$
Substituting in equation (2.3) results in:

$$u_{ij} = \frac{1}{2}\sigma_{ij} e_{ij} = \frac{1}{2} C_{ijkl} e_{ij} e_{lk} \rightarrow u = \frac{1}{2} e^T C e \tag{2.4}$$

where C is the elasticity tensor and e is the strain tensor.
Having calculated the strain energy of each component and set them in equation (2.2), the total strain energy of the basic cell will be obtained in terms of the strains of the masonry components. In order to calculate the strains of masonry components in terms of average strains, the basic cell should be subjected to compression along the axes x, y and z and shear in the xz, xy and yz planes (axes are shown in Fig. 2) and then the relation between average strains and masonry components strains will be obtained. Having calculated the strain energy in terms of average strains, the elasticity tensor of the homogenized medium can be calculated by using the equation (2.1) and also the elastic properties will be obtained by inverting the elasticity tensor:

$$E_{11}^{eq} = \frac{x}{4BC - F^2}, E_{22}^{eq} = \frac{x}{4AC - E^2}, E_{33}^{eq} = \frac{x}{4AB - D^2} \tag{2.5}$$

$$G_{12}^{eq} = 0.5G, G_{13}^{eq} = 0.5H, G_{23}^{eq} = 0.5I \tag{2.6}$$

$$\nu_{12}^{eq}=\frac{2DC-EF}{4BC-F^2},\nu_{21}^{eq}=\frac{2DC-EF}{4BC-E^2},\nu_{13}^{eq}=\frac{2EB-DF}{4BC-F^2},\nu_{31}^{eq}=\frac{2EB-DF}{4AB-D^2},\nu_{23}^{eq}=\frac{2AF-DE}{4AB-D^2},\nu_{32}^{eq}=\frac{2AF-DE}{4AC-E^2} \quad (2.7)$$

In which:

$$x=2\times[A(4BC-F^2)-D^2C+DEF-E^2B]$$

$$A=\frac{1}{2V^E}(C_{11b}f_1^2V_b+C_{11m1}V_{m1}+C_{11m2}n^2f_1^2V_{m2}),B=\frac{1}{2V^E}(C_{11b}f_1^2V_b+C_{11m1}n^2f_2^2V_{m1}+C_{11m2}f_2^2V_{m2})$$

$$C=\frac{1}{2V^E}(C_{11b}V_b+C_{11m1}V_{m1}+C_{11m2}V_{m2}),D=\frac{1}{2V^E}(C_{12b}f_1f_2V_b+C_{12m1}nf_2V_{m1}+C_{12m2}nf_1f_2V_{m2})$$

$$E=\frac{1}{V^E}(C_{12b}f_1V_b+C_{12m1}V_{m1}+C_{12m2}nf_1V_{m2}),F=\frac{1}{V^E}(C_{12b}f_2V_b+C_{12m1}nf_2V_{m1}+C_{12m2}f_2V_{m2})$$

$$G=\frac{2}{V^E}(G_bf_3^2V_b+G_{m1}n_2^2f_3^2V_{m1}+G_{m2}f_3^2V_{m2}),H=\frac{2}{V^E}(G_bV_bn_Gz^2+G_{m1}V_{m1}+G_{m2}V_{m2}z^2)$$

$$I=\frac{2}{V^E}(G_bf_3^2V_b+G_{m1}n_2^2f_3^2V_{m1}+G_{m2}f_3^2V_{m2})$$

$$n=\frac{E_b}{E_m},f_1=\frac{b+t_v}{b+nt_v},f_2=\frac{a+t_f}{a+nt_f},n_2=\frac{n_1b+t_v}{b+t_v},f_3=\frac{a+t_f}{a+n_2t_f},n_G=\frac{G_b}{G_m},z=\frac{b+t_v}{n_Gb+t_v}$$

$$C_{11}=\lambda+2\mu,C_{12}=\lambda,\lambda=\frac{\nu E}{(1+\nu)(1-2\nu)},\mu=\frac{E}{2(1+\upsilon)}$$

Where b, t_v, a and t_f are defined in Fig. 2, ε_{ij} is the average strain and ε_{ij}^k is the strain of the component k of masonry, E_b accounts for elastic modulus of brick, Em is the elastic modulus of mortar, G_b is the brick shear modulus and G_m is the mortar shear modulus. It is assumed that the elastic properties of horizontal and vertical mortar are the same, but considering different elastic properties for each other does not affect the homogenization procedure.

