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A Numerical Study on Optimizing the Geometry and Location of the Openings in Masonry Walls using Finite Element Method

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Abstract: Generally, buildings with masonry materials are among the numerous structures in any country due to ease of implementation, cost effectiveness and availability of their materials. The history of previous earthquakes shows that if these structures are positioned in the epicenter area of earthquakes >5.5 on the Richter scale they will at risk of cracking and collapse. Openings in brick buildings have always been considered as a weakness increasing the probability of collapse in these buildings. Architecture considerations and operational requirements cannot allow removing this important weakness. Therefore, their presence in masonry buildings multiples the risks of lateral forces, especially earthquake and necessitates performing more studies in this regard. This study investigates the behavior of masonry walls with layouts having matrix pattern for the openings to optimize the appropriate position and geometry for the walls having opening. All numerical models in this study were developed via. ABAQUS Software under pushover analysis using finite element method. The correct pattern of positioning the opening at the center of the wall was determined based on the results obtained. In other words the best position for opening in terms of length and width is at the center of the wall so that, the center of area of the opening coincides with that of the wall.

Key words: Numerical study, openings, masonry walls, finite element method, element

INTRODUCTION

Buildings with masonry materials are rather short and the number of their storeys rarely exceeds three. Unreinforced masonry buildings are the buildings in which the whole or a major part of vertical and lateral loads is imposed on the walls having masonry materials including brick, adobe, concrete blocks or ashlar. Horizontal and vertical ties in these buildings (if there any) are used for integrity of the structural system. To retrofit these buildings according to their purpose first the building should be evaluated in terms of vulnerability so that its defects would be identified. Then, these weaknesses will be removed using retrofit methods (NMPO, 2007). Building with masonry materials such as brick or adobe get seriously damaged during earthquake therefore inappropriateness of the masonry materials used in the building construction is well known. However, application of these materials in building construction is still common, especially in rural areas due to cost effectiveness, ease of manufacturing well isolation and building facade. That’s why, comparing the building performance between some countries reveals that after the same earthquake, thousands of people were died or became homeless just in one country or a significant capital was lost (Moghaddam, 2008). Large earthquakes, even moderate ones have sometimes created a disaster in some countries like Iran. According to the statistics, earthquakes such as the earthquake of magnitude 5.8 on the Richter scale occurred in Kaj Derakht in 1923 killed 780 people or the earthquake of magnitude 5.7 on the Richter scale occurred in Gisak, Kerman in 1977 destroyed a number of villages (Dartangol, Gisak, Sarbanj) and jikked 665 people. The earthquake occurred in Dashti City in 2013 killed 65 people and resulted in huge financial losses (Moghaddam, 2008). Improving the quality of the materials and construction procedure, making integrated and lighter roofs and implementing elements that increase the building flexibility (e.g., horizontal ties) can definitely increase the building resistance however, none of these measures guarantee the stability of structures against destructive earthquakes (Moghaddam, 2008). About a decade ago, an earthquake occurred in Bam, Iran in 2003 in which about 35000 people died because of the defects of traditional construction in the masonry buildings. In addition to this high fatality, the earthquake resulted in huge financial losses and destruction of historic buildings. Wall openings in buildings with masonry

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materials are weaker in terms of tolerating vertical and lateral loads. This study aims to find a pattern for crack propagation around the openings and finally makes some operational and economic suggestions to reduce the building damages and prevent demolition of the walls. Yanez *et al*. (2004) studied the behavior of the masonry walls with big openings in the buildings having masonry materials (cement and mud) under sixteen states and developed a pattern for demolition of the wall. In this study, sixteen samples were examined in real scale in this research to study the behavior of masonry wlls, eight of which were made of concrete blocks and the other eight samples were hollow bricks. The samples were designed to perform shear failure tests until formation of diagonal cracks in masonry panels. The test parameters included the type of building materials used in the bricks (concrete or clay soil) and opening size (four cases). The experimental results included evaluating the deformation capacity, energy dissipation properties, stiffness and resistance against demolition, shear cracking and maximum shear resistance. Then they compared the results obtained by examining the walls with/without opening in terms of stiffness and resistance against cracking and wall demolition (Yanez *et al*., 2004). Masayuki also performed an experimental study on the effect of window in cracking pattern of the reinforced walls in the masonry buildings and obtained the patterns. To do so they examined nine samples under different conditions with/without opening. Then they compared the models and concluded that the load bearing capacity significantly increases by reinforcing and retrofitting the areas around the windows in brick walls (Kuroki *et al*., 2010).

Characteristic strength of masonry wall: Compressive strength and fragmentation in masonry walls depends on: Compressive strength and fragmentation of the masonry materials. Composition of the mortar used and its age: different mortars have a significant role in the quality and resistance of the wall. These parameters are generally defined based on the primary materials, namely cement or lime mortar, mortar composed of cement and lime, combination of lime and pozzolan or hydraulic lime mortar. Mud mortar is also used in some areas in Iran, especially in rural areas. Low thickness relative to the height decreasing wall thickness against increasing its height and length makes the wall thin which in turn reduces wall resistance. Increasing the eccentricity of the wall axial load results in decreasing resistance. Increasing area of the openings in the wall results in decreasing resistance. Tensile and shear strength of the materials mainly depends on the adhesion and surface friction at the interface of masonry materials and the mortar. Generally, it can be argued that it is a small fraction of the compressive strength. As the ratio of cement or lime in the mortar increases its tensile and shear strength will increase as well.

Stiffness of shear wall: Since, the width of the brick wall is almost equal to and sometimes even greater than the wall height, lateral displacements of the wall cannot be only attributed to bending; shear can have a significant role in this regard. Total displacement of the wall under the force P is:

$$\delta = \delta_1 + \delta_2 \tag{1}$$

Where:

δ_1 = $ph^3/12EI$ is bending displacement

δ_2 = $ph/1.2AG$ is shear displacement. h, A and I are the wall's height, area and moment of intertia, respectively:

$$G = \frac{E}{2.6} \text{ shear modulus } I = \frac{tl^3}{12} = \frac{AL^2}{12} \tag{2}$$

$$\delta = \frac{ph}{EA} \times (\frac{h}{L})^2 + 2.16\frac{ph}{EA}$$

Therefore, the wall stiffness is (NMPO, 2007):

$$K = \frac{P}{\delta} = \frac{EA}{h[(h/l)^2 + 2.16]} \tag{3}$$

Elasticity and shear modulus masonry wall: Elasticity modulus of the masonry wall totally depends on the density and stiffness of the masonry unit (along with the mortar). For the brick of 1900 kg/m^3 density or the ashlar of 2400 kg/m^3 density, implemented with sand-cement mortar (ratio of 6:1) it can be considered equal to 2000 MPa. Elasticity and shear modulus determine the ductility of the materials. The valued of elasticity modulus, E and shear modulus, G are determined experimentally. Elasticity modulus as a linear coefficient is determined by vertical pressure test on a masonry wall. If the values obtained experimentally are not available the relationship between compressive strength of the masonry wall f_{wc} and elasticity modulus E can be used as the following (UNIDO, 1984):

$$E = 1000\, f_{wc} \tag{4}$$

Experimental results show that the actual value of E for different walls varies in the range of:

$$500\, f_{wc} < E < 3000\, f_{wc} \tag{5}$$

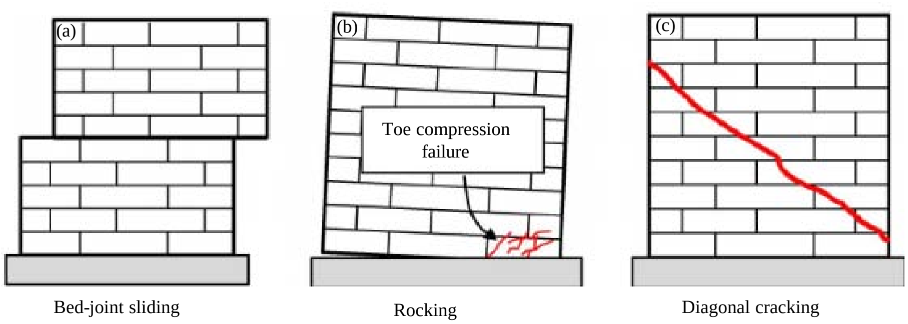

Fig. 1: Failure modes in unreinforced masonry walls: a) Bed-joint sliding; b) Rocking and toe compression and c) Stair-stepped diagonal and diagonal cracking (Ghiassi *et al.*, 2011)

