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Finite Element Modeling of Shear Strength of Infilled Frames with Openings

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ABSTRACT

Masonry infilled frame structure used in high rise buildings are frequently under the influence of lateral loads as a result of wind loads and earthquake forces. Most designers ignore the contribution of openings in masonry infill panel in the reduction of the shear strength of the infilled frames. In this paper the finite element modeling technique is used to model the shear strength of brick masonry infilled frames with different sizes and configuration of position of openings. The results obtained from the present analytical technique are compared against that from experimental test results in order to validate the model. Hence this model can easily be effective in the wind and seismic vulnerability analysis of reinforced concrete infilled frames with openings.

Keywords: *Finite element method, Masonry infilled frames, Openings, Shear strength*

1. INTRODUCTION

The interaction mechanism between an infill wall and the surrounding structural frame depends on the area of contact at the interfaces of the two components. Thus, the extent of composite action will depend on the level of lateral load, degree of bond or anchorage at the interface, and the geometric and stiffness characteristics of the two components [1].

Small scale tests [2],[3] of infilled reinforced concrete frames showed that, for a very strong infill, the columns can fail in shear. The researchers suggested that anchorage of the masonry infill to the surrounding frame would prevent separation and force the failure to take place in the masonry without causing premature shear/ flexure failure of the column. Full scale cyclic tests of single story steel frames infilled with clay tile masonry were conducted [4] to study seismic response. Typical results show the pinched shape of the hysteretic loops with two predominate stiffnesses. For small displacements, the infill-frame hysteretic loop was similar to that of the bare frame. This may indicate that a small gap existed between the infill wall and the frame. Recent test [5] of multistory small-scale infilled RC frames confirm the same pinched shape and two predominate stiffnesses of the hysteretic loops.

Various approximate methods have been proposed by researchers, the simplest and most highly developed being that based on the concept of equivalent diagonal struts, originally proposed by Polyakov [6] and subsequently developed by Stafford-Smith [7] Tests of small-scale two story infilled reinforced concrete frames [8] under simulated earthquake loads concluded that the diagonal strut analogy would yield reasonable prediction of lateral response. In this method, the system is modeled as a braced frame where the infill walls provide the web elements (equivalent diagonal struts). The geometric properties of the diagonal struts are functions of the length of contact between the wall and the columns, and also between the wall and the beams. Contact lengths ranging from one-fourth to one-tenth of the length of the panel are expected. Holmes [9] recommended that the width of the diagonal strut be equal to one-third of the diagonal length of the panel, whereas the New Zealand Code [10], specifies a width equal to one quarter of its length.

Also, assuming a beam on an elastic foundation, equations have been proposed [6],[7] to determine the relative stiffnesses of the beams, columns, and infill.

Once the geometric and material properties of the struts are calculated, conventionally braced frame analysis can be used to determine the stiffness of the infiIled frames, the internal forces, and the deflections. However, analytical models based on elastic behavior fail to reproduce the inelastic hysteretic characteristic under cyclic loads and cannot be used to determine system ductility.

The strut force obtained from the truss analysis is used to check the capacity of masonry infill walls. Although there is the possibility of crushing at the ends of the diagonal strut. Dhanasekar and Page [11] showed that the tensile and shear bond strengths of the masonry are critical to the behaviour and ultimate load capacity of infill frames. A more accurate approach is to check the state of stress in the strut at the center of the panel using an appropriate failure envelope that accounts for the inherent anisotropy of masonry, the planes of weakness along bed and head joints, and the orientation of the joints with respect to the principal stresses [12]. Because a shear-slip failure along a bed joint can double the shear in the column and result in a brittle failure with overstressing of adjacent columns, the design must ensure that the shear bond strength along these joints will not be exceeded. However, where masonry has a low shear strength along the bed joints or the designer has reason to believe that the masonry may fail prematurely along a bed joint, an analysis based on the knee-braced frame concept [10],[13] should be performed to assess the impact that this premature failure would have on the performance of the infilled frame structure. Alternatively, especially for high seismic areas, the infill should be reinforced to prevent shear-slip failure.

