Vulnerability of Hybrid Masonry Building under Seismic Action

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Abstract

Hybrid masonry building is a type of masonry building that uses steel columns and beams as a bearing system in order to meet architectural requirements for wider space. In this paper, masonry walls are modeled by finite element method and analyzed nonlinear statically. Real nonlinear properties of material are considered in the modeling, too. The results of model are compared with experimental modeling results to verify accuracy of numerical model. The vulnerability of hybrid masonry building under seismic load is investigated by creating three dimensional models through nonlinear static analysis.

Keywords: hybrid masonry structure, nonlinear static analysis, vulnerability

1 - Introduction

Masonry buildings are common constructions all over the world because of low-cost and availability of material as well as convenient and simple construction technology.
On the basis of available statistics, masonry buildings comprise 68 percent of total buildings of Iran except Tehran. Due to past earthquakes in Iran and severe loss of life and financial damages of masonry buildings, it seems essential to assess damage and behavior of these buildings.
In order to investigate the seismic behavior of these structures, several researches have been conducted. Benedetti et al, [1] designed some brick and stone buildings in the scale of 1:2 to simulate current masonry buildings in Mediterranean regions. They investigated seismic behavior of masonry buildings by primitive construction technology and also evaluated workability of strengthening methods of these buildings. Tambarotta and Logomorsion [2] used a finite element model to evaluate drift of brick shear wall on the basis of properties of mortar between bricks and their characteristic equation.
The results obtained from the model are compared with experimental results of lateral loading of brick-wall samples. Schneider et al [3] in 1998 investigated seismic behavior of non-reinforced masonry building combined with steel frame. In this research, five brick walls with wide opening were subjected statically to coplanar deformation. Moreover, they studied effect of size and location of openings on variation of stiffness and ductility of masonry wall. Galano and Gusella [4] presented criteria for seismic behavior of masonry walls along with steel X bracing.
In Iran, Tasnimi [5] studied behavior of reinforced and non-reinforced walls under cyclic loads. He showed the strength of brick walls decrease drastically after few cycles.
This paper discusses seismic behavior of hybrid masonry buildings that were commonly constructed in several parts of Iran. These structures were used to accommodate wider space between masonry walls for the purpose of answering architectural requirements. Outspread space is provided by lodging series of steel columns in middle

of the floor. Vertical loads are distributed between masonry wall and steel columns by simply supported steel girders. Destruction of a hybrid masonry building in BAM earthquake in Iran is shown in figure 1.

Figure 1. A destructed hybrid masonry building of BAM earthquake in Iran 2004

Herein, two different approaches namely micro and macro element are used for numerical modeling and nonlinear static analysis of hybrid masonry building. Then, vulnerability assessment is carried out to elaborate the strengthening approach by changing type of support of beam on the wall.

2 - Numerical modeling

The masonry building modeling is done by two approaches (i.e. micro element and macro element) and is compared with experimental test model. In macro element approach, brick and mortar form a unit and the property of brick and mortar are considered together. (Figure 2-a)
In micro element model, brick and mortar are modeled separately and the property of each one will be assigned individually. This modeling can show cracks and stiffness degradation due to bond weakness between brick and mortar (Figure2-b).

Finite Element modeling is realized by ANSYS software. Solid 65 and Combine7 Element properties are used respectively for numerical analysis modeling of masonry material and modeling hinged joints. Also two nonlinear criteria namely Concrete and Druker Pruker are applied to consider nonlinear behavior of masonry material [Table 1&2]. Geometric and material property of the hybrid masonry building modeled is brought in Table 3.