Similarly, the shear modulus can be estimated from the tensile strength of the masonry wall G using Eq. 6:

$$G = 3000\ f_{wt} \tag{6}$$

and its actual value for different walls varies in the range of:

$$1000\ f_{wt} < G < 5000\ f_{wt} \tag{7}$$

The experimental results also show that the changes in tensile strength in masonry walls with respect to compressive strength is not much:

$$0.05\ f_{wc} < f_{wt} < 0.07\ f_{wc} \tag{8}$$

Masonry wall failure: Generally, three types of failure occur in masonry walls shear failure, sliding-shear failure and bending failure. If the wall is under high vertical load and the height/length ratio of the wall is <1, shear failure mode will occur, shown in Fig. 1a. If the height/length ratio is <1 (around 2) and the vertical load is too high, again there will be the possibility of shear failure. If the shear strength of the wall is little and the lateral load is large relative to the vertical load, sliding-shear failure will occur, shown in Fig. 1b. The height/length ratio of the wall in this case is usually 1.5 and close to 1. If the wall has sufficient shear strength and its height/length ratio is 2, bending failure will occur, shown in Fig. 1c. If the value of the vertical load is low, bending failure will occur in case of low shear strength.

Investigating the vertical sliding caused by shear failure of narrow bases: When horizontal and vertical forces are simultaneously imposed on a shear wall the status of stresses within the wall components will be according to Fig. 2. It is clear that there are three potential failure surfaces oblique, horizontal and vertical surface (Moghaddam, 2008).

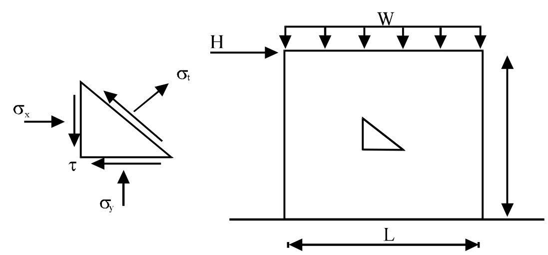

Fig. 2: Status of stresses in an element of a shear wall under vertical and horizontal forces

Tensile failure: Failure on an oblique surface is tensile and passes through the bricks. Therefore, when reaches the tensile strength of the bricks, failure will begin. Bricks usually have a relatively good tensile strength and do not experience this kind of failure since the shear failure will occur in horizontal or vertical surfaces before reaches the resistance limit of the brick. If perforated brick and very string mortar is used the shear strength of horizontal and vertical joints will increase the failure will occur on the oblique surface and it will pass through the bricks. However, this situation rarely occurs in practice (Abrams and Shah, 1992).

Numerical analysis using finite element method: Numerical modeling of a brick wall is generally divided into two categories: micro modeling and macro modeling. Brick wall is a composite material composed of three components brick, mortar and brick-mortar interface. In micro modelling, each component is separately modelled (Fig. 3a). Although, this kind of modeling has a high accuracy it is very complicated in terms of calculation and modeling procedure and is not applicable for large dimensions. In macro modeling, the brick wall is modelled as a homogeneous material with uniform mechanical properties. This kind of modeling is very simple and its calculations are much less compared to micro modeling (Fig. 3b).

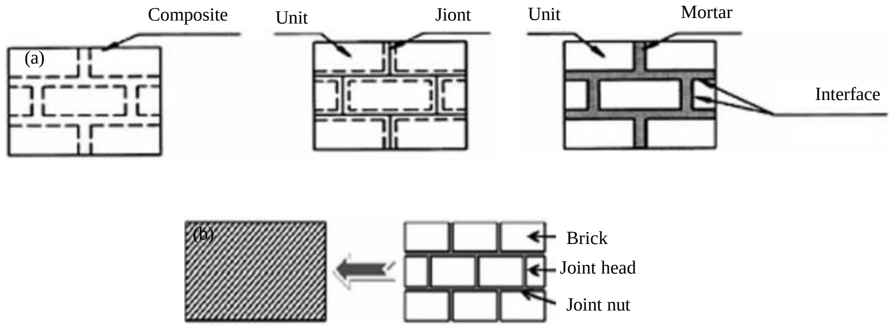

Fig. 3: Micro and macro modelling of masonry walls, Hong and laefer (2008) and Baloevic *et al*. (2016): a) Micro modelling of the brick wall and b) Macro modelling of the brick wall

MATERIALS AND METHODS

In this study, first the results of pushover analysis of masonry walls obtained by ABAQUS Software were validated. After validation of the results of numerical model and experimental samples the numerical models presented in this study were analyzed. Generally, 20 numerical models of masonry walls with/without opening were modelled in terms of number, size and position using ABAQUS Software and then examined by pushover analysis. It has to be noted that ABAQUS is a set of simulation software based on finite element method which is able to solve a wide range of problems from relative simple linear problems to complex non-linear problems. ABAQUS includes a wide range of different elements by which any geometry can be modelled. According to its design this software can be used for modelling of problems beyond structural problem of civil engineering. Given the items mentioned above this Software was used in this study. It has to be noted that the technique used in numerical simulation of all models is micro finite element method.

Numerical models validation: Abrams and Shah (1992) performed an experimental study entitled "The effect of alternating loads on unreinforced masonry walls" which is used here to evaluate and compare the results of numerical and experimental results. Their research included the results of three tests on the behavior of unreinforced walls when confronting in-plate lateral loads (Abrams and Shah, 1992). The parameters studied were length/height ratio and the extent of overhead loads. Geometrical properties of the wall include a masonry wall of 1.82 m length and 1.82 m height under two lateral loads of 110 klb caused by a hydraulic jack, shown in Fig. 4. Mechanical and strength properties of one specimen of their samples are given in Table 1. Comparison of the experimental results with numerical modelling is shown in Fig. 5 as a force-displacement plot which indicates that the plots of experimental work and numerical modelling are consistent.