3.VERIFICATION OF THE RESULTS

Lourenco and Zucchini [10] had used a micro-mechanical model for the homogenization of masonry with considering the actual deformations of the basic cell and including the additional internal deformation modes with regard to the standard two step homogenization procedure and they showed how good their model is in agreement with finite element results. In this section, to check the accuracy of the adopted procedure, the results are compared with Lourenco and Zucchini's [10] homogenization model.

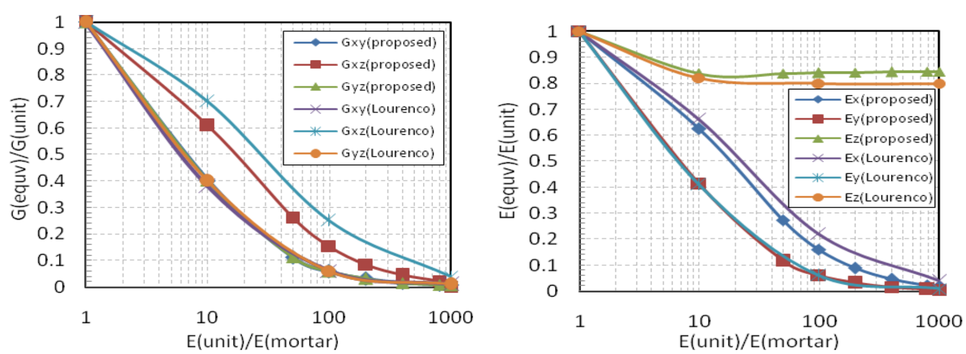

Figure 3 Comparison between shear and Young's modulus of the proposed model and Lourenco model

The very good agreement between proposed model and Lourenco and Zucchini's [10] model is obvious in Fig. 3 and this indicates that how much this simple and applicable proposed procedure for homogenization of brick masonry is accurate. Also, as said before, the other advantage of this technique is that the results are in close-form and the proposed relations can simply be used to evaluate the elastic properties of the homogenized masonry wall and modeling it as a continuum medium.

Also the accuracy of the results of the proposed homogenization procedure will be checked through modeling of some structural walls with a finite element software, each one with two different approaches. The first approach is modeling in a micro phase and the second one is macro modeling the wall by using the continuum properties of the wall computed by the proposed relations.

In the first example, a brick masonry wall simply supported at the bottom with the length of 272 cm and height of 209 cm has been modeled in macro and micro phases. An opening is also placed in the middle of the wall with the dimensions of 104x71 cm. The thickness of the wall is kept 10 cm. In the micro model the brick's dimensions are 200x100x50 mm and the thickness of the mortar joint is assumed to be 1 cm. The mechanical properties of the brick and mortar used in the modeling are summarized in Table 1, while the continuum mechanical properties calculated with proposed relations are summarized in Table 2.

Table 1 Mechanical elastic properties of brick and mortar

	Brick	Mortar
Young's Modulus(kg/cm2)	100000	10000
Poison Ratio	0.15	0.15

Table 2 Mechanical elastic orthotropic properties of homogenized material

Ex(eq)	62599	Gxy(eq)	17480
Ey(eq)	41880	Gxz(eq)	35675
Ez(eq)	82835	Gyz(eq)	17480

The wall is subjected to an in-plane load applied at the top of the wall. The deformed shape of the micro model wall is shown in Fig. 4. The displacement of the top right corner node of the wall in the micro and macro model is shown in Table 3. The good agreement of the results of the macro model with the micro model is obvious.

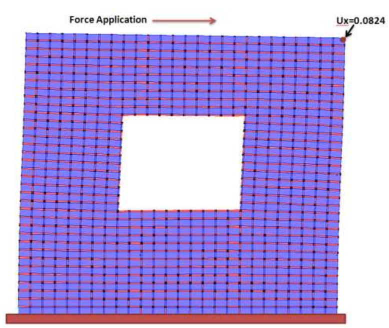

Figure 4 The deformed shape of the micro model under in-plane load

Table 3 The in-plane displacement of the URM wall

	In-plane Node Displacement
Macro-model	0.081
Micro-model	0.082

In the second example, a 104x89 cm masonry panel has been subjected to out of plane loading with different conditions of supporting at 4 sides. Table 4 comprises the displacement of the central point of the micro and macro model of the wall for all cases of supporting types.