Infill walls frequently contain openings of different sizes and locations. The effect of small openings for running conduits, cables, and ducts and of openings outside the diagonal struts, may be negligible. However, in assessing the effect of openings, it should be noted that when the load reverses, the other diagonal of the panel becomes a strut. Dawe and Seah [2] studied the effect of openings in masonry infilled panels in frames. The load-deflection curves indicate that the openings greatly reduced stiffness and load-carrying capacity compared to infill walls without openings. This is attributed to the opening interfering with the diagonal bracing action, thereby causing premature shear failure of the sections on either side of the opening. Failure in many cases was initiated by separation of the wall from the frame on each side of the opening. For a particular specimen, the inclusion of steel reinforcement around the opening increased the initial stiffness, but did not increase the ultimate load. For another specimen, with the opening located away from the load, diagonal cracks developed and the partial strut that developed resulted in a slightly higher ultimate load than for openings located nearer to the load. For this reason, and because lateral load is usually applied in both directions, it appears that the best solution is to locate the door opening at the center of the wall.

Other experimental studies show that centrally placed openings in square panels can reduce the stiffness of in filled frames by as much as possible and the ultimate load of the panel by up to 40% [13],[14].

Development of simple analytical procedures for infill frames with openings is not easy to accomplish due to the many parameters that affect the behavior, including wall geometry and the location, shape, and size of openings, hence it had been recommended that masonry infill with openings be designed in the same way as shear walls in a load bearing masonry building, with shear distributed to the parts in accordance with their rigidities; and with each part designed for the appropriate self-weight, shear, and bending moment.
Again where previous experimental research on the response of RC frames with masonry infill walls subject to static and dynamic lateral cyclic loads [15], [16] have shown that infill walls lead to significant increases in strength and stiffness in relation to bare RC frames. Considering conventional seismic design, which focuses on accelerations and strength, it may be difficult to recognize the benefits of increases in stiffness. However, research and field evidence [17]-[19] has shown that increases in stiffness are beneficial because they lead to reductions in the magnitude of the deformations induced by ground motions.

Most multistory building are under the influence passive vertical loads which comes upon the beam and very active lateral loads which may be due to wind and earthquake forces which must be taken into account in the formulation of building codes. The shear stress state of a structure should be estimated which can develop to critical lateral sway state of the infilled frame with or without openings, while it can be deduced that the infill panels improves the shear strength of the frame, their contribution is often ignored because of lack of knowledge of the behaviour of the composite frame and the infill. However, while extensive experimental research on rigid infilled frames have been made by [20],[21],[23] and analytical investigation by [24]-[28], the aims of this work is to investigate the redistribution of shear stress of masonry infilled plane frames using an analytical finite element technique and considering the influence of the size and position of openings in the infill panel to the shear strength of the composite frame and infill material.

2. THEORETICAL ANALYSIS

To properly carry out this research work, a two-dimensional finite element model for the micro-modeling of infilled structures using constant strain triangular elements will be developed to analyze the shear strength response of the masonry infilled reinforced concrete frame structure with different sizes and positions of openings and validated against the available experimental and numerical data for nonlinear static analysis of infilled frames subjected to in-plane lateral loading. After, obtaining the result of the finite element model, a one-strut model also proposed by the author is adopted and modified to consider the effect of a special case of a central window openings on the shear strength behaviour of infilled frames. This model would be easily employed in seismic vulnerability analysis of existing frames having infill panels with openings.

2.1 Finite Element Method of Analysis for a Continuum

For the purpose of the finite element analytical study of masonry structure, the triangular elements shall be used and the formulation that would be adopted is the displacement approach. In using this method the nodal displacements are the basic unknown, while the stresses and strain are assumed constant for each element.

The basic steps of this method are summarized as follows:

- The continuum is separated by imaginary lines or surfaces into a number of finite element.
- The elements are assumed to be interconnected at a discrete number of nodal points situated on their boundaries.
- The displacements of these nodal points will be the basic unknown parameters of the problem.
- A function is chosen to define the state of displacement within each finite element in terms of its nodal displacements.
- This displacement functions now define uniquely the state of strain in terms of the nodal displacement, which will in turn together with the elastic properties of the material definite the state of stress throughout the element and hence, also on its boundaries.
- Considering the forces concentrated at the nodes and equilibrating the boundary stresses and any distributed loads, a formulation of the stiffness matrix of the element is obtained and hence the global (complete) stiffness matrix of the whole continuum is obtained.
- Setting up and solving the final equilibrium equations for the whole structure and considering the boundary conditions to give the nodal displacement.

The finite element method of analysis used for this work would involve voluminous numerical works which will be considerably simplified by matrix formulation of the whole problem which is suitable for computerization.