Selecting the opening cross section: In order to select a reasonable and suitable cross section for the opening to model their optimal positioning, first a square opening was placed at the center of a wall with 2800×5000 mm dimensions and then pushover analysis was performed on different models by changing opening dimensions in an area about 0-25% of wall area. The model dimensions were selected so that they would be within the common regulations and standards framework and also be practical and consistent with the reality. In this regard, a square opening with a lintel was first considered according to the commission regulations. In the design commission of constructing buildings against earthquake it is suggested that the lintel length be 30 cm more that the opening sides. Changing the opening dimensions as 20 cm increase in height and 20 cm increase in length, 6 models were defined in the following and 7 models were obtained for suitable cross section by positioning the openings at the center of a wall of 5 m length. The properties of these models are given in Table 2 based on the ratio of opening area. The general characteristic of all models in this section is that the center of area of the opening coincides with that of a wall with 2800×5000 mm dimensions. Many design commission of constructing buildings against earthquake today suggest that the maximum opening area in masonry wall shouldn't exceed 1/3 of the wall's total area. This suggestion has been considered in selecting all openings mentioned in Table 2. The results of pushover analysis on the sample without opening and the sample with square openings of 800, 1000, 1200, 1400, 1600 and 1800 mm side are shown in Fig. 6. According to this Fig. 6 it can be argued that the force-displacement plots related to 800, 1000, 1200 and 1400 mm openings has a significant distance with the force-displacement plots of 1600 and 1800 mm openings. This significant distance

Table 1: The properties of experimental sample masonry wall

Compressive strength (kpsi)	Age (day)	Block dimensions (length×width× height) (cm)	Wall's area (cm^2)	L/h ratio	Wall's length (cm)	Wall's thickness (cm)
50	95	20×9×6	3640	1	182	20

Table 2: Properties of the walls modelled based on the ratio of opening area

Model properties	Opening size (mm×mm)	Wall's length (m)	Opening area/wall area ratio (%)
W5	Without opening	5	0.0
W5-C-80	800×800	5	4.7
W5-C-100	1000×1000	5	7.1
W5-C-120	1200×1200	5	10.3
W5-C-140	1400×1400	5	14.0
W5-C-160	1600×1600	5	18.3
W5-C-180	1800×1800	5	23.1

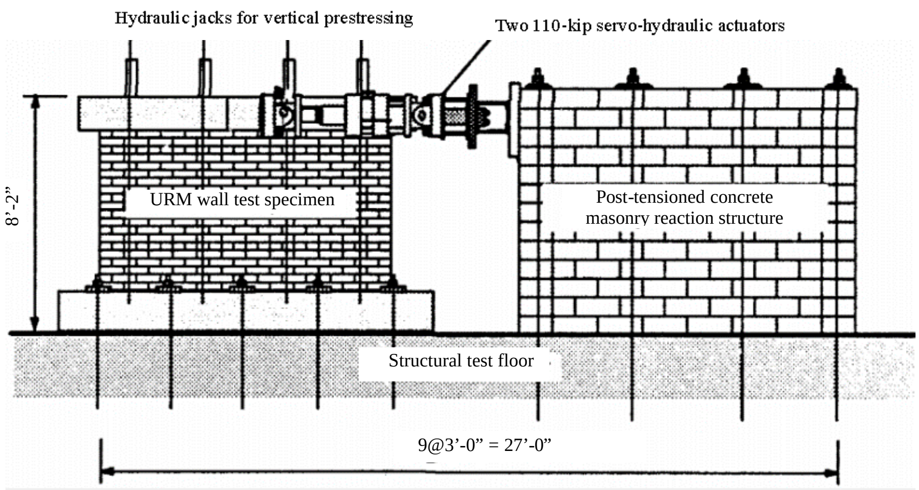

Fig. 4: Loading of the experimental model

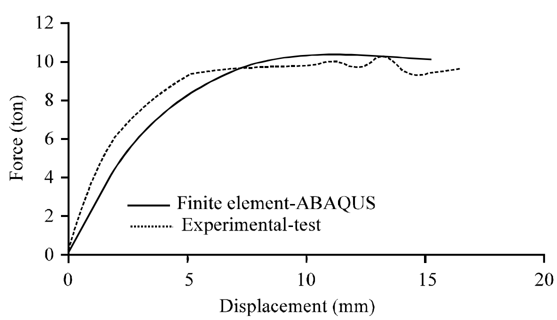

Fig. 5: Comparison between the results of numerical model and experimental sample

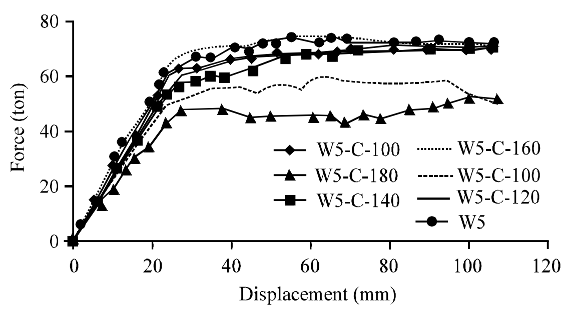

Fig. 6: Selecting the opening dimensions of numerical models based on area

implies a relatively high reduction in the load bearing capacity of W5-C-160 and W5-C-180 models. This indicated that these openings were not suitable and they should be selected from the 800, 1000, 1200 and 1400 mm openings. Given the fact that 1200 mm is a frequent size for openings implemented in masonry buildings and also given the good match between force-displacement plots of experimental samples and the 1200 mm opening this opening was selected for positioning analysis.

Selection opening position for optimization: Selecting the dimensions of a square opening as 1200 mm, now it is time to conduct the feasibility studies on opening position optimization. According to Fig. 7 opening position varied along three horizontal axes A, B and C and three vertical axes 1, 2 and 3 which resulted in 10 models described in Table 3. The matrix pattern in positioning acts in a way that if the opening is located at any of the matrix elements, all other elements of the positioning matrix will be without opening.

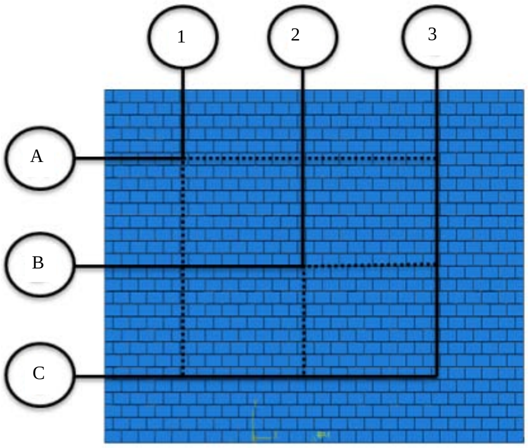

Fig. 7: Variation of opening positioning

Table 3: Introducing the models specifications

Opening position	Wall length (m)	Opening size (cm×cm)	Model characteristic
Without opening	5	0	W5
Opening at A1	5	120×120	W5-A1
Opening at B1	5	120×120	W5-B1
Opening at C1	5	120×120	W5-C1
Opening at A2	5	120×120	W5-A2
Opening at B2	5	120×120	W5-B2
Opening at C2	5	120×120	W5-C2
Opening at A3	5	120×120	W5-A3
Opening at B3	5	120×120	W5-B3
Opening at C3	5	120×120	W5-C3

RESULTS AND DISCUSSION

Investigating the status of horizontal and vertical stresses

Walls with opening along axis 1: In this study, stress contours in horizontal and vertical directions in the models are shown based on changing opening position at the end of pushover analysis. Failure in all models with an angle of about 45° implies creation of a shear failure in the walls modelled. In this study, the stress status along X and Y axes are shown in Fig. 8 and 9, respectively. It is clear from the fig that the maximum stress along the lateral load and vertical load is 107 kg/cm^2 and 533 kg/cm^2, respectively. The appearance of cracks in the wall with an angle of about 45° indicated occurrence of shear failure in the wall. It has to be noted that two sets of equivalent pressure are created on the wall. Given the 5 m length of the wall these sets are created at beginning and ending parts along the wall.

