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SEISMIC ASSESSMENT OF UNREINFORCED MASONRY WALLS BASED ON FEM MICRO MODELS

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ABSTRACT

Seismic rehabilitation of the existing un-reinforced masonry buildings is an important and timely issue in the field of earthquake engineering community. This issue has been of interest in Iran since many un-reinforced masonry schools are located in the moderate to high active seismic regions. One of the common strategies, for the rehabilitation of un-reinforced masonry walls, is one-side shotcrete method. This rehabilitation method has been comprehensively investigated in this paper by means of the Finite Element Method (FEM) micro models i.e. modelling brick and mortar. A set of different walls was taken into consideration with various aspect ratios, mortar quality, wall thickness and gravity load conditions. The OpenSees platform was utilized in order to build the micro models. The increase in the strength of the rehabilitated walls is compared with the strength of the un-rehabilitated walls and the results are summarized for the engineering purposes. This strength increase is somehow significant in the majority of the wall cases.

Key words: Seismic rehabilitation; Shotcrete; un-reinforced masonry wall

INTRODUCTION

Unreinforced masonry (URM) buildings have shown poor seismic performance during most of the past earthquakes. Sever damages are associated with these types of buildings and the total loss of lives is usually remarkable. Approximately, 70 percent of the whole buildings are associated to masonry structures in the world (Masonry Society, 1989). These systems are usually quite brittle (low ductility) with low tensile and compressive strength and high initial

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stiffness. Masonry buildings usually have high stiffness at the beginning of earthquake motion, however, quick damages based on the low ductility phenomenon cause a significant drop in the stiffness and large deformation in which finally goes to the total collapse of the structure. Various types of seismic rehabilitation methods have been developed in order to overcome these shortcomings. Most of these methods try to increase the strength of URM walls e.g., exterior plasters (Taghdi et al., 2000), cement injection (Santa Mari, 2006), shotcrete (ElGawady, 2004), post-tensioning the URM walls (Turer, 2007), constructing new ties (Karantoni, 1992) and employing local material such a Bamboo (Gulkan, 2004; Dowling, 2005). Covering the URM walls with steel mesh and shotcrete is one of the conventional methods among the rehabilitation strategies. The strength increase, obviously depends on the mesh characteristic as well as the shotcrete thickness. In a former diagonal tension experiment, it has been shown that 90 mm one side shotcrete is able to increase the wall strength by 6 to 25 times (Kahn, 1984). However, this strength increase is not so significant in the case of static cyclic test (Abrams, 2001). In another study, three different tests were designed in order to investigate the shotcrete effects on the in-plane wall behaviour (ElGawady, 2004). The three studied cases were: 1) using 40 mm shotcrete without steel mesh, 2) using 40 mm shotcrete with steel mesh only on one side, and 3) using 20 mm shotcrete with steel mesh in both sides. The results show that the ultimate strength is increased by an approximate factor of 3.6 in the both cases of one side and two sides rehabilitated walls. However, the ductility is greater in the case of two sides shotcrete when compared with the one side shotcrete. In terms of the wall displacement, the ultimate drift in the rehabilitated wall is 3.5 percent, which is twice the ultimate drift of the un-rehabilitated wall.

The perimeter walls shotcrete is one of the common seismic rehabilitation techniques in the case of schools in Iran, which is the focus of this study (Azarbakht, 2011). For this purpose, the numerical micro FEM models were constructed by employing OpenSees platform. Different parameters such as wall thickness, wall length, mortar quality and gravity axial load were taken into consideration in order to cover a relatively wide range of walls. The nonlinear static analysis procedure was performed for each case and the force-deformation relationship is calculated. Finally, the ultimate base shear is calculated and reported as the main results.