Table 1. Material property for macro element in ANSYS

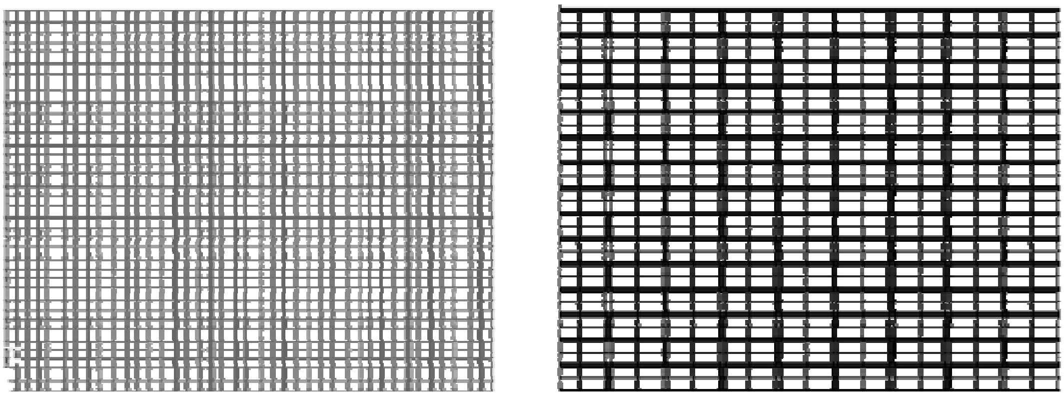
Yield Drucker-Prager Critertion		William And Warnke Surface	
c	.45 Mpa	fc	15 Mpa
η	18.1°	ft	.45 Mpa
$\bar{\phi}$	37.45°	$\beta\chi$	0.6
E	2800 Mpa	$\beta\tau$	0.1

Table 2. Material property for micro element in ANSYS

Yield Drucker-Prager Critertion			William And Warnke Surface		
	Mortar	Brick		Mortar	Brick
c	0.25 Mpa	2.8 Mpa	fc	10.5 Mpa	18 Mpa
η	16°	23°	ft	0.25 Mpa	2 Mpa
ϕ	31°	45°	$\beta\chi$	0.6	0.6
E	2100 Mpa	17500 Mpa	$\beta\tau$	0.1	0.1

Table 3. Geometric and material property of the hybrid masonry building for Micro Model and Macro Model and Experimental Model

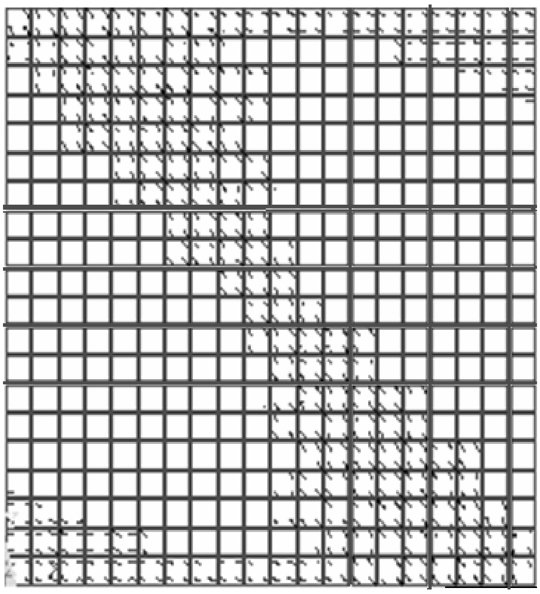
Length	99 (cm)
Width	10(cm)
Height	100(cm)



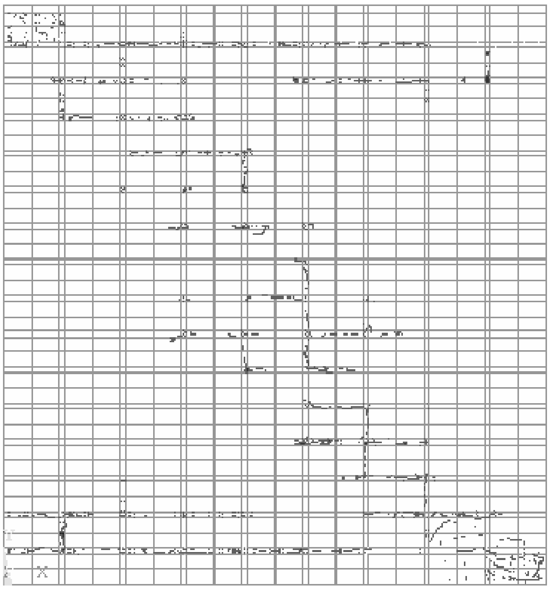
a) Macro element modeling b) Micro element modeling

Figure 2. Meshing model of masonry wall in ANSYS software with two macro element and micro element approach.