For the purpose of this masonry infilled reinforced concrete frame analysis, the formulation used will be the displacement approach. In using this method the nodal displacements are the basic unknown, while the stresses and strains are assumed constant for each element. The basic approach is to obtain the triangular element stiffness matrix for a plane stress problem is well documented. We will only present some essential features in this work.

The element stiffness matrix $[K^e]$ would be a 6 x 6 matrix for this plane elasticity triangle shown in Figure 1, because there exist a two degree of freedom (DOF) at each node of the triangular element hence the Nodal force vector $[F^e]$ can be related to the displacement vector in equation 1.

$$\{F^e\} = [K^e]\{\delta^e\} \quad (1)$$

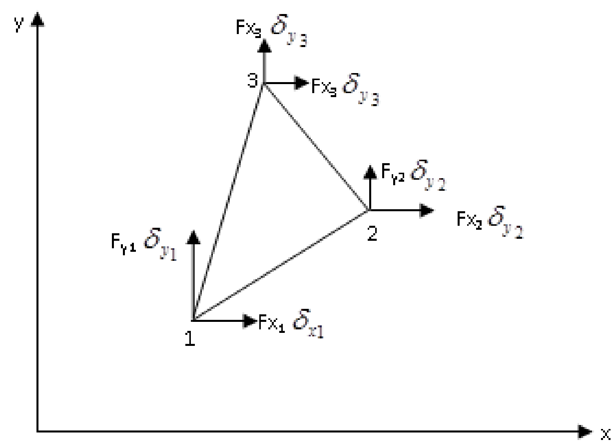


Figure 1: Two dimensional triangular element typical of that used in plane stress problems.

Hence a two dimensional displacement patterns may be expressed in terms of two linear polynomials as

$$\delta_x = \alpha_1 + \alpha_2 x + \alpha_3 y \quad (2)$$

$$\delta_y = \beta_1 + \beta_2 x + \beta_3 y \quad (3)$$

Where α_i and β_j are constants which may be determined from the co-ordinates of the model points of the elements.

This can be simplified as

$$\{\delta\} = |C|\ \{\alpha\, \beta\}$$

Rearranging to give coefficient

$\{\alpha\, \beta\}$ in terms of the displacements

$$|C|^{-1}\ \{\delta\} = \{\alpha\ \beta\} \qquad (4)$$

A simplified expression can be obtained for the strains in the elements as a function its geometry

$$\{\varepsilon\} = |H|\ \{\alpha\, \beta\} \qquad (5)$$

Equation 3 and 4 can be combined to obtain

$$\{\varepsilon\} = |H|\ |C|^{-1}\{\alpha\} \qquad (6)$$

hence $|B| = \ |H|\,|C|^{-1}$

where [H] represent the stress – displacement matrix . The stress-strain relationship depends on the material of the element, hence considering the mechanical properties of the material the matrix D can be obtained as hollows

$$D = \begin{bmatrix} \dfrac{E_x}{1 - v_{xy}\ v_{yx}} & \dfrac{E_x v_{yx}}{1 - v_{xy}\, v_{yx}} & 0 \\ \dfrac{E_y v_{xy}}{1 - v_{xy} v_{yx}} & \dfrac{E_y}{1 - v_{xy} v_{yx}} & 0 \\ 0 & 0 & E_y \big/ 2\,(1 + v_{yx}) \end{bmatrix} \qquad (7)$$

Where E_x and E_y represent modulli of elasticity in the x and y direction respectively V_{xy} and V_{yx} represents poisson's ratio in the xy and yx plane respectively.

The overall interrelationship between nodal forces and applied stresses may be written in simplified matrix form as

$$\{F\} = |A|\ |\sigma| \qquad (8)$$

Where $|\sigma|$ in the component of normal stress (σ_x, σ_y) and shear stress (τ_{xy}) and matrix $|A|$ contains constant dimensional values then the stiffness matrix for the triangular element can be formed since the matrix $|D|\ and\ |B|$ are also available.

$$|k^e| = |A|\ |D|\ |B| \qquad (9)$$

The stiffness matric $|k^o|$ for a single triangular element in thus a 6 x 6 matrix, hence when a structure is modeled by a large number of triangular elements, the global stiffness matrix becomes extremely large and can only be handled by a suitable computer programme such as the visual basic computer programme for the micro modeling of infilled frame structure developed by the author.