NUNERICAL WALL MODELLING

The nonlinear behaviour of masonry walls is a kind of complex problem and mostly depends on the cracking type, boundary condition, geometrical characteristic, gravity axial load, and material property in which the latter is obviously a non-homogeneous material. Each cracking type has its own force-deformation relationship that makes the definition of the wall behaviour complex. Therefore, many simulation approaches have been proposed in order to numerically model the nonlinear behaviour of masonry walls (Lourenco, 1996). The equivalent frame approach and the finite difference methods are popular among researchers (Saghafi, 2010; Galasco, 2006). However, several limitations are belong to these methods, including: capability to simulate second order effects between perpendicular walls, model the re-distribution of forces and model the wall nonlinear behaviour. Finite element methods are the most conventional and reliable methods which can be used in this aspect (Oliveira, 2003). These methods are categorized as: micro, simplified micro and macro models. All of the wall elements, including bricks and mortar, are discretely modelled on the micro modelling approach. However, the macro modelling approach uses continuous elements in order to simulate the mortar and wall behaviours together (Lourenco, 1996). In the case of the simplified micro modelling, combinations of micro and macro elements are used. The micro models are obviously more complex than the macro models which restrain their applicability and usually are employed for different individual elements (especially in the case of experimental tests) rather than the whole structure.

In this study, the focus is on the micro modelling of different individual masonry walls by employing the OpenSees platform (OpenSees). The OpenSees 'Eight-Nodes Brick' element was used in order to simulate wall bricks. This element is similar to the Solid65 element within the ANSYS platform. As the vertical mortar lines are not in a same line, as seen in Figure 1, two 'Eight-Nodes Brick' elements were used in order to construct an individual brick. Zero-Length elements were used to model the available mortar between bricks. The Zero-Length elements have shear behaviour by using 'Concrete02' material and the compression and tension behaviours by using the 'Concrete06' material. It is worth noting that the modelling of the mortar elements are crucial since any wall failure initiates from the mortar section especially in the mortar horizontal line.

It is assumed that the one centimetre thickness mortar is fully filled the space between the bricks. The bricks are isotropic elastic elements with the elastic module equal to 1670 Mpa and poison coefficient equal to 0.15. Different mortar qualities are taken into consideration as categorized in Table 1. The bottom wall nodes are fixed and the top nodes have the same displacement since the diaphragm is assumed to be rigid. The gravity axial loads are also applied to the wall top nodes.

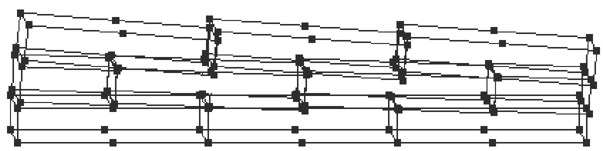

Figure 1. Schematic wall mesh elements in a deformed shape.

Table 1. Assumed mortar properties in this study.

Material quality	Mortar compressive strength f_c' (kg/cm^2)	Mortar Tension strength f_t (kg/cm^2)	Mortar Shear strength τ (kg/cm^2)
Good (G)	170	20.0	3.00
Moderate (M)	100	12.0	2.20
Poor (P)	40	5.0	1.60

DIFFERENT WALLS CHARACTERISTICS

The micro models in this study consist of individual walls with different mortar quality, wall length, wall thickness and gravity axial load as seen in Table 2. The mortar material quality is divided into three bins including good, moderate and poor conditions. The ratio of wall length over the wall height is assumed to be 1, 2, 3 and 6 by considering the common constant wall height equal to 3 m. Two cases were assumed for the ratio of wall height over the wall thickness, i.e. 300/22 and 300/35. The gravity axial load is another important characteristic which should be taken into account. For this purpose, two cases of steel I-beam jack arch slabs are assumed. In the first case, the joists are assumed to be perpendicular to the wall length. Therefore, the gravity loads (including dead and live loads), corresponding to the half of each adjacent wall span, are transferred to the wall. The common wall spans are usually equal to 4m which means that the ”4×wall length” area is taken into account in determining the gravity loads. In the second case, the joists are assumed to be parallel to the wall length. Therefore, the gravity loads, corresponding to the half of one adjacent joist span, are transferred to the wall from each side. The joist spans are usually equal to 1m which means that the ”1×wall length” area is taken into account in determining the gravity loads. As this study is focused on the one story masonry buildings, no gravity load, from upper stories, is taken into consideration. The whole assumed parameters are summarized in Table 2 which makes 48 different cases for further analyses.

