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EFFECT OF OPENINGS AND ASPECT RATIO ON OVERALL PERFORMANCE OF RC FRAMED BRICK INFILLED BUILDING

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Abstract

India and nearby countries in Asia witness major earthquake in recent days and in past. Although after witnessing many earthquakes in past, for aesthetic purpose big window openings in wall and even whole brick wall replaced by glass can be seen in metro cities and suburban areas in cities of India. Opening and aspect ratio in wall plays great role in strength and stiffness of wall and overall behavior of building. Without understanding effect of openings and aspect ratio on strength, stiffness and behavior of wall it can be dangerous to use such practices in construction of building. In this research study, effect of opening and aspect ratio on overall behavior of building has been studied. This numerical study has been done by considering a RC framed brick infill wall using Applied Element method. Applied element method is capable of showing crack initiation, crack propagation till total collapse of building. This research study will focus on importance of placement of opening and consideration of aspect ratio for RC infilled brick masonry building.

Keywords: Brick masonry wall, Applied Element Method, aspect ratio, opening, strength

1. Introduction

In Past earthquakes in India; typical failures observed in brick masonry buildings are [1]:
a. Vertical cracks at wall junctions or failure at connection
b. Shear cracks or 45^0 bi-directional cracks in wall panels
c. Cracks due to in plane movement
d. Out of plane (flexure) failure of wall leading to collapse
e. Shear failure in RC columns

1.1 Past research on behavior of RC brick infill buildings:

To understand the behavior, failure pattern and damage to the brick masonry buildings; Analytical and experimental studies were carried out in past. This research study was done using numerical method so past research study focusing on analytical methods is given below.

1.1.1 Analytical Studies: Modeling methods:

For the analysis of masonry buildings basically three approaches were considered, that is; detailed micro modeling, simplified micro modeling and macro modeling. Detailed micro modeling considers the two components of masonry, brick and mortar separately. The interface represents a potential crack/slip plane with initial dummy stiffness to avoid interpretation of the continuum [2]. This approach provides detailed insight of the structural behavior but it is computationally costly [3]. In the second approach, mortar and brick properties are considered as combined and so brick masonry thus considered as a set of elastic blocks bonded by potential fracture/slip lines at the joints. In this approach, brick arrangement is kept as input variable of the analysis and therefore walls with discontinuities such as windows and door openings can be analyzed [2,4]. The third approach is macro modeling, it uses homogenization techniques which considers masonry as a periodic media i.e. elements arranged in uniform pattern.

Two stages of homogenization are used, one for the orthotropic material and the other for smeared cracking of the material [5]. Macro models are capable to analyze large structures, but it cannot consider discontinuities and details. Regardless of the type of modeling adopted the important failure mechanisms, characteristic of masonry, considered by Lourenco [2] are (a) Cracking in the joints; (b) Sliding along bed or head joints at low values of normal stress; (c) Cracking of the units in direct tension; (d) Diagonal tension cracking of the units at values of normal stress sufficient to develop friction in joints; (e) Splitting of the units in tension as a result of mortar dilatancy at high values of normal stress.

1.1.2 Masonry structures (URM and RM) and loading (static and dynamic):

Review on macro model: Macro model approach use simplified model of frame and panel to get overall behavior based on the physical understanding. In past research work in analytical studies, macro model developed as a diagonal strut model for infilled frame, it was based on the analytical work conducted by Polyakov (as reported by Mallick and Severn, 1967) [6]. Later, Holmes (1961) proposed that the equivalent diagonal strut should have a width equal to one third of the length of the panel and later Stafford Smith, (1962) improved the approach based on experimental data [7, 8]. Some methods were also proposed for predicting the approximate lateral stiffness of single and multi-storey frames. The equivalent width of strut was found to lie between 1/4th and 1/11th of the diagonal length, depending on the span to height ratio of the frame, Smith (1968) [8]. A study on the effect of openings and shear connectors in infill frames concluded that opening should not be there at either end of a loaded diagonal as strength will be reduced, Mallick and Garg (1971) [9]. Openings should be located in the middle third of the panel instead of near end, as opening help in transferring gravity loads of the portion above the opening by arch action which also prevents progressive collapse in such infill frames (Smith, 1967). Further work was continued by many other researchers, who refined the model, mainly by considering several struts to represent the panel, Crisafulli (2000) [10].