3. STRUCTURAL MODELING OF INFILLED FRAME STRUCTURE

Detailed experimental results of specimens have been summarized in [2]. Among several specimens tested under lateral load in their investigation specimen WC3 would be singled out for this present investigation. The specimens is a single panel of 3600mm long by 2800mm high masonry infilled frame with a 0.8 x 2.2m central opening. This particular specimen corresponds to model MIP04 of this work. The basic method was to allow a horizontal load increase up to failure load and applied at the upper corner of the Reinforced concrete infilled frame. From the foregoing the values obtained from experimental test would be compared with result of finite element analysis on the micro model in order to validate the model.

3.1 Consideration of Size of Openings on the Shear Strength of Infilled Frame Structure

In order to investigate the effect of the size of openings on the lateral strength and stiffness of infilled, reinforced concrete frames, a parametric study would be conducted using the finite element analysis on the infilled brick masonry. The effect of the opening size on the shear strength would be studied for values of parameters denoted by □ and □n which is defined as percentage of the opening area to the solid infill panel area and ratio of the infill panel strength with openings to that without openings respectively.

Hence a number of one-story one-bay infilled structure with varying size of opening would be analyzed using finite element method aided by the suitable computer program code. A typical structural micro model for the analysis is shown below (Figure 2) with a 30kN horizontal load acting at the top corner of the infilled reinforced concrete frame structure.

In order use a suitable mechanical property for masonry, values have been obtained by the author via experiment work during doctorate research work. See Table 1.

Table 1: Material elastic properties

Material	Moduli of elasticity		Poisson's ratio	
	E_x (kN/m^2)	E_y (kN/m^2)	V_{xy}	V_{yx}
Concrete	2.9 x 10^7	2.9 x 10^7	0.20	0.20
Masonry	4.4 x 10^6	7.41 x 10^6	0.22	0.33

To conduct properly this investigation the central opening of a one-bay infilled structure is varied, but with particular interest on opening ratio of 0-25%. The following structural models tagged M1P01-M1P05 would be considered with each model having a particular percentage opening in the infill plane.

MIP01 = 0%
MIP02 = 5%
MIP03 = 10%
MIP04 = 17%
MIP05 = 25%

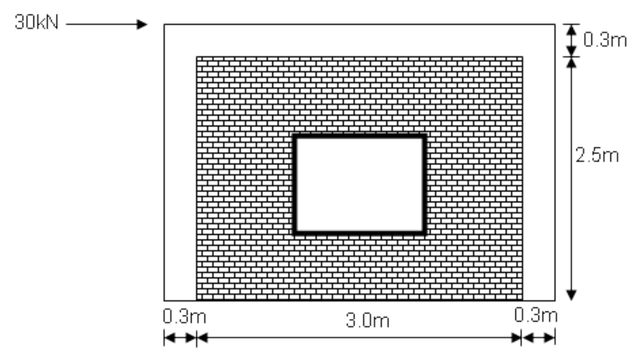


Figure 3: Infilled reinforced concrete frame structure with central opening

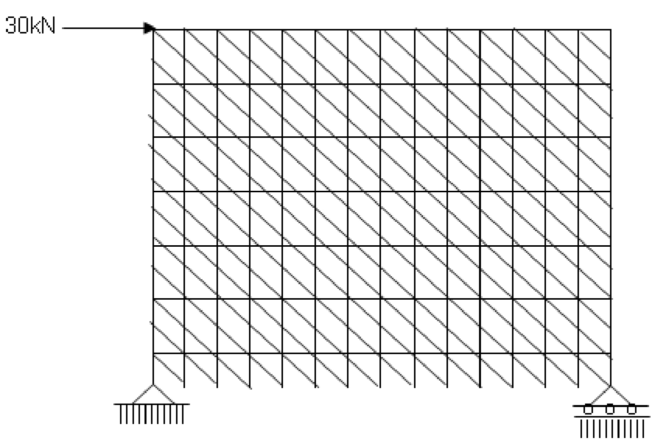


Figure 4:Triangularly meshed micro-model ready for finite element analysis

From the result of the finite element analysis the values of shear strength reduction factor λ_m would be plotted against the values of the opening percentage β. Later a consideration may be made using the shear strength factor λ_m to stimulate the equivalent width of the compressed diagonal strut, for the macro-modeling of infilled frame structure with openings.