These 48 unreinforced masonry walls were analysed in two conditions consisting a) without rehabilitation, and b) with rehabilitation with steel mesh and one side 5cm shotcrete. The shotcrete layer is modelled by using ‘Concrete06’ material with the compressive, tension and shear strengths, respectively, equal to 200, 25 and 3 kg/m^2. The steel mesh size is 10 and 15 cm, respectively, in the cases of 6mm and 8mm bars. The yield strength of steel is 2400 kg/cm^2. The steel mesh material is modelled with ”Steel02” within the OpenSees platform. The Zero-Length elements were also used to construct the shotcrete layer with behaves parallel to the existing wall body. The steel mesh characteristics are summarized in Table3.

Table 2. Different wall variables considered in the wall analysis in this study.

Variables	Values			
Mortar Quality	Good		Fair	Poor
Length over height (L/h)	1/3	2/3	3/3	6/3
Height over thickness (h/t)	300/22		300/35	
Wall gravity load	P (joists parallel to the wall length)		V (joists perpendicular to the wall length)	

Table 3. Different types of steel mesh for the shotcrete rehabilitation procedure.

Type	Reinforcement Space	Reinforcement Diameter
1	15 (cm)	8 (mm)
2	10 (cm)	8 (mm)
3	10 (cm)	6 (mm)

PUSH OVER ANALYSIS OF 48 MICRO MODELS

From the geometrical point of view, the un-rehabilitated walls consist of eight models as mentioned in the previous section. By taking the three mortar qualities, see Table 1, 24 combinations are available. In addition, two gravity axial loads will increase the combinations to 48 cases. In order to distinguish the different walls, a naming standard has been set here. For example, ‘G-2-35-V’ is corresponding to the 35cm thickness wall with good mortar quality (G), 2m length and joists perpendicular to the wall length (V). ‘F-3-22-P’ is also representative of the 22cm thickness wall with fair (moderate) mortar quality (F), 3m length and joists parallel to the wall length (P). All the FEM models are set up within the MATLAB package and interfaced with the OpenSees platform. The in-plane behaviour is only taken into consideration and the wall is constrained in the out-of-plane degree of freedoms. Each model has been analysed with the nonlinear static procedure up to entering the nonlinear behaviour and numerical global instability occurs. The force-displacement relationships are shown in Figure 2 to Figure 5 for both the un-rehabilitated and rehabilitated walls. As can be seen in these figures, it is obvious that the shotcrete layer has increased the strength and ductility of the walls significantly. Most of the un-rehabilitated walls show negligible ductility and the behaviour is quite brittle.

To more deal with this problem, the maximum base shears of each un-rehabilitated and rehabilitated wall are summarized in Table 4. The level of strength increase is shown in Table 4 which reveals that the mortar quality is the governing parameter in which the maximum increase is in the case of good mortar quality. However, the results based on the gravity axial load is interesting. The maximum strength is quite higher when the joists are perpendicular to the wall length which means that more gravity loads are transferred to the wall when compared with the parallel joists case. For example, the 3m length, 22cm thickness wall with good mortar quality and perpendicular joists, which is rehabilitated with type 2 (see Table 3), shows 1.83 times more strength than the similar case with the parallel joists. This ratio is 1.33 in the case of 35cm thickness wall. The one meter length walls have different behaviours as the consequence of their special aspect ratio. As seen in Figure 2, the shear failure occurs in the one meter length walls with good mortar quality whereas the toe compression failure is the case in the one meter length walls with poor mortar quality. The shear failure is almost the case in the 2m length walls. In the cases of 3m and 6m walls, significant increase is seen as shown in Figures 4 and 5.

The results show that the mean strength increase is approximately 2.06 in all the one meter length, 22cm thickness walls with rehabilitation type 1 whereas this ratio is 1.6 in the 35cm thickness walls. This mean ratio is 3.02 in the case of 2m length walls with 22cm thickness whereas it is 2.18 in the case of 35cm thickness walls. In addition, the mean strength increase is approximately 2.26 in all the 3m length, 22cm thickness walls with rehabilitation type 3 whereas this is 1.59 in the 35cm thickness walls. Therefore, this is concluded that the strength increase is less in 35cm thickness walls when compared with 22cm thickness walls. The strength increase is always greater in the rehabilitation type 2 in comparison with types 1 and 3. However, there is no meaningful trend between type 1 and 3. Finally, the strength increase is quite significant in the walls with parallel joists, although, their absolute shear strength is smaller than the walls with perpendicular joists.