Effect of single strut and multi strut versus 4 node panel element was studied by Crisafulli (1997, 2007) [12,13] and it has been understood that If single strut is considered for the analysis, single strut resisting compressive and tensile forces cannot describe the internal forces induced in the members of the frame properly but when a 4 node panel element allows lateral stiffness of panel and strength of masonry panel, particularly for a shear failure along mortar joints or diagonal tension failure is expected. Strength and stiffness degradation with respect to opening and closing of masonry gaps was studied by Madan et al (1997) [14] for static non-linear analysis as well as dynamic analysis. Equivalent braced frames with infill walls were studied by Diptesh Das and C.V.R. Murty (2004) [15]. For the analysis and design of infilled frame subjected to in plane forces, a method is proposed based on equivalent diagonal strut approach by considering a single strut approach though it cannot capture local effects but at the same time it is useful for the analysis of large structures. So, the RC frames with unreinforced masonry walls were modeled as equivalent braced frames with infill walls replaced by “equivalent struts”. Reduction factor for effective width of diagonal strut was studied by Goutam Mondal and Sudhir K. Jain (2008) [16]. They proposed a reduction factor for effective width of diagonal strut to account for the central window opening in the infill reinforced concrete frame. Parametric study has been done to obtain lateral stiffness of infill frame with varying window opening. Two types of analysis methods considered, first is finite element method and single equivalent diagonal strut method. Finally, the width of equivalent diagonal strut for the single equivalent diagonal strut method is estimated so as to obtain the same lateral stiffness as estimated from the finite element method.

Review on micro model: Modeling of units as Elastic continuum elements were done by Page (1978) [17], initially units were modeled as elastic continuum elements, bonded with interface elements. Based on experimental study elastic interface (σ, τ) was developed. In the yield surface contains two compressions and one tension branch. The marked change in slope in compression corresponds to a change in the failure mode from pure shear failure in the joint to combined joint/unit failure.

Strain softening model for compression with a tension cut-off was proposed by Arya and Hegemier (1978) [19]. A von Misses strain softening model for compression with a tension cut-off was used for the units of a masonry considered. Joints were modeled with interface elements by incorporating cohesion and friction angle in softening and tension cut-off for brittle behavior. Experimental results on shear walls were checked with the collapse load obtained from the model. Analytical work has been done by Lourenco (1996, 1997) to incorporate all types of failure related to brick masonry [2, 18]. All the damage was concentrated in the relatively weak joints. The joint interface yield surface considered to include all the failure mechanisms except tensile cracking. Interface cap model was developed. The interface model includes a compression cap in which the complete inelastic behavior of masonry in compression is considered. Around same period, a continuum model has been developed by Gambarotta et al in 1996 for brick masonry [4]. In plane stress condition, the constitutive equations were developed. Brick masonry is considered as a stratified medium with two layers i.e. the mortar head joints and brick unit's representative layer and bed mortar joint layer.

In detailed study of brick joint action, a standard compressive test was performed by J.G. Rots, 1991. It has been observed that horizontal compressive stress arise in mortar and horizontal tensile stress arise in bricks and the later stresses govern ultimate failure under compression; also it has been studied that the mortar joint, the peak stress in brick amounts to 6.5 times the average stress and is likely to initiate cracking and spalling of brick and / or delamination along the brick / joint interface. (J. G. Rots, 1991) [20]. Later, a new homogenization technique to investigate the elastic-brittle behavior of masonry panels subject to incremental lateral loading has been investigated by Lee and Pande et al (1996) [21]. First brick units were homogenized with perpend joints to give equivalent elastic properties of a stacked system and then these stacked systems was then homogenized with the bed joints to obtain equivalent material properties for masonry. Jahangir Bakhteri et al (2004)[22] considered composite material for brick masonry which showed accurate stress distribution for the prism considered.

Around same period, In numerical modeling using AEM, Bishnu Pandey (2004) [23] observed that principal crack is dependent on the imposed displacement and not on the pre compression load. Also, when the mortar strength is higher; then the load carrying capacity of the wall also increases at all stages of loading. Effect of lintel band was also been studied. A significant effect in wall behavior was observed due to lintel especially on crack pattern. Crack appeared in wall without band is disappeared in wall with band. In case of transverse loading out of plane failure can be withstand by avoiding crack using lintel band. (Bishnu Pandey, 2004)[23]. Earthquake loading and effect of retrofitting was studied by Paola, 2006 [3]. The behavior of wall under monotonic lateral loading was studied by considering earthquake loading and sustainability of masonry building was studied after retrofitting. In their work as an advantage of AEM they could study the crack initiation, crack propagation till full collapse of building. Around same period Guragain et al [24], did the numerical simulation by AEM for brick masonry wall under lateral loads and especially cyclic loads in order to understand the behavior of brick masonry building in earthquake. Material model considered by him was the damage model proposed by Gambarotta et al (1997) [4] for cyclic loading case. The constitutive equation was based on damage mechanics and takes into account the mortar damage and the brick mortar decohesion which are considered to take place during crack opening and friction sliding along the interface. (Guragain also studied different failure behavior with respect to wall aspect ratio.