As described in Table 2 the opening in the model W5-A1 is a square of 1200 mm dimension, located at the top left corner at position A1 shown in Fig. 7, 10 and 11 show this opening after pushover analysis of the stresses in horizontal and vertical directions, respectively.

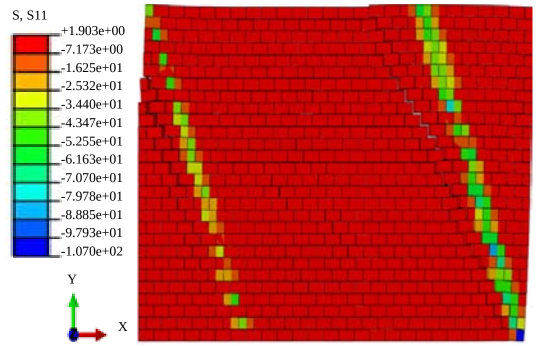

Fig. 8: Stress contour along X axis for the wall W5

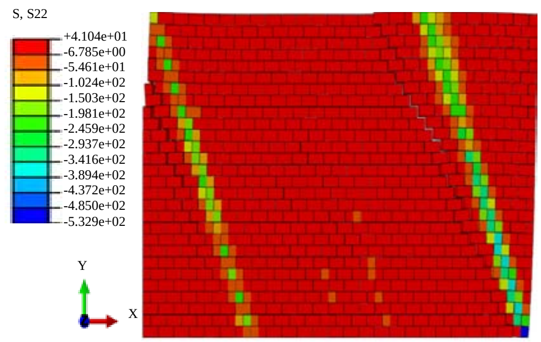

Fig. 9: Stress contour along Y axis for the wall W5

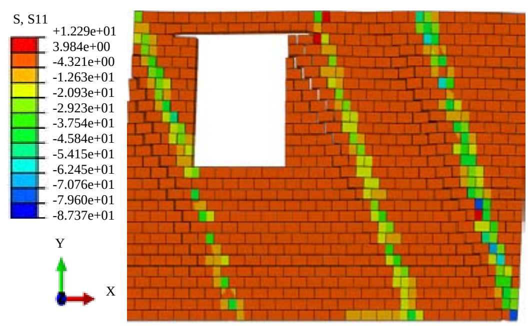

Fig. 10: Stress contour along X axis for the wall W5-A1

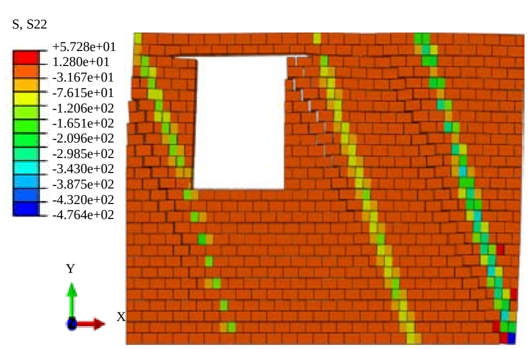

Fig. 11: Stress contour along Y axis for the wall W5-A1

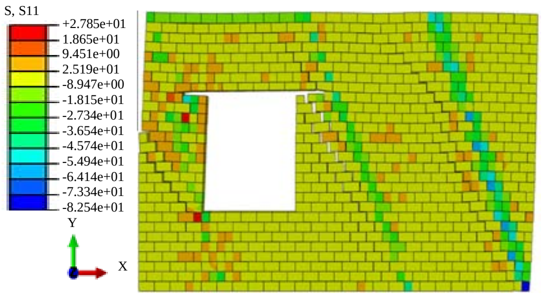

Fig. 12: Stress contour along X axis for the wall W5-B1

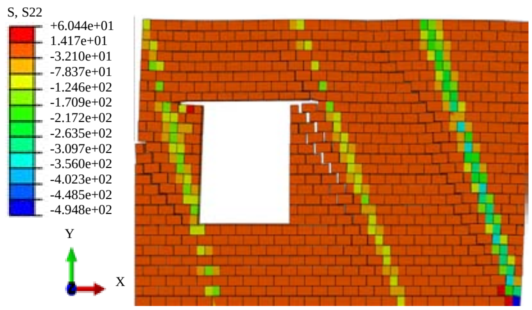

Fig. 13: Stress contour along Y axis for the wall W5-B1

According to these Fig. 7-11 the maximum stress along horizontal axis in the model W5-A1 is 87 kg/cm^2 while according to Fig. 8 it is equal to 107 kg/cm^2 in the wall without opening (model W5). According to Fig. 11 the stress along vertical axis in the model W5-A1 is 476 kg/cm^2 while according to Fig. 6, it is equal to 533 kg/cm^2 in the wall without opening (model W5). Another point to be noted is creation of three sets of equivalent pressure in the wall having opening at the position A1. It is clear from (Fig. 10 and 11) that the sets in the left hand side of the wall are distributed around the opening while there is no change in the right hand side of the wall.

The results of pushover analysis in the model W5-B1 indicated that the maximum stress along horizontal axis is 83 kg/cm^2 (Fig. 12) while the maximum vertical stress in this sample is 595 kg/cm^2 which is increased by 4% compared to the sample A1 (Fig. 13). It has to be noted that the pressure sets created in this sample is similar to the model A1.

The results of finite element analysis in the sample W5-C1 shows that the horizontal and vertical stress due to applying load in the wall plate at the end of loading is 117 kg/cm^2 and 537 kg/cm^2, respectively. The corresponding stress contours are shown in Fig. 14 and 15, respectively. The important note to consider in loading of this sample in comparison with the samples A1 and B1 which have opening along the axis 1 is deactivation of the equivalent pressure set between the opening and end of the wall.

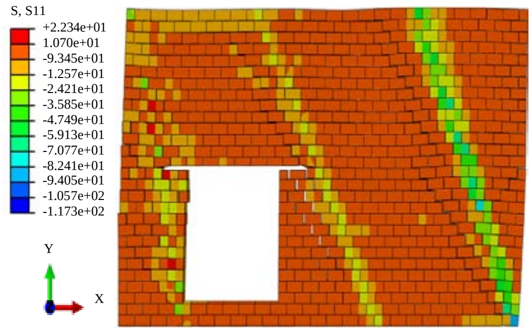

Fig. 14: Stress contour along X axis for the wall W5-C1

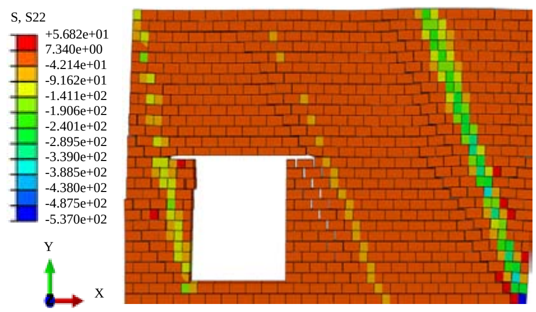

Fig. 15: Stress contour along Y axis for the wall W5-C1

Walls with opening along axis 2: The results of samples with opening along axis 2 are shown in Fig. 16. This Fig. 16 shows horizontal and vertical stress contours in the walls having opening along axis 2. The stress in horizontal direction in the models W5-A2, W5-B2 and W5-C2 is 95, 83 and 86 kg/cm^2, respectively while all the models of this axis only have two sets of pressure at each side of the opening. The stress in vertical direction in the models mentioned above is 497, 514 and 522 kg/cm^2, respectively.