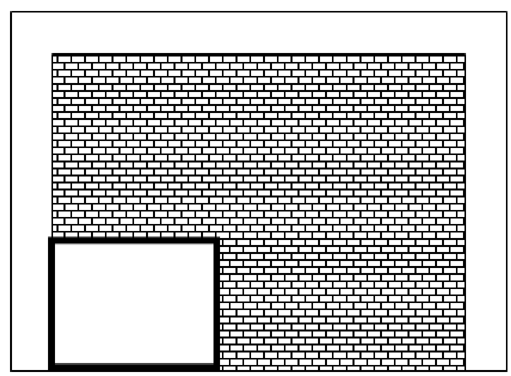
3.2 Consideration of the Effect of Position of Opening on the Shear Strength of Infilled Frame

By investigating the varying configuration of the positioning of openings in the previous models (M1P01-M1P05) the effect on the shear strength of infilled frame is thus studied for the following cases as is displayed in Figure 5

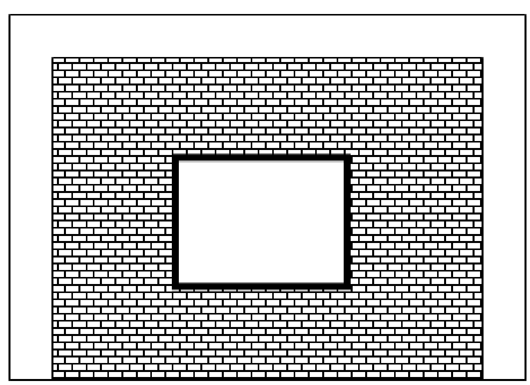
a. Opening position is underneath the compressed diagonal

b. Opening position is just on the compressed diagonal

c. Opening position is above the compressed diagonal



(a)



(b)

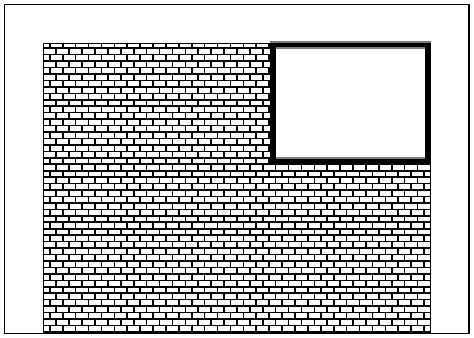

(c)

Figure 5: Different configuration of opening position on an infilled frame structure

4. COMPUTER PROGRAMME FORMULATION

In other to implement the finite element method, a computer programme for two dimensional finite element analysis developed by the author would be used. The computer programme is divided into two parts (subroutines). The first part consists of the routines for the control numbers and data input modulus, the second part consists of routines for tabulated nodal displacements and element stresses. The basic steps to obtain the element stiffness matrix $[K^e]$ and stress matrix [H] have already been discussed in details and would involve voluminous numerical work, hence this processes were well built up in the subroutines to take care of the overall analysis. The input data consists of specifying the geometry of the idealized structure, its mechanical properties, the loading and the support condition. The data also includes certain control numbers that would help the efficiency of the program such as the total number of nodes and elements.

THE INPUT data for the micro-model is as follows:

a. Nodal point coordinates indirection x and y for each node.

b. Element properties: This includes the mechanical properties E and v for masonry and concrete in two directions x and y, the thickness (t) of the structural model and any other data defining each element, and the structures as a whole e.g. the percentage opening.

c. Boundary conditions: These consist of the restraints of the nodes of the supports and the stiffness of the elastic supports

d. Loading: Consists of the component of the lateral load placed at the top Conner of the structure.

THE OUTPUT consists mainly of

a. The components of displacements $\{\delta\}$ at each node in the directions x and y and the maximum displacement (δ_{max}) for a the model

b. The stresses in each element as follows

- Component of normal stresses (σ) in the directions X and Y
- The shearing stress (τ_{xy})
- The maximum shear stresses τ_{max}

The bulk of the input data for the finite element micro-modelling of masonry infilled structure will consist mainly of coordinates of nodal points and element properties. The typical structural model for the validation of micro-model would consist of 216 elements and 218 nodal points. Note that manual development of the mesh would entail considerable expenditure of time and labour, hence the mesh generation subsidiary programme would aid the generation of this mesh and the corresponding coordinates of the nodal points of the elements automatically. The output from this subsidiary programme consists mainly of

- Coordinates x and y of all the nodal points numbered in a consecutive order.
- Element properties for all the triangular elements generated and numbered in a specific order.

These outputs are then used as input data for the main programme.