1.1.3 Experimental studies:

In past many experimental studies were done to understand the behavior of brick masonry buildings and collapse pattern and crack occurrences in the building and brick and mortar joints during earthquake [25]. Masonry wall can be considered in two ways depending on their functional use. First is bare wall and second is Infill wall. Different types of loading conditions considered in past experimental studies i.e. in-plane and out of plane loading, cyclic and dynamic loading, pseudo dynamic loading, quasi static loading etc. whereas in this study in-plane lateral loads are considered as research interest.

1.2 Applied Element Method

In AEM, structure is assumed to be virtually divided into small square elements each of which is connected by pairs of normal and shear springs set at contact locations with adjacent elements. These springs bear the constitutive properties of the domain material in the respective area of representations (Figure 1). Global stiffness of structure is built up with all element stiffness contributed by that of springs around corresponding element. Global matrix equation is solved for three degrees of freedom of these elements for 2D problem. Stress and strain are defined based on displacement of spring end points of element edges. Details of Applied Element scheme can be found in literatures [23,27, 28].

Flow chart of the numerical scheme is as given in Chart 1. [23]

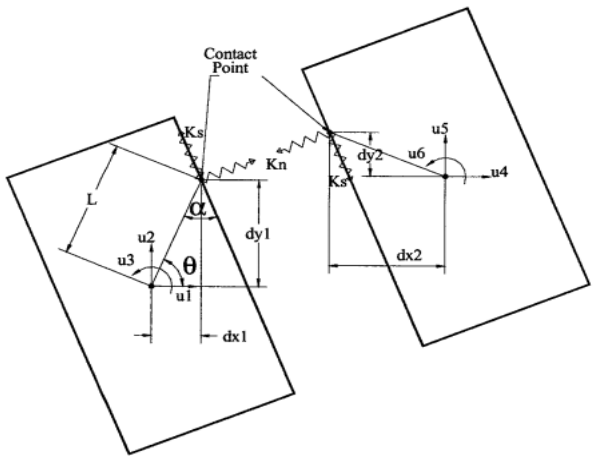

Fig. 1 Element shape, contact point and degrees of freedom [6]

1.2.1 Discretization for brick masonry:

Anisotropy of the masonry is accounted by considering masonry as a two phase material with brick units and mortar joint set in a regular interval. Structure is discretized such that each brick unit is represented by a set of square elements where mortar joints lie in their corresponding contact edges (see Figure 2).

In spring level, springs that lie within one unit of brick are termed as ‘unit springs’. For these springs, the corresponding domain material is brick as isotropic nature and they are assigned the structural properties of brick. Springs that accommodate mortar joints are treated as ‘joint springs’. They are defined by equivalent properties based on respective portion of unit and mortar thickness.

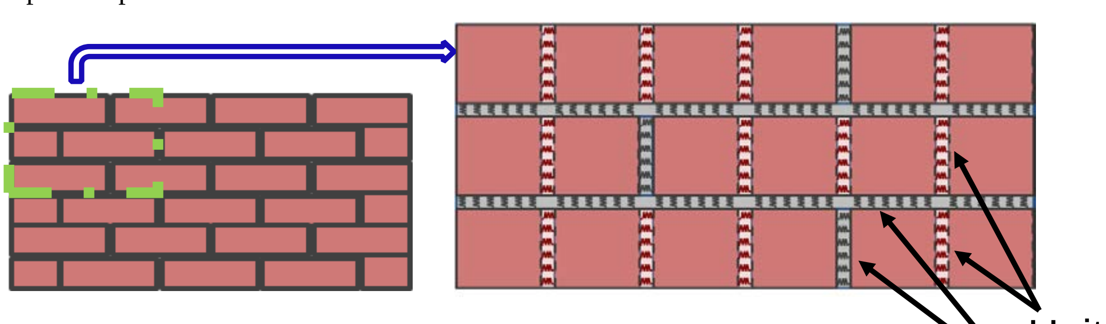

Fig.2 Masonry discretization: Details of brick unit spring and mortar joint spring

Figure 2 shows the configuration of brick units, joints and their representation in this study. The initial elastic stiffness values of joint springs are defined as in Equation 1 and 2 [23].

$$K_{nunit} = \frac{E_u\ t\ d}{a};\ \ K_{njoint} = \frac{E_u\ E_m t\ d}{E_u \times t_h + E_m(a - t_h)} \tag{1}$$

$$K_{sunit} = \frac{G_u\ t\ d}{a};\ \ K_{sjoint} = \frac{G_u\ G_m t\ d}{G_u \times t_h + G_m(a - t_h)} \tag{2}$$

Where E_u and E_m are Young's modulus for brick unit and mortar, respectively, whereas G_u and Gm are shear modulus for the same. Thickness of wall is denoted by 't' and 't_h' is mortar thickness. Dimension of element size is represented by 'a' and 'd' is the fraction part of element size that each spring represent. While assembling the spring stiffness for global matrix generation, contribution of all springs around the structural element are added up irrespective to the type of spring. In the sense, for global solution of the problem, there is no distinction of different phase of material but only their corresponding contribution to the stiffness system.