Walls with opening along axis 3: The results of samples with opening along axis 3 are shown in Fig. 17. This Fig. 17 that the stress in horizontal direction in the models W5-A3, W5-B3 and W5-C3 is 90, 89 and 90 kg/cm^2, respectively while the stress in vertical direction in these models is 371, 421 and 441 kg/cm^2, respectively. The point to be noted about samples having opening along this axis is that three sets of equivalent pressure is created in all samples, just like axis 1.

In order to select the position and optimal location among the wall openings matrix, the force-displacement curve of numerical models must be investigated. In this regard Fig. 18 elaborates the results of pushover analysis of walls having opening compared to the wall without opening. It is clear that presence of an opening reduces capacity and ductility (the area under force-displacement curve). According to Fig. 18a, the

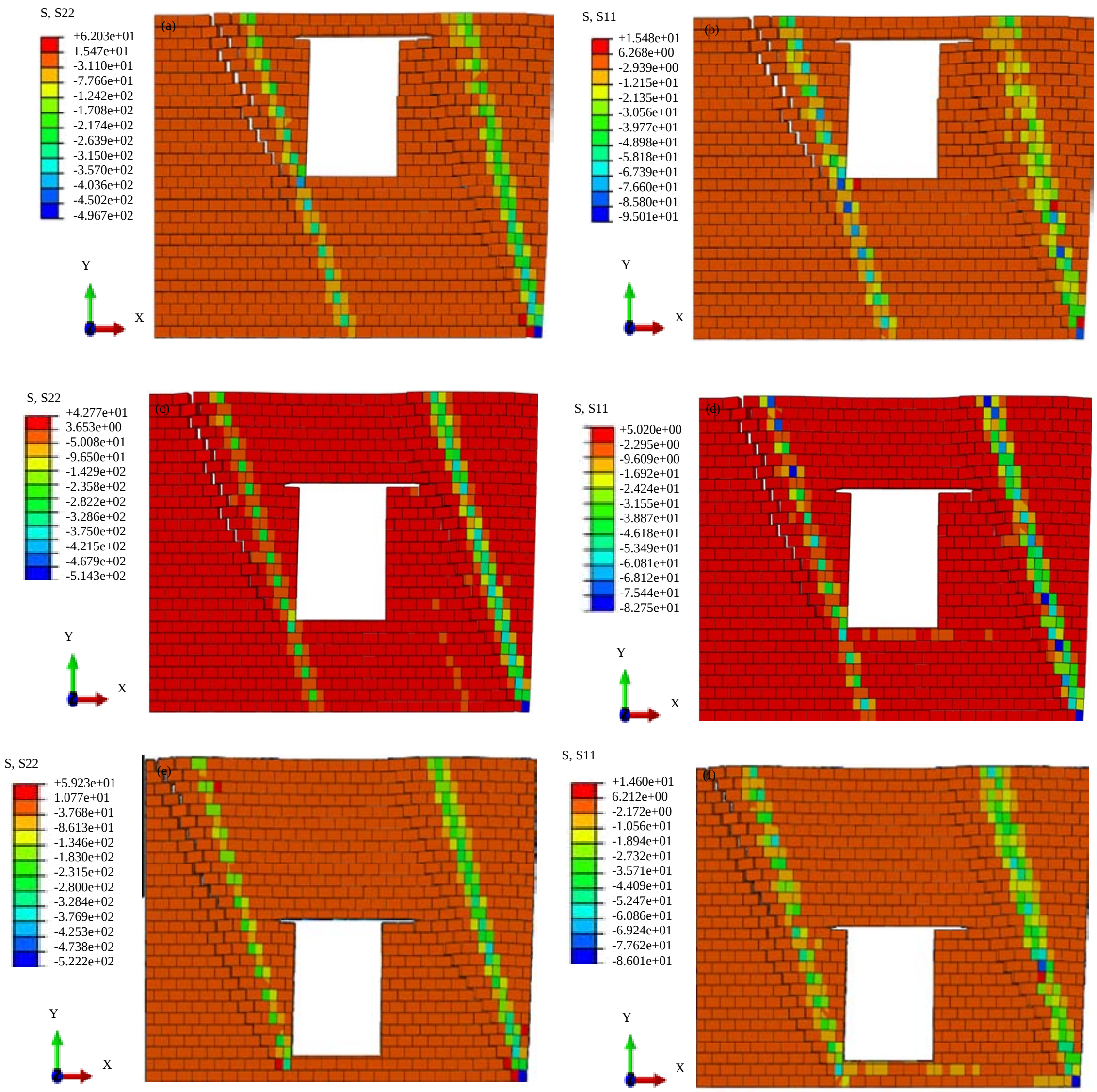

Fig. 16: Horizontal and vertical stress contours in the samples with opening along axis 2: a) Stress contour along Y axis for the wall W5-A2; b) Stress contour along X axis for the wall W5-A2; c) Stress contour along Y axis for the wall W5-B2; d) Stress contour along X axis for the wall W5-B2; e) Stress contour along Y axis for the wall W5-C2 and f) Stress contour along X axis for the wall W5-C2