Vertical pressure due to dead and live loads on roof assumed as 0.3 Mpa that is uniformly distributed among the beams on top of the walls. Lateral loading is applied as an increasing one-way loading on roof level. Roof such as rigid diaphragm distributes the lateral load into the brickwork. In order to validate accuracy of above numerical models, these results are compared with experimental results of the test carried out by Vermeltfoort et al.[5]. Comparison of results indicates good agreement between numerical analysis and experimental results (Figures 3,4 and 5).



a) Micro element approach



b) Macro element approach

Figure3. Cracks occurred in wall as a result of numerical analysis by macro and micro element approach.

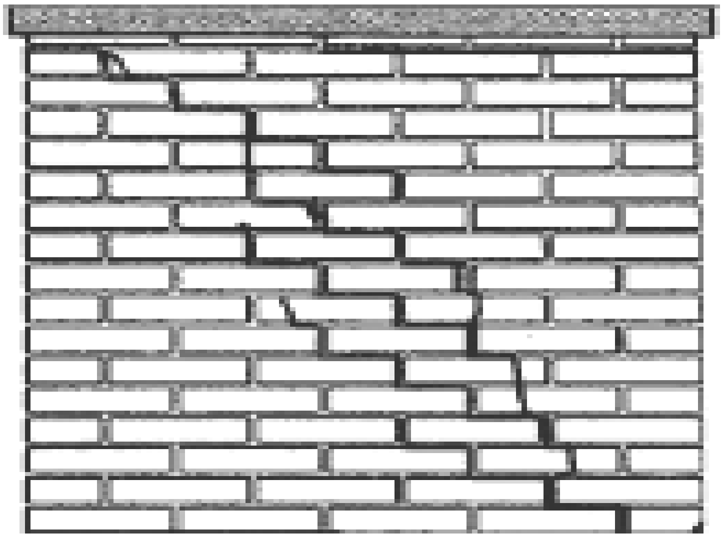


Figure4. Cracks in experimental model

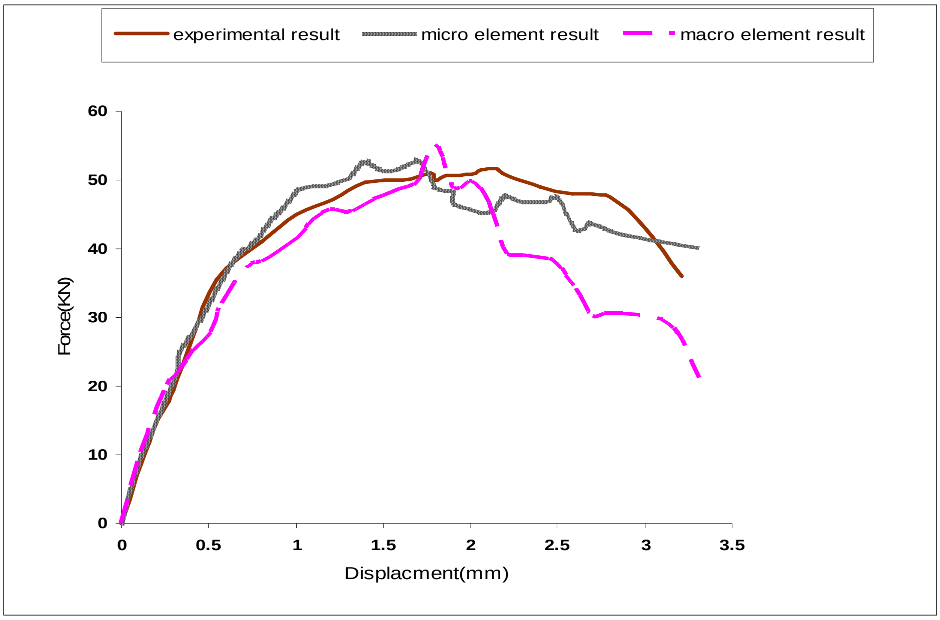


Figure5. Results of numerical and experimental modeling

Figure 5 shows that both type of modeling are appropriate. Numerical model results are in very good agreement with experimental model. Thus these models and elements are well-suited for modeling and can be used to three dimersional analysis of masonry building. Location and direction of cracks for both of micro and macro analyses agree with experimental results shown in Figure 4. Force-displacement graphs obtained from macro and micro models analysis show good agreement with experimental results of Vermeltfoort tests. Results show that force – displacement graphs obtained from micro element model analysis have better form and less discrepancy in comparison with macro element model. However, differences are not meaningful in a way that necessitates using of micro element model for engineering applications. For research works which are focused on small volume models micro element modeling is justifiable. However, long run-time of the micro element model is the main limitation of its application in comparison with macro element modeling. Micro element modeling makes it possible to identify the weak points between mortar and brick. However, macro element modeling can not show these weak points separately, because it takes mortar and brick as a unit. Results of macro and micro element modeling are shown in Figure 3. In this research, macro element modeling is preferred to micro element modeling, because of long run-time of micro element model.