1.2.2 Masonry material model

Material model used is a composite model that takes into account of brick and mortar with their respective constitutive relation with elastic and plastic behavior of hardening and softening. Brick springs were assumed to follow principal stress failure criteria with linear elastic behavior. Once there is splitting of brick reaching elastic limit, normal and shear stress are assumed not to transfer through cracked surface in tensile state. The brick spring's failure criterion is based on a failure envelope given by Equation 3:

$$\frac{f_b}{f_b^{'}} + \frac{f_t}{f_t^{'}} = 1 \tag{3}$$

Where f_b and f_t are the principal compression and tensile stresses, respectively, and f'_b and f'_t are the uniaxial compression and tensile strengths, respectively.

Coulomb's friction surface with tension cut-off is used as yield surface after which softening of cohesion and maximum tension takes place in exponential form as a function of fracture energy values and state variables of damage. The cohesion and bond values are constant till the stress first time when stress exceeds the respective failure envelopes. Figure 3 and 4 shows the degradation scheme of bond and cohesion. Failure modes that come from joint participation of unit and mortar in high compressive stress is considered by liberalized compression cap as shown in Figure 5. The effective masonry compressive stress used for cap mode follows hardening and softening law as shown in Figure 6. The tension cut-off, f_1, and the sliding along joints, f_2, exihibit softening behavior whereas the compression cap experiences hardening at first and then softening. The failure surfaces used in this study derived from Lourenço, (1997)[2], with some simplification are as given in Equations (4), (5) and (6). (Figure 6)

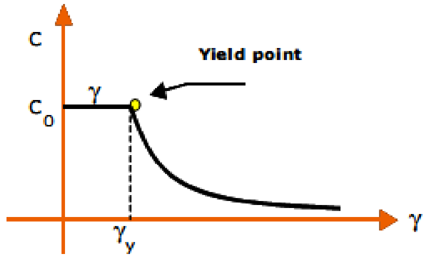

Fig. 3 Cohesion degradation [23]

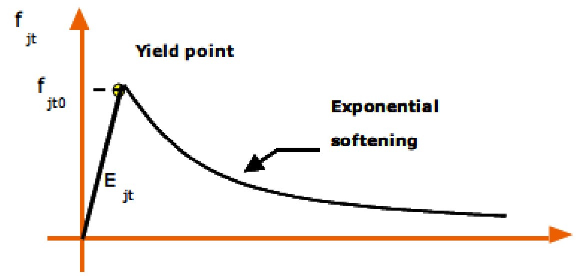

Fig. 4 Bond degradation [23]

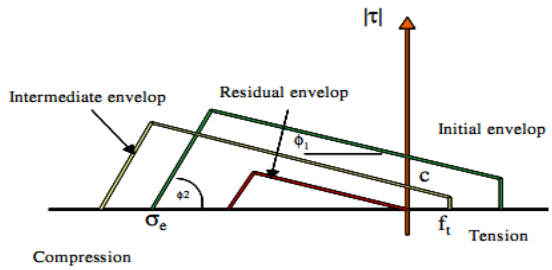

Fig. 5 Failure criteria for joint spring [5,9]

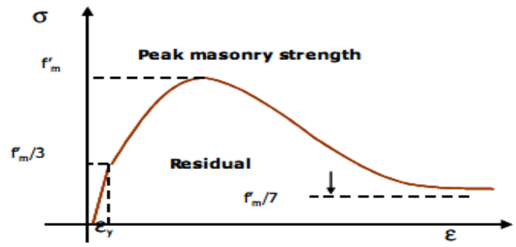

Fig. 6 Hardening and softening for joint spring in compression cap [5]

$$f_1(\sigma, K_1) = \sigma - f_t \ \exp\left(-\frac{f_t}{G_f^I} K_1\right) \quad (4)$$

$$f_2(\sigma, K_2) = |\tau| + \sigma \ \tan(\phi_1) - c \exp\left(-\frac{c}{G_f^{II}} K_2\right) \quad (5)$$

$$f_3(\sigma, K_3) = |\tau| + \sigma \ \tan(\phi_2) \{(\sigma_3(K_3) - \sigma)\} \quad (6)$$

In above equations K_1, K_2 and K_3 are hardening and softening parameters for tension, shear and compression behavior respectively. $G^I{}_f$ and $G^{II}{}_f$ is fracture energy in tension and shear respectively.