Table 4 The out-of-plane displacement of the URM wall

Supporting	Macro-model	Micro-model
4-sides	0.0067	0.0064
Bottom & Top sides	0.0143	0.0149
Left & Right Sides	0.015	0.0168

4.HOMOGENIZATION OF RETROFITTED MASONRY WITH REINFORCED CONCRETE LAYER

In this section the elastic properties of retrofitted masonry will be derived through the proposed homogenization method. The basic cell selected for the homogenization process is shown in Fig. 5. The calculations have been done in such a way that the thickness of the wall and concrete layer are inserted in the relations and so the proposed relations can be used for any thickness of them.

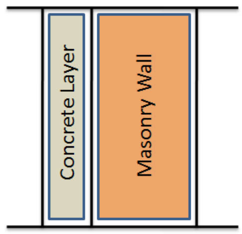

Figure 5 The basic cell of retrofitted masonry

The masonry is assumed as a continuum orthotropic material and the concrete layer is assumed isotropic and the calculations is done like the previous section. The calculated elastic properties of the retrofitted wall are as follows:

$$E_{11}^{eq} = \frac{x}{4BC - F^2}, E_{22}^{eq} = \frac{x}{4AC - E^2}, E_{33}^{eq} = \frac{x}{4AB - D^2} \quad (4.1)$$

$$G_{12}^{eq} = 0.5G, G_{13}^{eq} = 0.5H, G_{23}^{eq} = 0.5I \quad (4.2)$$

$$\nu_{12}^{eq} = \frac{2DC - EF}{4BC - F^2}, \nu_{21}^{eq} = \frac{2DC - EF}{4AC - E^2}, \nu_{13}^{eq} = \frac{2EB - DF}{4BC - F^2}, \nu_{31}^{eq} = \frac{2EB - DF}{4AB - D^2}, \nu_{23}^{eq} = \frac{2AF - DE}{4AB - D^2}, \nu_{32}^{eq} = \frac{2AF - DE}{4AC - E^2} \quad (4.3)$$

In which:

$$x = 2\times[A(4BC - F^2) - D^2C + DEF - E^2B]$$

$$A = \frac{1}{2(t_m + t_c)}(C_{11w}t_w + C_{11c}t_c), B = \frac{1}{2(t_m + t_c)}(C_{22w}t_w + C_{11c}t_c), C = \frac{1}{2(t_m + t_c)}(C_{33w}t_w n_3^2 f_3^2 + C_{11c}t_c f_3^2)$$

$$D = \frac{1}{(t_m + t_c)}(C_{12w}t_w + C_{12c}t_c), E = \frac{1}{(t_m + t_c)}(n_3 f_3 C_{13w}t_w + f_3 C_{12c}t_c), F = \frac{1}{(t_m + t_c)}(n_3 f_3 C_{23w}t_w + f_3 C_{12c}t_c)$$

$$G = \frac{2}{(t_m + t_c)}(G_{12w}t_w + G_c t_c), H = \frac{2}{(t_m + t_c)}(n_{13}^2 f_{13}^2 G_{13w}t_w + f_{13}^2 G_c t_c), F = \frac{2}{(t_m + t_c)}(n_{23}^2 f_{23}^2 G_{23w}t_w + f_{23}^2 G_c t_c)$$

$$n_3 = \frac{E_c}{E_{m3}}, f_3 = \frac{t_m + t_c}{n_3 t_m + t_c}, n_{13} = \frac{G_c}{G_{m13}}, n_{23} = \frac{G_c}{G_{m23}}$$

Where E_c is the concrete Young's modulus, E_{m3} is the masonry Young's modulus in z direction, t_w is the thickness of the masonry wall, t_c is the thickness of the concrete layer, G_c is the concrete shear modulus, G_{12w} is the masonry shear modulus in xy direction, G_{13w} is the masonry shear modulus in xz direction and G_{23w} is the masonry shear modulus in yz direction.

5.STRUCTURAL COMPARISONS OF RETROFITTED MASONRY

In this section a retrofitted masonry wall is modeled with macro and micro approaches and has been subjected to in-plane and out-of-plane loads. The displacements of the wall in each condition are shown in Table 5 for in-plane loading and in Table 6 for out-of-plane loading. It should be noted that the applied loads in this example are not the same as the examples in the section 4 and the results are not comparable. It is clear that under the same condition of supporting and loading, the displacements of the retrofitted wall will be much smaller than the bare wall.