3 - Characteristics of three dimensional model

The verified model of masonry wall is used for three dimensional numerical model of hybrid masonry building. A typical one-story hybrid masonry building is considered with a plan dimension 8.8mx7.8m and walls thickness, 0.33m (Figure 6). Seismic vulnerability of Hybrid masonry models is evaluated in three following categories:

1) Hybrid masonry building without concrete ties
2) Hybrid masonry building with horizontal concrete ties in roof level
3) Hybrid masonry building with vertical concrete ties in walls and horizontal ones in roof level

Assumed static loads in model include weight of roof, walls and steel structural element.

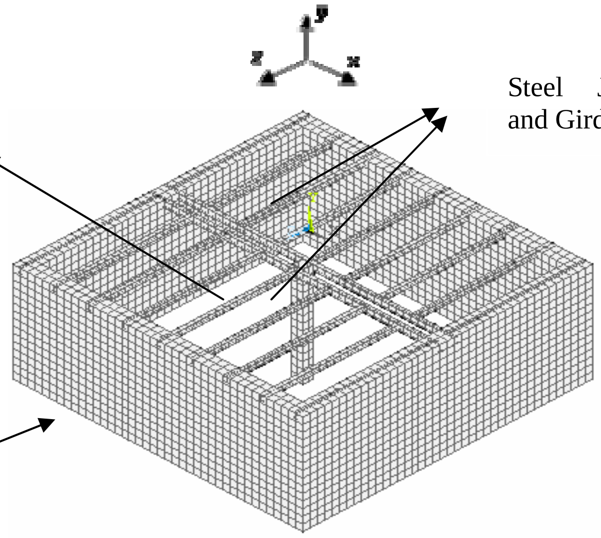


Figure 6. Three dimensional model

4 - NonLinear static method

In this method according to seismic rehabilitation guidelines for constructed structures in Iran lateral load induced by earthquake is applied gradually to the structure increasingly in a static manner. This load applying continues till the displacement of a control point reaches a target value or the structure collapses. Deformations and Internal forces obtained from nonlinear static analysis must be checked with acceptance criteria.

5 - Determination of Target Displacement

Target displacement for structures with rigid diaphragm should be estimated by considering nonlinear behavior of the structure. In this research structure is displaced more than target displacement to observe the structure behavior up to the collapse point.

6 - Vulnerability Assessment

6-1- Acceptance criteria for in plane behavior of wall

In order to examine in-plane behavior of masonary walls (force controlled elements), design forces calculated from linear / nonlinear static analysis should be less than lower limit of wall strength. The expected lateral strength (Q_{ce}) for non-reinforced masonry material according to shear strength of wall is:

$$Q_{ce}=V_{bjs}=V_{me}A_n \qquad (1\text{-}6)$$

Where:
A_n: net cross-section with mortar
V_{me}: expected shear strength
V_{bjs}: expected shear strength of wall according to sliding of mortar joint.
Lower limit of lateral strength (Q_{cl}) of masonry walls on the basis of diametral tensile stress is expressed as follows:

$$Q_{cl} = V_{dt}=0.5\, f_{dt}\, A_n\, (L/h_{eff})\, (1+ (f_a/f_{dt})), \qquad (2\text{-}6)$$

f_a: compressive stress resulting from gravity loads according to this load combination: (Q_G= 1.1(Q_D+Q_L))
F_{dt}: lower limit of diametral tension strength of masonry material.
V_{dt}: lower limit of shear strength on the basis of diametral tension for wall low limit
Q_D: Dead load
D_L: 0.2 Live Load
If expected lateral strength of walls due to shear in mortar-brick joint is less than diagonal tension strength of the wall, due to non ductile behavior of the wall called as force controlled element. If mortar-brick joint shear strength is more than diagonal tension strength of the wall, the behavior of walls can be considered as a ductile element and called as displacement controlled element [9, 10, 11,14].