1.2.3 Material model for concrete and steel and Failure criteria can be referred in literature [23].

Numerical scheme: Spring characteristics of concrete, masonry and interface are taken into separate consideration before assembling their stiffness contribution to the corresponding element centroids. Displacement vector obtained from global solution has been assigned to corresponding spring to get the spring force in proportion to their stiffness. In this stage, participation of masonry and concrete in interface region has been given consideration to derive the stress in both parts of material.

2. Analytical Study of URM building using AEM

2.1. Specimen Structure geometry and loading details

2.1.1 Description of geometry:

Building considered for the analysis is as shown in Figure 3.11. Building height is 4m and width is 3.9m. Column and beam cross section is considered as 0.3m X 0.3m. Reinforcement is provided as per the requirement. Brick wall panel has dimension of 3.3m X 3.7m X 0.3m. Brick size is considered as per the local brick in practice in India.

In this study, initially a framed wall building (see Figure 3.11) with reinforcement (see Figure 3.12 (a) and (b)) is considered and it has been studied under displacement control cases for Monotonic static condition. Displacement control is capable to give the response of building in post yield. Response of the Infill wall in terms of Base shear versus drift ratio is plotted and structures behavior is studied through this response.

2.1.2 Loading Parameters:

A displacement control technique for monotonic static case has been considered, as this method is capable of giving post peak behavior. A lateral displacement of 0.02m is applied in 100 increments on the wall.

2.2 Studies Considered:

Two parametric studies have been considered in this analysis.

i. Effect of aspect ratios

ii. Effect of openings

i. Effect of aspect ratios

In order to study effect of aspect ratio (h/w) on strength of the wall, four cases have been considered in this analysis as shown in Figure 10. Aspect ratio (h/w) of 0.5, 1.0, 2.0 and 4.0 is considered and displacement of 0.02m is applied laterally in 100 increments.

ii. Effect of openings

In order to understand the effect of openings on behavior of wall, an Infill wall of size 3.9m X 4.0m is considered for the analysis. Five cases were considered for the study. In first case, full infill wall without opening is considered. In second case, opening in the centre of wall has been considered. In third case, door opening on left side is considered whereas in fourth case door opening in the middle has been considered.

2.2.1 Effect of Aspect ratios

In order to study effect of wall aspect ratio (h/w) on strength of the wall, four cases have been considered in the analysis as shown in Figure 7. Aspect ratio (h/w) of 0.5, 1.0, 2.0 and 4.0 has been considered and displacement of 0.02m is applied laterally in 100 increments.

Geometry, boundary conditions and loading are as given below:

Geometry: Geometry is as shown in Figure 7

Boundary conditions: Base elements are considered as fixed

Loading conditions: Displacement control used.