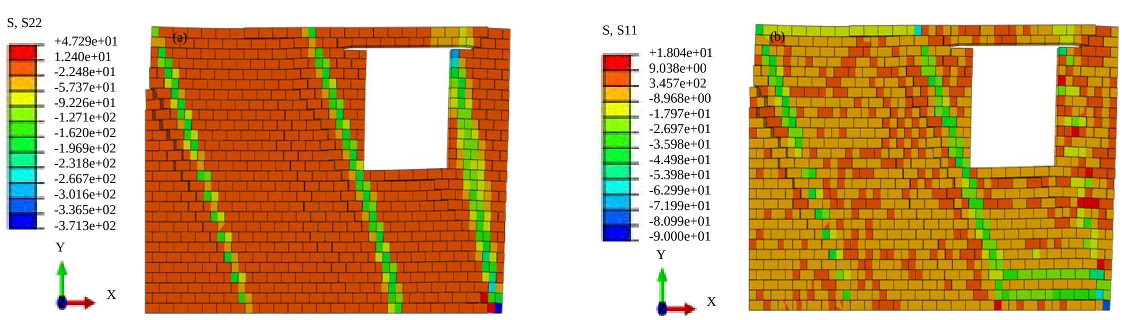

Fig. 17: Continue

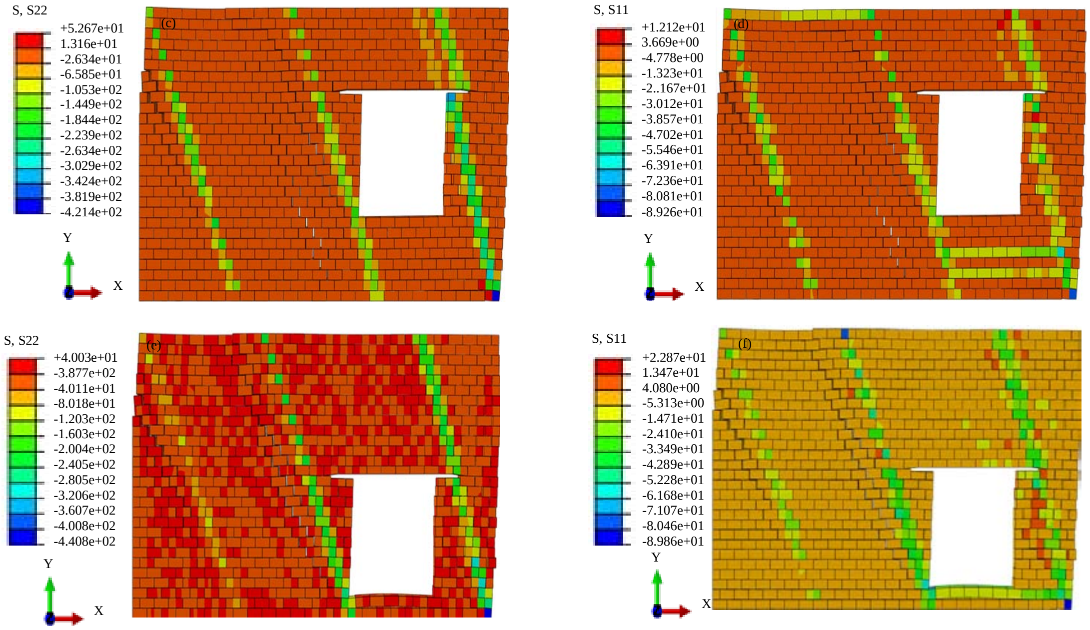

Fig. 17: Horizontal and vertical stress contours in the samples with opening along axis: a) Stress contour along Y-axis for the wall W5-A3; b) Stress contour along X axis for the wall W5-A3; c) Stress contour along Y-axis for the wall W5-B3; d) Stress contour along X-axis for the wall W5-B3; e) Stress contour along Y axis for the wall W5-B3 and f) Stress contour along X axis for the wall W5-C3

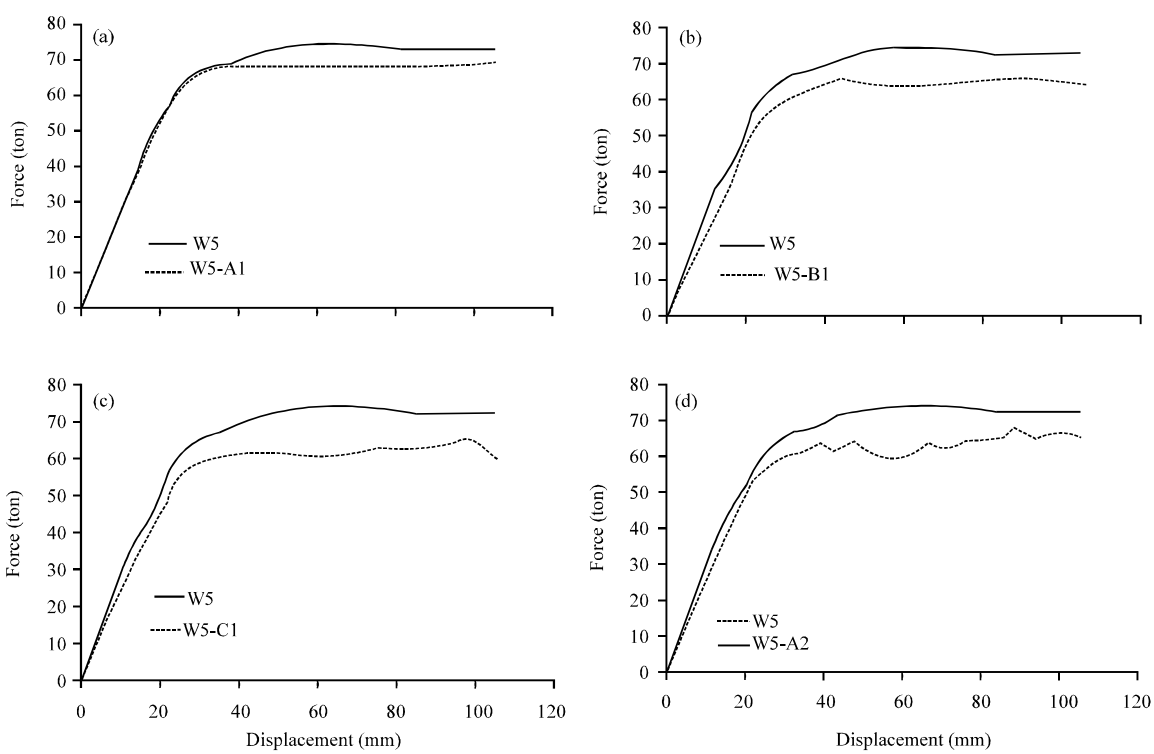

Fig. 18: Continue

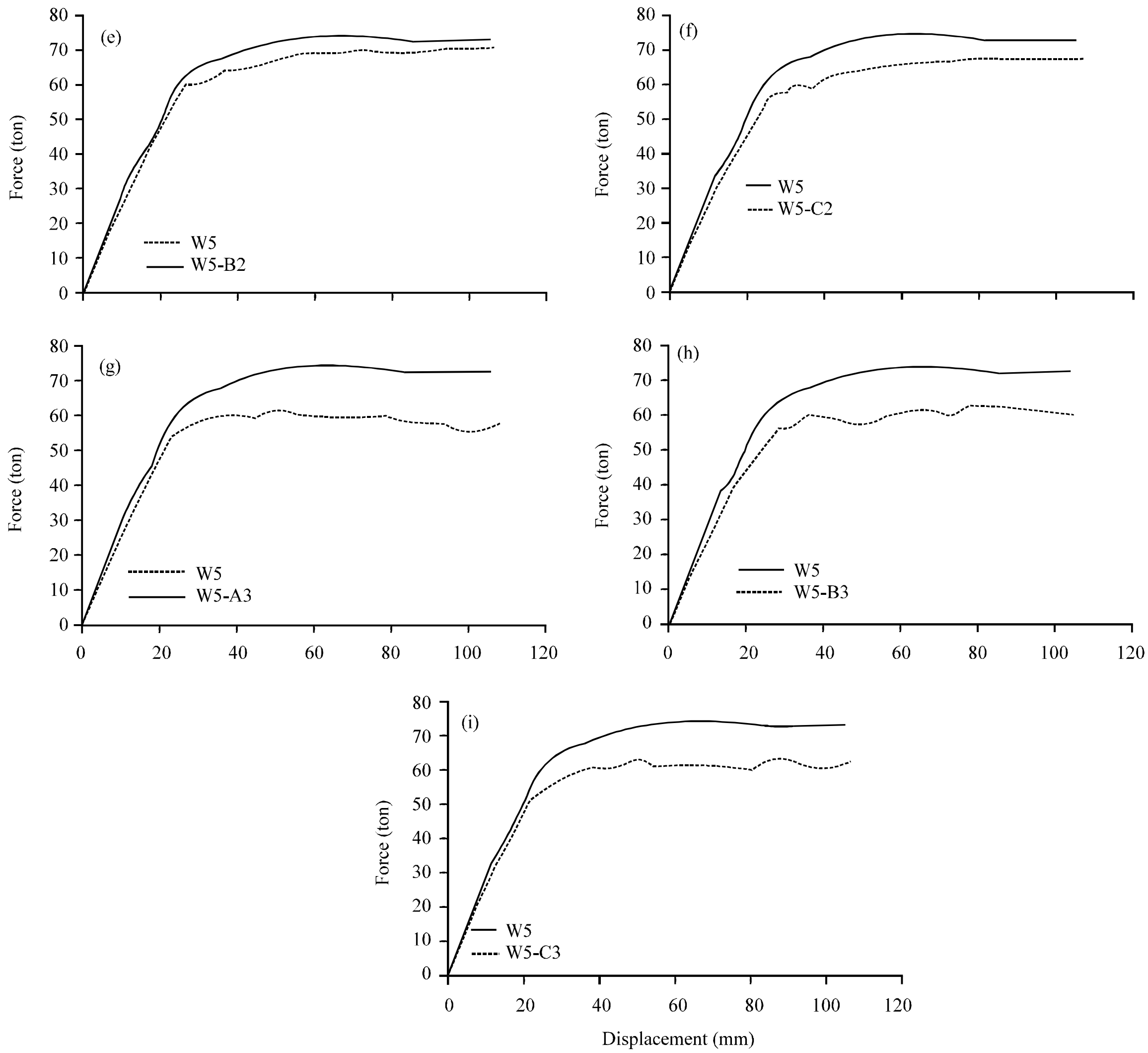

Fig. 18: Force-displacement curve of models having opening compared to the model without opening