6-2- Acceptance criteria for Out - of - plane behavior of wall

Out-of- plane behavior of masonry wall for performance level of Immediate Occupancy (IO) is assumed as force controlled element and tensile stress resulting from flexure should be less than the expected strength of tensile flexure (f_{CE}).
However out-of-plane behavior of masonry wall in performance levels of Life Safety (L.S.) and Collapse Prevention (C.P) is assumed as deformation controlled element. Accordingly the behavior considered for this elements in push-over analysis should follows the force-displacement curve shown in Figure 7. The parameters in Figure 7 are described in Table 4.

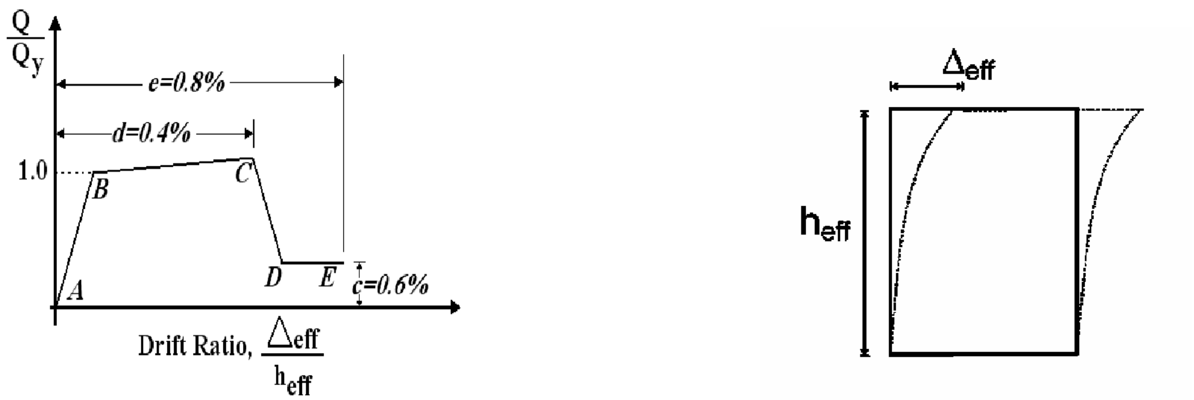


Figure 7. Force Displacement curve for masonry elements..

Table4. Criteria of acceptance whit displacement control

Performance level								
Secondary member		member main			Parameters of deformation			
C.P.	L.S.	C .P.	L.S.	I.O	c	d	e	behavior of masonry element
0.8	0.6	0.4	0.3	0.1	0.6	0.4	0.9	slide shear

C.P: Collapse Prevention L.S: Life Safety I.O: Immediate cupancy)

7- Hybrid masonry building without concrete ties

This type of hybrid masonry building was more commonly used than other construction types in Iran. There is no vertical and horizontal concrete tie in these buildings. Results of nonlinear analysis indicate these buildings experiences severe damages even in low displacement. Most of cracks are occurred in connection of the steel beams and masonry walls. These cracks reduce shear strength of the walls and increase their relative displacement and finally collapse the structure. Results of vulnerability assessment are listed in Table 5, 6.

Table 5. Evaluation of in-plane behavior Hybrid masonry building without concrete ties in x direction

Performance Level	Control Criteria for In-Plane	
	Displacement	Force
I.O	Un-acceptable	Un-acceptable
L.S	Un-acceptable	
C.P	Un-acceptable	

C.P: Collapse Prevention L.S: Life Safety I.O: Immediate occupancy)

Table6. Evaluation of out-of-plane behavior hybrid masonry building without concrete ties in z direction

Performance Level	Control Criteria for Out-of-Plane	
	Displacement	Force
I.O	-	Un-acceptable
L.S	Un-acceptable	
C.P	Un-acceptable	

C.P: Collapse Prevention L.S: Life Safety I.O: Immediate occupancy)

As cited in Table 5&6, hybrid masonry buildings without concrete ties are not acceptable for any of the control criteria. It seems that due to sliding of steel girders under seismic loads, masonry walls experience large displacement at the top and finally collapse. In this type of buildings, tensile stress due to flexure is more than tensile strength of wall and for this reason, structure is vulnerable.