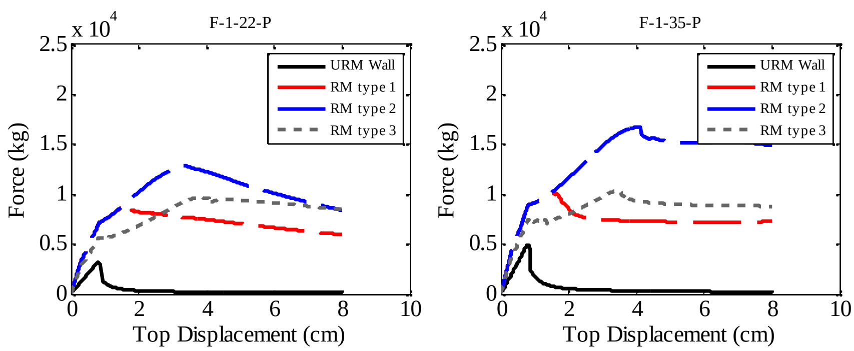

Figure 2. Force displacement relationship of the 1 meter length walls, moderate material and parallel joists.

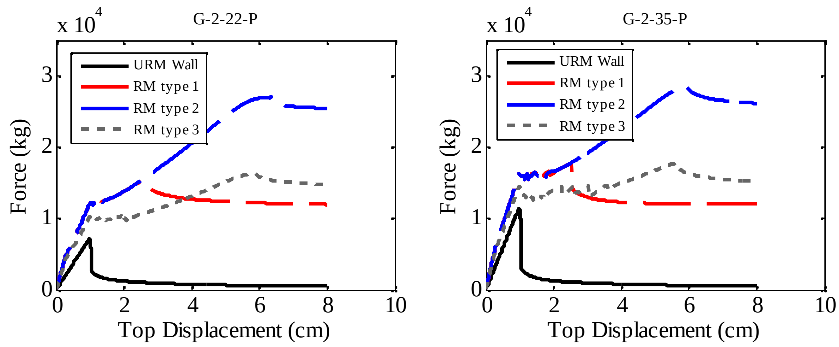

Figure 3. Force displacement relationship of the 2 meters length walls, good material and perpendicular joists.

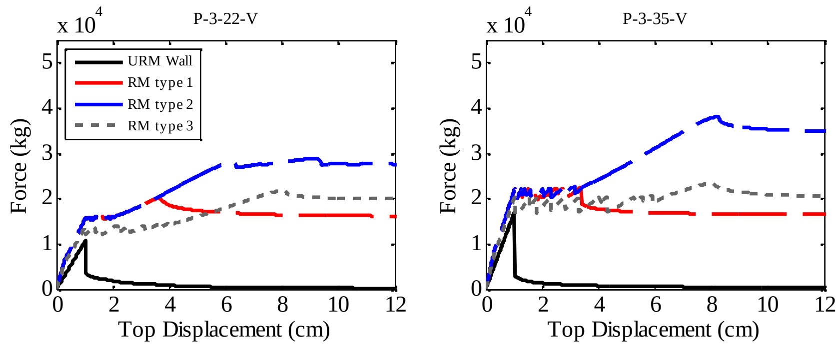

Figure 4. Force displacement relationship of the 3 meters length walls, poor material and perpendicular joists.

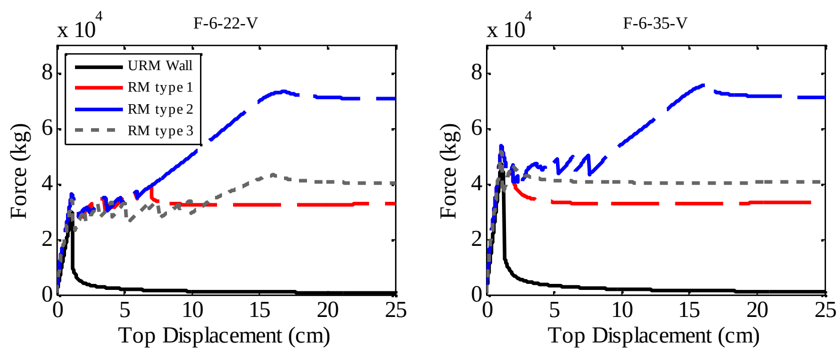

Figure 5. Force displacement relationship of the 6 meters length walls, moderate material and perpendicular joists.