diagonal crack for the model W5-A1 has been appeared under a force equal to 24 tons while appearance of diagonal crack in the model W5 (without crack) requires a force about 35 tons. It is clear from Fig. 18a that the final failure in model W5-A1 has occurred under a force about 63 tons while the force leading to failure in the model W5 was 65 tons. According to, the force-displacement curve shown in Fig. 18b and c the force leading to diagonal crack for the models W5-B1 and W5-C1 was 25 and 17 tons and their final failure occurred at a load equal to 58 and 56, respectively. This implies that opening displacement along axis 1 has reduced the wall capacity. Furthermore, the force-displacement curves shown in Fig. 18d-f represent capacity and ductility in the models W5-A2, W5-B2 and W5-C2, based on which it can be argued that the force leading to appearance of diagonal cracks for these models was 25, 28 and 29 tons and their final failure occurred at the load equal to 57, 58 and 52 tons, respectively. This fact implies that although opening displacement along axis 3 has reduced the wall capacity, the location B2 had a better ductility compared to other points. Regarding the force-displacement curves, Fig. 18g-i represent capacity and ductility in models W5-A3, W5-B3 and W5-C3, based on which it can be argued that the force leading to appearance of diagonal cracks for these models was 25, 30 and 25 tons and their final failure occurred at the load equal to 55, 51 and 54.5 tons, respectively. This fact implies that although opening displacement along axis 2 has reduced the wall capacity, the location B3 showed an unsatisfactory performance compared to the other points.

Investigating the behavior of wall having opening along axis 1-3: In order to provide an appropriate presentation

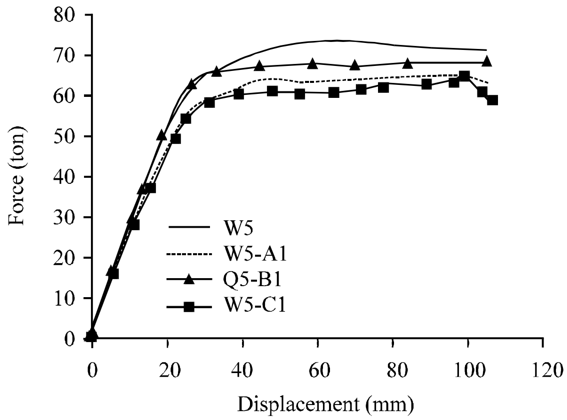

Fig. 19: Investigating models behavior along axis 1

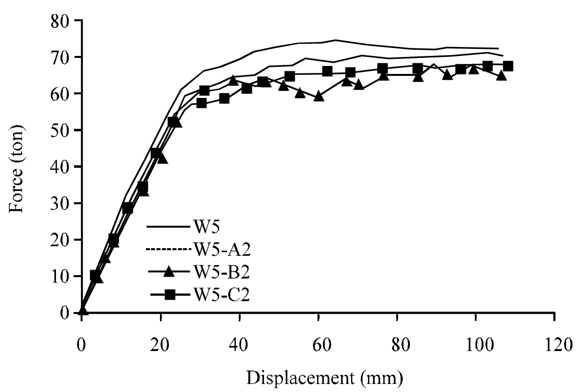

Fig. 20: Investigating models behavior along axis 2

of the status of opening along axis 1-3, all capacity curves in any direction are gathered in this section and shown in Fig. 19-21. Figure 19 represents the capacity curve of models W5, W5-A1, W5-B1 and W5-C1 having opening in vertical direction along axis 1. The structure response will be moderate and more reasonable in case of positioning the opening at B1 while positioning it at C1 will lead to minimum load bearing capacity.

On the other hand, force-displacement curve of the models W5, W5-A2, W5-B2 and W5-C2 having opening in vertical direction along axis 2 is shown in Fig. 20. Comparing the curves indicates that when the opening is positioned at B2 it will have the maximum load bearing capacity along axis 2 which is consistent with the reality, given its position at the center of the wall. If the opening is positioned at A2, its force-displacement curve won't have any significant difference with that of the model B2 until final failure. If the opening is located at C2 it will have the minimum load bearing capacity. Moreover, the capacity curve of models W5, W5-A3, W5-B3 and W5-C3 having opening in vertical direction along axis 2 is shown in Fig. 21. Comparing these curves illustrates that when

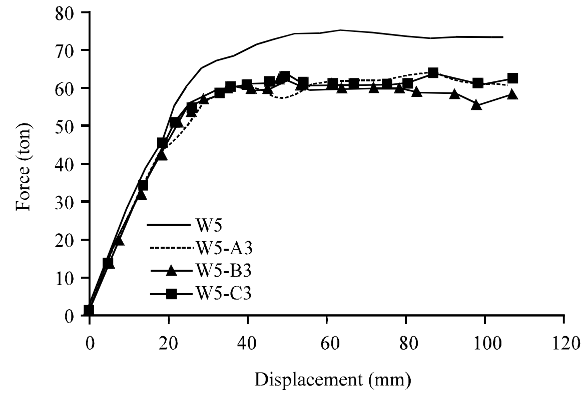

Fig. 21: Investigating models behavior along axis 3

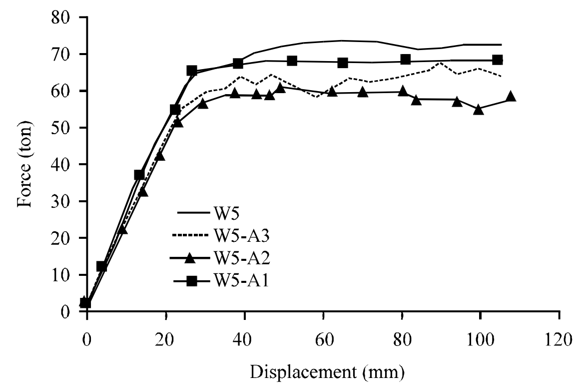

Fig. 22: Investigating models behavior along axis A

the opening is positioned at A3 or B3 the load bearing capacity along axis 3 doesn't differ significantly due to long distance from the point of applying force while positioning the opening at C3 will again lead to minimum load bearing capacity which is more critical compared to other samples.