8 - Hybrid masonry building with horizontal concrete ties in roof level

Horizontal concrete ties in roof level were used in some hybrid masonry building. The horizontal concrete ties postpond collapse of building during earthquake. However, its vulnerability is not decreased sufficiently. Besides, number of cracks has increased in the location of longitudinal beams and has concentrated in concrete tie and the beneath brick wall. In the following table [Table 7&8] results obtained from vulnerability assessment are presented.

Table 7. Evaluation of in-plane behavior hybrid masonry building with horizontal concrete ties in roof level in the direction of X axis.

Performance Level	Control Criteria for In-Plane	
	Displacement	Force
I.O	Un-acceptable	Acceptable
L.S	Un-acceptable	
C.P	Acceptable	

Table 8. Evaluation of Out-of-Plane behavior hybrid masonry building with horizontal concrete ties in roof level in the direction of Z axis.

Performance Level	Control Criteria for Out-of-Plane	
	Displacement	Force
I.O	-	Un-acceptable
L.S	Un-acceptable	
C.P	Acceptable	

The above observations show that hybrid masonry building with upper tie is acceptable only in threshold of collapse. It is controlled by force and acceptable for in-plane behavior. However, it is not acceptable for out-of-plane behavior. Proper performance of this case compared to previous one is mainly due to the existence of upper tie that increases bearing capacity and ductility.
Absence of vertical tie impairs behavior of walls as well as life support and immediate occupancy.
In this building the value of tensile stress resulting from out-of-plane flexure is more than tensile strength of wall.
In the above building, performance level in threshold of collapse is acceptable which indicates the positive effect of tie in masonry building.

9 - Hybrid masonry building with vertical concrete ties in walls and horizontal ties in roof level

Both vertical and horizontal ties are used in this building. Horizontal ties are located above whole walls and vertical ties are located in the corners and in the middle of the walls. Applying vertical and horizontal tie in the above-mentioned building influenced the behavior of building and increased ductility. Cracks were obvious in connection joint of beam and wall, especially continuous beams, which finally caused failure. Results of vulnerability assessment are presented in tables 9&10.

Table 9. Evaluation of in-plane behavior hybrid masonry building with vertical and horizontal concrete ties in the direction of X axis.

Performance Level	Control Criteria for In-Plane	
	Displacement	Force
I.O	Un-acceptable	Acceptable
L.S	Acceptable	
C.P	Acceptable	

Table 10. Evaluation of out-of-plane behavior hybrid masonry building with vertical and horizontal concrete ties in the direction of Z axis.

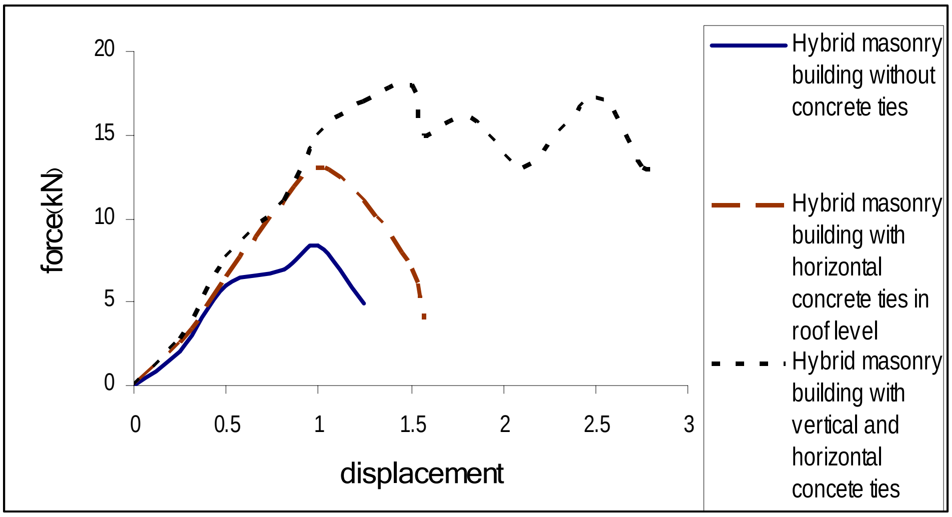
Performance Level	Control Criteria for Out-of-Plane	
	Displacement	Force
I.O	-	Un-acceptable
L.S	Acceptable	
C.P	Acceptable	