Table 5 The in-plane displacements of the retrofitted wall

	In-plane Node Displacement
Macro-model	0.001
Micro-model	0.001

(without opening)

	In-plane Node Displacement
Macro-model	0.0108
Micro-model	0.0111

(with opening)

Table 6 The out of plane displacements of the retrofitted wall

	Out-of-plane Node Displacement	
Supporting	**Macro-model**	**Micro-model**
4-sides	0.0474	0.0476
Bottom & Top sides	0.0703	0.0714
Left & Right Sides	0.1015	0.1057

(without opening)

	Out-of-plane Node Displacement	
Supporting	**Macro-model**	**Micro-model**
Bottom & Top sides	0.1968	0.1988

(with opening)

It is obvious how the good agreement is between the results of the micro-model and macro-model in both in-plane and out-of-plane loading and this indicates how much good the developed homogenization method can predict the linear behavior of retrofitted masonry.

6.HOMOGENIZED YEILD SURFACES

Derivation of failure surfaces of brittle materials such as masonry is a very difficult task and it is the object of a long-time debate among researchers even for simple loading conditions. The purpose of this section is the derivation of yield surfaces of the homogenized model. These surfaces distinguish the linear behavior region of the homogenized masonry. For this reason, considering the assumptions made for developing the homogenization method, if a back analysis is done, the stresses of each masonry component can be computed in terms of homogenized material stresses (average stresses). Then, the yield surface is defined by the stresses in which any of the components reaches its failure criteria. Both brick and mortar are assumed isotropic. Lourenco and Zucchini [10] used the classic von Mises criterion for the compression behavior and the Rankine criterion to describe the tensile behavior of masonry components. Because the masonry is a frictional material and using independent pressure criteria does not produce acceptable results, in this study a Mohr-Coulomb criterion as a pressure dependent failure criterion is used.
Fig. 7 shows the resulting yield surfaces of homogenized bare and retrofitted masonry in a case that the principle stresses coincide with material axes which happen in the absence of shear stresses. The retrofitted masonry is layered with a concrete layer with equal thickness to masonry wall. The inner surface that is formed by the intersection of the yield surfaces of the components is the yield surface of homogenized masonry. The assumed parameters are as follows:

$$f_{cb} = 100,\ f_{tb} = 4,\ f_{cm} = 34,\ f_{tm} = 2, \frac{E_m}{E_b} = 0.1, \upsilon_m = \upsilon_b = 0.2$$

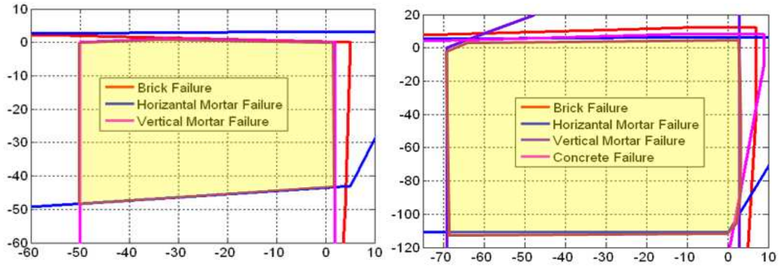

Figure 6 yield surface of homogenized masonry(left) and retrofitted masonry(right)

Retrofitting the masonry with concrete layer has widen the yield surface of the material and also increased the strength of material in both x and y direction.

6.CONCLUSIONS

Linear seismic evaluation of masonry buildings needs analytical modeling of them firstly. This task cannot be done unless the elastic properties of the masonry are known. This paper presents a new approximate method of homogenization of masonry that helps computing the elastic properties of the masonry through the properties of its components. This method is simple and applicable for all bond patterns of brick masonry walls and the result are in close-form. A basic cell of brick masonry wall is homogenized with the proposed method in the elastic range. Then the masonry wall retrofitted with concrete layer has been homogenized and the relations for computing the elastic properties have been derived. Finally, the anisotropic failure surfaces of bare brick masonry and retrofitted brick masonry with concrete layer have been extracted and the noticeable increase in the strength after retrofitting is shown.

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