0.02m displacement applied in 100 loading steps

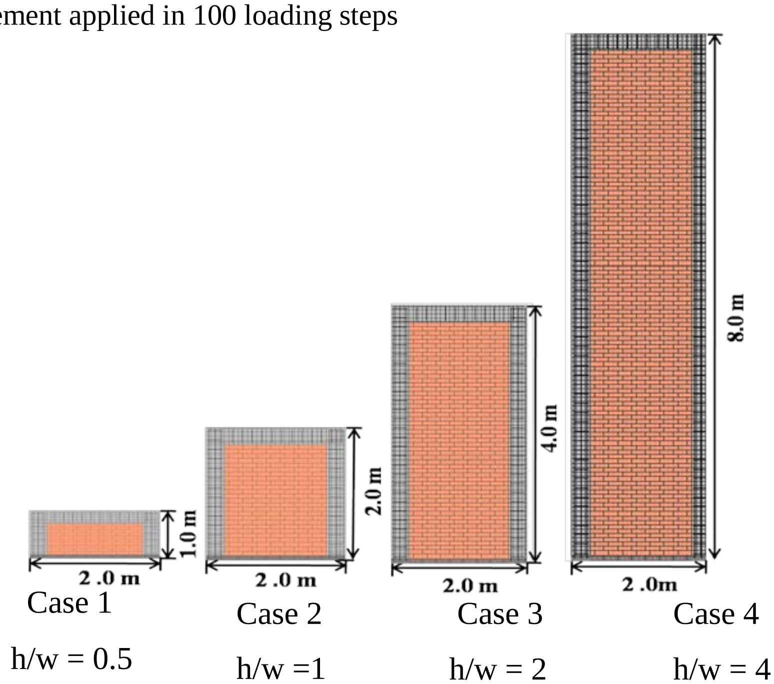

Fig. 7 Aspect Ratio considered case 1,2 3 and 4

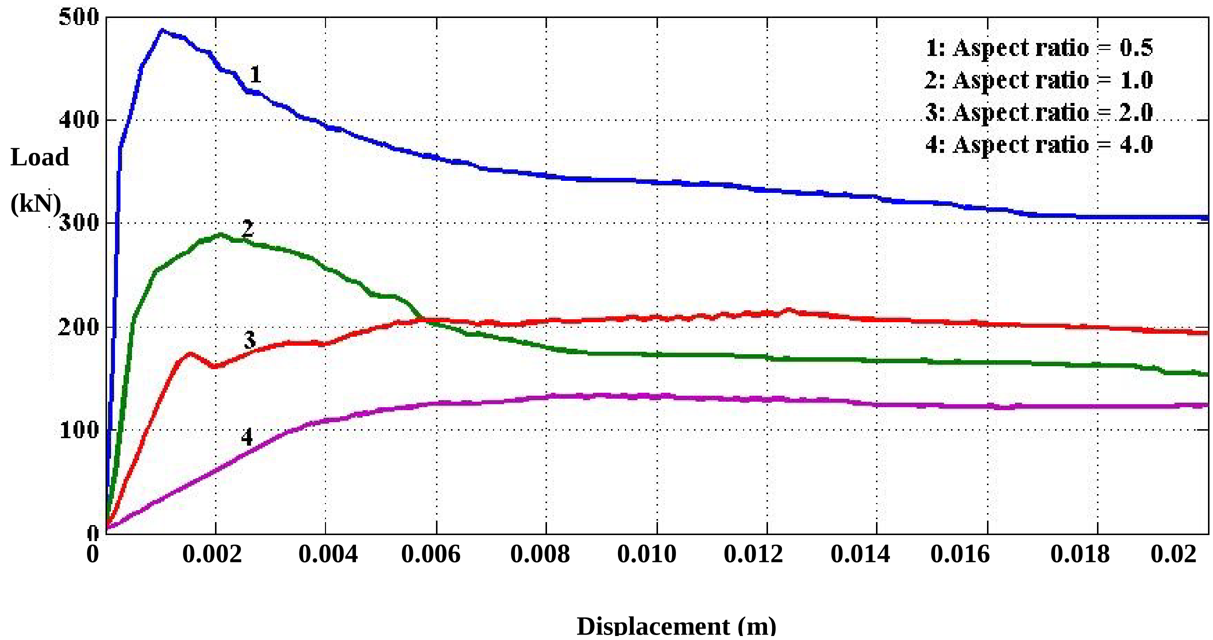

Fig. 8 Effect of aspect ratio on Wall strength

Aspect ratio plays important role in providing stiffness and strength to the wall. If aspect ratio is less (see case 1) i.e if height is less than length of the wall, wall stiffness and strength is much higher because under lateral load displacement is very less due to less height. Shear is predominant in this case. Less aspect ratio gives more load carrying capacity to the wall as shown by curve 1 in Fig.8.

In case 2, height is equal to length of wall i.e. aspect ratio is 1. In this case, as height of the wall increased; under lateral load; strut action can be observed and shear is predominant. Load carrying capacity is decreased by 40% when compared to case 1. So when aspect ratio for particular cases is changing from 0.5 to 1; strength of the wall reduces to 60% for 50% increase in aspect ratio for the first two cases.

In case 3, height of the wall is 4times more than case 1. Under lateral load strut action cannot happen due to more height but shear is still predominant here. Strength of the wall is reduced to 35% when compared to case 1 and it is reduced to 60% when compared to case 2. So for increase in aspect ratio from 0.5 to 2; strength is reduced by 65% when compared with case 1 and 3.

In case 4, height of the wall is 8 times more than length of wall. Aspect ratio for such slender wall considered as 4. Due to high aspect ratio wall is predominant in bending. Its strength is reduced to 25% when compared with case 1. So when aspect ratio is increased by 8 times strength is reduced by 75%. For such cases horizontal bands are needed to strengthen weaker section.

From this analysis, it can be observed that increase in aspect ratio contributes in reduction in strength and stiffness of wall. We can say that aspect ratio is inversely proportional to strength of the wall for the cases considered in this study.

2.2.2 Effect of openings

In order to understand the effect of opening on global behavior of wall, an Infill wall of size 3.9m X 4.0m is considered in the analysis. Four cases were considered for the study. In first case, full infill wall without opening is considered. In second case, opening in the centre of wall has been considered. In third case, door opening on the left side is considered whereas in fourth case door opening in the middle has been considered. Geometry, boundary conditions and loading are as given below (Figure 9 and 10):

Geometry:

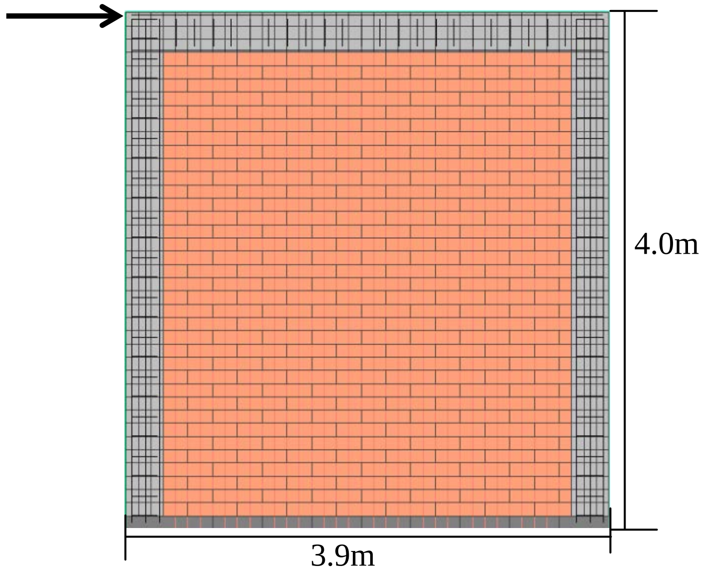

Fig. 9 Numerical model of brick infill wall

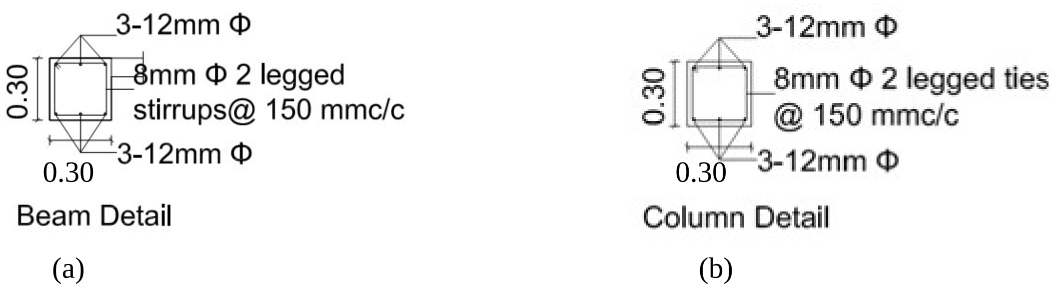

Fig. 10 Reinforcement details for (a) Beam (b) Column

Boundary conditions: Base elements are considered as fixed

Loading: Displacement control used. 0.02m displacement applied in 100 loading steps.

Details of opening considered:

Case1: Infill wall of size 3.9m X 4m without opening

Case 2: Central opening of size 1.2m X 1.2m

Case 3: Door opening of size 1.0m X 2m

Case 4: Door opening of size 1.0m X 2m

Figure 11 shows base shear versus drift ratio relation for the four cases considered.

For case 1, wall considered was without opening for the comparison with rest of the cases. In this case under lateral loading wall is capable to take load easily till 350kN. It almost shows linear behavior till this load with minor cracks. It can be clearly seen that infill wall without opening having more load carrying capacity due to more strength and stiffness of wall when compared with other cases.

For second case central opening is in the center of the wall. Load carrying capacity of the wall is reduced by 50% due to central opening. In this case, at first diagonal zigzag cracks arise along opening in compression diagonal, as loading increases these cracks progress further. Shear is predominant in this case; central opening in wall makes it weaker. Strut action is not effective enough, as lateral load acting on wall due to opening ;

strut action is not complete.