As cited in Table 9&10, the above masonry structure in the case of Immediate occupancy is not acceptable. However, results are satisfactory for other criteria. Horizontal and vertical ties applied in the building, indicate the effect of tie to enhance performance level of masonry building

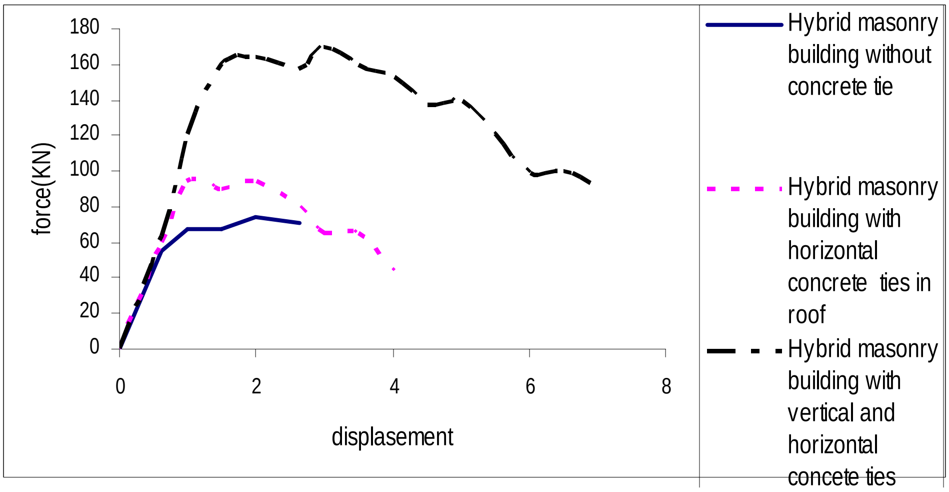
The tensile stress resulting from flexure is more than tensile strength of wall. Thus structure is vulnerable in the case of force control for out-of-plane in X and Z directions. The behavior of above-mentioned structure in the case of threshold of collapse and life support is satisfactory. The main reason for favorable behavior of this building compared to previous building is due to proper tie system.

10 - Application of concrete ties in seismic rehabilitation

As it described before, seismic behavior of hybrid masonry building without tie is non ductile and faces destructive damages during earthquake. The results clearly reveal that reinforced concrete ties have an influential effect to prevent failure and decrease vulnerability. Thus it seems essential to use whole shear capacity of wall and increase ductility of structure by using ties. Distance between ties in these buildings that is more than allowable limit recommended by Iranaian national code (No. 376), should be decreased by establishing ties between them. Care should be taken for proper bracing of beams inside the horizontal tie. The next step is to assess the out-of -plane behavior of walls which is determinant in most masonry buildings and strengthening of walls against out-of-plane loads. In the Figure 8, behavior of different strengthed structures is illustrated.



a) Out-of- plane behavior



b) in-plane behavior

Figure8. Displacement-force curve resulting from pushover analysis for hybrid masonry building.

Comparison of graphs show that reinforced walls with ties have better performance in out-of- plane behavior and are more ductile compared to non-reinforced structures. However, non-reinforced and horizontally tied masonry buildings behave the same and there is not much difference between their behaviors.

11 - Conclusion

Surrounding masonry walls in hybrid masonry buildings were modeled by micro and macro element and analyzed by nonlinear static method. Experimental results were used to verify analytical model analysis. Seismic vulnerability of hybrid masonry building with and without concrete ties was investigated and results show that damages are mainly concentrated in the support of steel girders on roof. Vulnerability assessment of hybrid masonry buildings with only vertical or only horizontal concrete ties confirms seismic performances of these buildings are not acceptable for level of immediate occupancy during earthquake.
Buildings with horizontal and vertical concrete ties show better ductility in comparison with buildings without them. Buildings reinforced with vertical and horizontal ties are vulnerable only in out-of-plane direction.
The results indicate that application of vertical and horizontal tie in hybrid masonry buildings improve seismic performance of these building compared to the case of employing only horizontal ties.

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