Table 4. The maximum base shear strength in the case of existing and rehabilitated walls for different types.

Maximum base shear strength (kg)								
Wall thickness	22 cm				35 cm			
Wall name	URM	RM type 1	RM type 2	RM type 3	URM	RM type 1	RM type 2	RM type 3
F-1-P	3194.61	8838.21	12917.46	9717.80	5053.99	10119.73	16764.50	10431.97
F-1-V	6337.79	11882.30	15487.54	9471.98	10061.40	15284.68	19223.99	13154.21
F-2- P	5304.92	13775.06	25809.69	15503.86	8393.67	15328.36	27099.48	16384.13
F-2-V	10512.33	16023.85	27840.84	17270.04	16701.27	22144.61	29791.77	20021.16
F-3- P	7449.21	18528.91	36275.54	21237.96	11774.55	20324.41	37314.57	22249.90

F-3-V	14756.80	22268.20	38010.73	23302.81	23444.32	29119.67	40097.08	27027.58
F-6- P	14907.06	34775.55	71216.98	41127.23	23637.84	36901.29	72497.94	42436.47
F-6-V	29684.53	38782.58	73148.74	43116.63	47123.18	53775.61	75653.99	51645.54
G-1-P	4335.39	10059.84	16756.27	10393.04	6883.67	11628.79	17976.99	11649.96
G-1-V	8610.59	14880.40	19116.01	12992.18	13708.54	19993.26	22116.21	17439.38
G-2-P	7199.63	15232.36	27053.70	16346.10	11436.55	17725.37	28442.00	17759.84
G-2-V	14281.46	20871.43	29945.36	19353.02	22735.43	29279.18	33254.83	26639.43
G-3-P	10100.21	20155.76	37218.25	22190.56	16043.52	22818.64	38780.39	24109.46
G-3-V	20062.52	26771.72	40386.47	25335.84	31931.59	38612.89	43478.54	36024.95
G-6-P	20248.52	36780.09	72496.59	42361.96	32202.36	40739.56	74460.32	44456.34
G-6-V	40398.82	47902.02	75628.88	45719.38	64318.79	71813.22	79683.56	69213.17
P-1- P	2315.63	4959.98	4960.05	5411.13	3676.51	7271.74	7498.59	6983.40
P-1-V	4592.82	6872.72	6872.72	6840.28	7293.20	9724.08	9598.86	10007.87
P-2-P	3845.41	10465.56	10731.22	8714.65	6105.43	13985.49	16605.81	8710.51
P-2-V	7628.16	13927.36	14708.87	10683.80	12106.47	17009.11	17009.19	15207.73
P-3-P	5395.83	17555.48	19649.58	19376.22	8566.96	18827.89	30303.52	21379.38
P-3-V	10697.27	20023.09	28929.30	21879.36	16974.70	22518.97	38186.09	23570.82
P-6-P	10788.00	33067.59	67639.44	40417.10	17127.68	35018.32	71437.05	41312.41
P-6-V	21590.07	36164.79	71523.71	41733.21	34281.86	40494.47	73474.78	43485.08

CONCLUSIONS

The effects of 5cm, one side and three types of shotcrete rehabilitation strategies have been numerically investigated in this paper. These rehabilitation strategies are the most conventional approaches in the masonry schools in Iran. The increase in the wall strength is obtained by means of nonlinear static procedure with employing FEM micro models of 48 different walls. Different mortar quality, aspect ratios and gravity loads are the main characteristics which were taken into consideration. The base shear versus the wall top displacement is derives in all un-rehabilitated and rehabilitated cases. All the FEM micro models were constructed automatically within the MATLAB package and linked with the OpenSees platform in order to conduct the push-over analyses. The maximum shear strength is summarized in Table 4 which indicates that the strength increase is significant in most of cases which varies wall to wall. As an example, the strength increase is more in the case of 22cm thickness walls when compared with 35cm thickness walls. In addition this ratio is quite more meaningful in the case of walls with parallel joists compared with the walls with perpendicular joists. Validation of the numerical results with the results based on experiments can shed light into the problem for the future researches.

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