Investigating the behavior of wall having opening along axis A-C: Similar to vertical direction, the status of changing opening position in horizontal direction along axis A-C is collected in Fig. 22-24 and monitored. Figure 22 represents the capacity of models W5, W5-A1, W5-A2 and W5-A3 having opening in horizontal direction along axis A. Comparing the curves illustrates that when the opening is positioned at A1 the load bearing capacity will increase due to addition of the lintel and consistency of the wall elements, so it will have no significant difference with the wall without opening. If the opening is positioned at A2, given the symmetry of the wall the load bearing capacity would be much higher than the case in which opening is positioned at A3. According to this Fig. 22, it can be concluded that since the direction of applying external loads such as the load due to

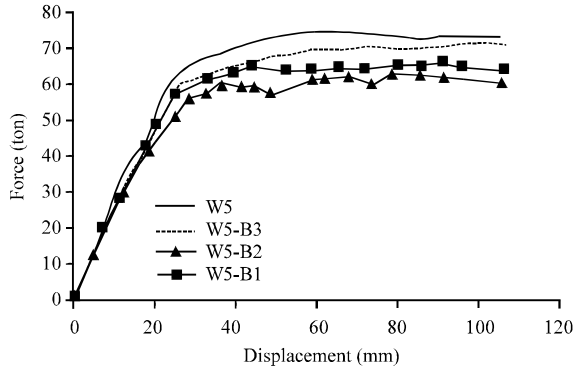

Fig. 23: Investigating models behavior along axis B

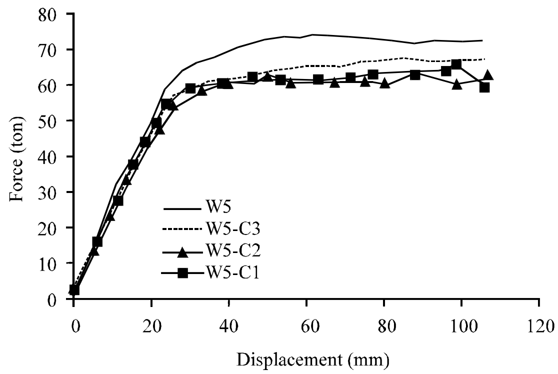

Fig. 24: Investigating models behavior along axis C

earthquake is unknown it would be better to position the opening along axis 2, i.e., the wall vertical symmetry line. The force-displacement curve of models W5, W5-B1, W5-B2 and W5-B3 having opening in horizontal direction along axis B is shown in Fig. 23. Comparing the curves shown in these three figs indicates that the curves associated with B1 and B2 don't have a significant difference until final failure and their load bearing capacity is also similar. If the opening is positioned at B3 it will have less load bearing capacity compared to the case when it is positioned at B1 or B2. The capacity curves of models W5, W5-C1, W5-C2 and W5-C3 having opening in horizontal direction along axis C is shown in Fig. 24. Comparing the force-displacement curves shown in these three figs illustrates that the curves associated with C1-C3 have similar behavior until final failure. However, the wall having opening at its center will have a greater load bearing capacity after final failure. It has to be noted that the load bearing capacity when the opening is positioned at C1 and C3 is significantly less than the case in which it is positioned at C2.

Base shear for models based on opening number and position: In order to investigate in-plate behavior of the walls having numerous square openings, dual openings of 1200 mm side length were positioned inside the wall, shown in Fig. 25. The position of openings mentioned above varies in horizontal direction along axis A, B and C. The capacity curve of models W5, W5-A2, W5-B2 and W5-C2 is shown is Fig. 25 based on which it can be argued that the load bearing capacity of the wall is maximum when the two openings are positioned in the horizontal axis of symmetry, i.e, axis B2. It is also clear that when the two openings are positioned along axis A, the load bearing capacity decreases significantly which indicates appearance of short column phenomenon similar to concrete structures. Therefore, in case of presence of multiple openings in a wall it is better to positing them in the central area of the wall.

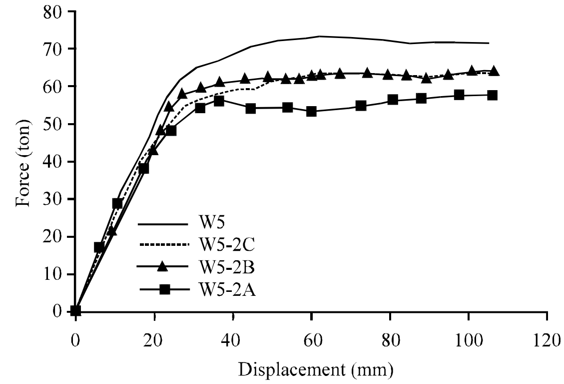

Fig. 25: Capacity curve of models having dual openings

CONCLUSION

Generally, most of the buildings in many of the countries around the world are masonry buildings. This kind of structures have a weak performance against lateral loads, especially earthquake. Therefore, studying and characterizing these structures in any region, considering the climatic conditions and relative risk of earthquake and investigating the possibility of fundamental reinforcement of these buildings and fixing their weaknesses is inevitable. Given the emergence of a new generation of finite element analysis software and lack of comprehensive studies on unreinforced masonry wall openings this study discussed optimal positioning of the opening in terms of capacity curve if the wall having opening and elaborated its 20 models. Generally, if a masonry wall has an opening it is better to position the opening at the wall's center of area, so that its capacity curve would be close the capacity curve of a wall without opening. The findings of this article acknowledged that the diagonal crack in model W5-B2 is greater than the diagonal crack appeared in all models having one opening whose force is 28 tons. The final failure in model W5-B2 also occurred at a force equal to 58 tons which indicates an 8% decrease in failure capacity compared to the case without opening. It is suggested that the compressive strength increases by increasing the opening distance from the corner. Since, this is a function of the direction of the force applied on the wall and also since the wall might be subjected to alterative forces of earthquake during its life cycle it is betted to position the opening as close to the wall center as possible, so that it would have a better performance. The same is true by increasing opening area (their number) and they show similar behavior in unreinforced masonry walls.

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REFERENCES

Abrams, D.P. and N. Shah, 1992. Cyclic load testing of unreinforced masonry walls: Technical report No. ACTC-92-26-10. Advanced Construction Technology Center Project titled NDE of Masonry Building, pp: 1-51.

Baloevic, G., J. Radnic, D. Matesan, N. Grgic and I. Banovic, 2016. Comparison of developed numerical macro and micro masonry models for static and dynamic analysis of masonry-infilled steel frames. Latin Am. J. Solids Struct., 13: 2251-2265.

Ghiassi, B., M. Soltani and A.A. Tasnimi, 2011. Seismic evaluation of masonry structures strengthened with reinforced concrete layers. J. Struct. Eng., 138: 729-743.

Hong, T.L. and D.F. Laefer, 2008. Micro vs. macro models for predicting building damage underground movements. Proceedings of the CSM-2008 International Conference on Computational Solid Mechanics, November 27-30, 2008, CSM, Ho Chi Minh City, Vietnam, pp: 1-10.

Kuroki, M., K. Kikuchi and H. Nonaka, 2010. Experimental study on reinforcing methods for window openings in confined masonry walls. Proceedings of th 35th International Conference on Our World in Concrete and Structures, August 25-27, 2010, Oita University, Oita, Japan, pp: 1-9.

Moghaddam, H., 2008. Seismic Design of Brick Buildings. Institute of Scientific Publications of Sharif University, Tehran.

NMPO., 2007. The office of technical affairs, developing the criteria and reducing the risk of earthquake, seismic rehabilitation guidelines for unreinforced masonry buildings. National Management and Planning Organization, Tehran, Iran.

UNIDO., 1984. Building construction under seismic conditions in the balkan region 3: Design and construction of stone and brick masonry buildings. United Nations Industrial Development Organization, Vienna, Austria. http://www.urbis-libnet.org/vufind/Record/ICCROM.ICCROM37895

Yanez, F., M. Astroza, A. Holmberg and O. Ogaz, 2004. Behavior of confined masonry shear walls with large openings. Proceedings of the 13th World Conference on Earthquake Engineering, August 1-6, 2004, WCEE, Vancouver, Canada, pp: 1-14.