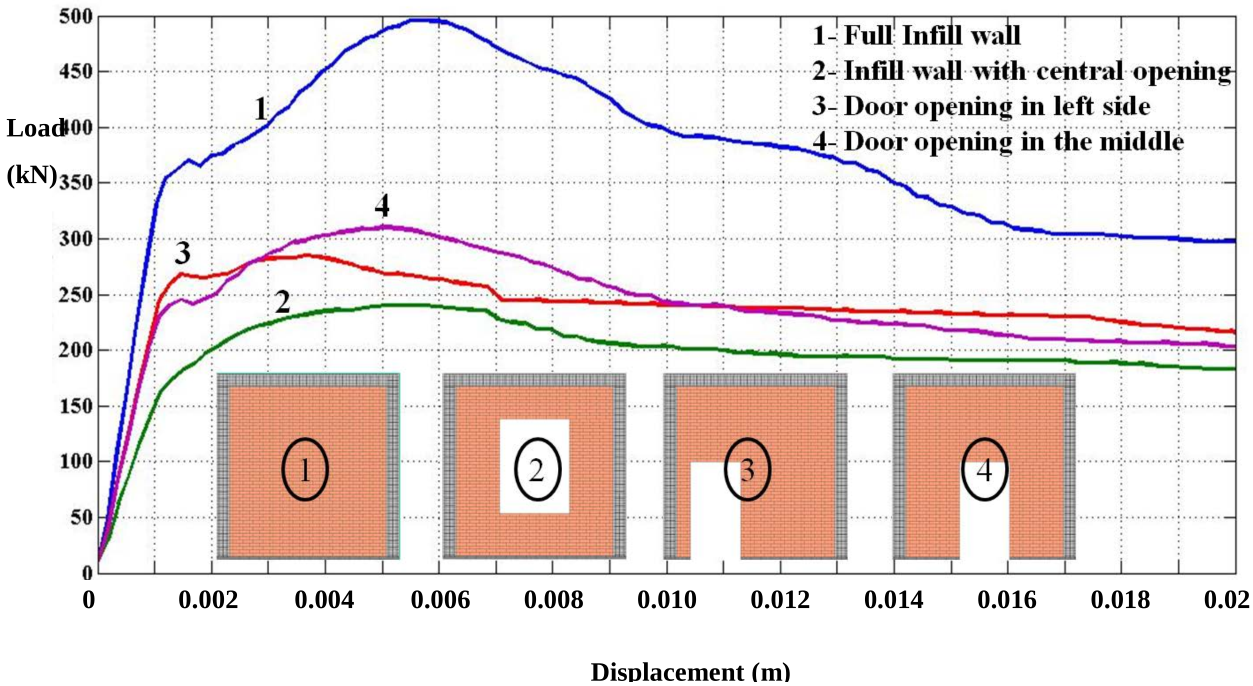

Fig. 11 Effect of opening on capacity of Wall

For case 3, door opening is in left side, which makes brick wall perform better than second case. In case 3, at the initial stages of loading; wall shows better load carrying capacity (270kN)(Curve no. 3) as opening does not fall in the middle of the tension diagonal but in later stages stiffness of the wall is continuously decreasing due to weaker pier at the left side where stresses are more at the base. Overall strength of wall due to opening in left side is reduced by 46% when compared to case 1.

For case 4, positioning of door is considered in the middle, cracks initiated in the left diagonal at first due to which load carrying capacity decreased initially in curve no. 4, but as loading increases, load is distributed in both the piers which makes wall to carry more load (310kN), but at later stage decrease in strength and stiffness can be seen due to progressing cracks in piers due to tensile stress. Load carrying capacity of the wall decreased by 36% when compared with case 1.

3. Conclusions:

This research study has been done for the particular Aspect ratio and openings in wall. Aspect ratio and openings in wall plays important role in providing stiffness and strength to the wall. From this study it can be concluded that if aspect ratio is less (see case 1) i.e. if height is less than the length of the wall then wall stiffness and strength is much higher because under displacement is very less due to less height and shear is predominant in this case. Less aspect ratio gives more load carrying capacity to the wall as shown by curve 1 in Fig.8.

In case 2, height is equal to length of wall i.e. aspect ratio is 1. In this case, as height of the wall increased; under lateral load; strut action can be observed and shear is predominant. Load carrying capacity is decreased by 40% when compared to case 1. So when aspect ratio for particular cases is changing from 0.5 to 1; strength of the wall reduces to 60% for 50% increase in aspect ratio for the first two cases.

In case 3, height of the wall is four time more than case 1. Under lateral load strut action cannot happen due to more height but shear is still predominant here. Strength of the wall is reduced to 35% when compared to case 1 and it is reduced to 60% when compared to case 2. So for increase in aspect ratio from 0.5 to 2; strength is reduced by 65% when compared with case 1 and 3.

In case 4, height of the wall is 8 times more than length of wall. Due to high aspect ratio wall is predominant in bending. Its strength is reduced to 25% when compared with case 1. So when aspect ratio is increased by 8 times strength is reduced by 75%. For such cases horizontal bands are needed to strengthen weaker section.

From this analysis, it can be observed that increase in aspect ratio contributes in reduction in strength and stiffness of wall. We can say that aspect ratio is inversely proportional to strength of the wall for the cases considered in this study.

Position of opening in walls plays important role in overall strength and stiffness of wall. Window Opening in centre of wall reduces strength of wall by 50%; whereas door opening in left side of wall reduces strength of wall by 46% and door opening in the middle of the wall reduces strength to 36% when compared with the strength of the wall without any opening.

For case 1, wall considered was without opening for the comparison with rest of the cases. It almost shows linear behavior till this load (350kN) with minor cracks. It can be clearly seen that infill wall without opening having more load carrying capacity due to more strength and stiffness of wall when compared with other cases.

For second case central opening is in the center of the wall. Load carrying capacity of the wall is reduced by 50% due to central opening. Shear is predominant in this case; central opening in wall makes it weaker. Strut action is not effective enough, as lateral load acting on wall due to opening; strut action is not complete.

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