5. DISCUSSION OF RESULTS

The complex state of stress induced in the structural models subjected to shear loads was studied by finite element analysis in this work. The state of displacement at any point of the structure in two directions δ_x and δ_y at any point of the structure is obtained. Also the components of stresses σ_x, σ_y and τ_{xy} was also obtained, with particular interest on the maximum shearing stress. A study of the distribution of these stresses reveals that the state of stress induced has a controlling influence on the failure of the infilled frame structure. More information about the failure criterion of the structure can be obtained by the loading history of the structure. Hence, to investigate the shear response of the structure, the shear stress path for any point on the structure is studied by observing the shear stress τ_{xy} against the normal stress σ_x from zero shear load upto a reasonable failure load obtained by the finite element elastic analysis on the solid infilled frame structure.

The study of the distribution of these stresses for the rigid frame reveals that the state of stress induced has an effect on the failure criteria of the infilled panel. The distribution of the normal and shear stresses from the result outputs, are seen to be in good agreement with previous experimental results by [20] and previous analytical works by [28]. The results indicate higher values of stresses in zones around the compressed diagonal and the loaded corners. Hence two modes of infill failure are readily observed from the results. The first failure mode is observed as higher stresses that will initiate cracks extending from the center of the infill along the diagonal towards the loaded corners, while the second failure mode occurs at the loaded corners and the extent of the crushed region limited to the length of contact length.

Also, load displacement curve obtained from finite element analytical modeling of MIP04 model was seen to be similar to the experimental data obtained by Dawe and Seah [2] as shown in Figure 6 in order to validate the finite element software for the micro-modeling of masonry infilled concrete frame structure with openings.

The maximum value for shear stress τ_{xy} for the different models considered can be obtained from the result of finite element analysis. These results show that the shear stress τ_{xy} is a function of factors such as the applied lateral force the dimensions and the elastic properties of the structure. Hence, more general formula for shear strength and hence ultimate shear load will consist of one which includes such variables.

In other to investigate the effect of opening size and the its position on the shear strength of masonry infilled frames; a study was conducted for various values of a parameter denote by β and λ_m as defined previously in section 3.1. To this end the infilled frame structural models with central openings denoted as MIP01, MIP02, MIP03, MIP04, MIP05 corresponding to 0-25 percent openings are analyzed. The central openings are considered to be square in shape. The structural models are subjected to lateral loads which could be the result of seismic forces, and a finite element analysis of the models carried out to determine the effect of opening sizes on the lateral strength of masonry infilled frames. Here the estimated shear strength factor λ_m (defined as the ratio of infilled panel strength with opening to that without opening) is used for comparison of the numerical data obtained.

A number of one-story one-bay infilled structures with varying size of the central opening were analysed to investigate the relationship between the shear strength factor and the opening percentage using the visual basic computer software developed. The structure was studied under a 30kN horizontal loading with a similar uniform load distribution in the surrounding frame and the infill wall surface.

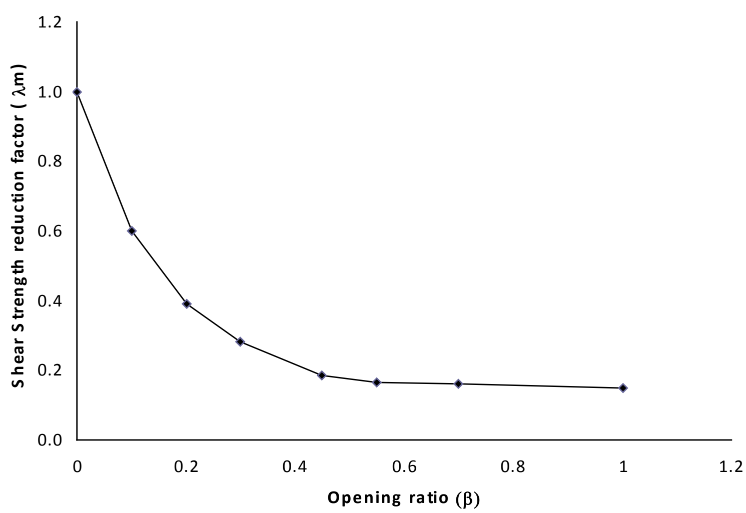


Figure 6: Variation of shear strength reduction factor of infilled frame with opening ratio for a case of central opening.

The influence of the position of the opening to the shear strength of the infilled frame was studied by considering varying configuration of the opening position on the infilled panel as shown in Figure 5 in section 3.2. Figure 7 shows the influence of the opening position on the shear strength reduction factor. The result shows that there is higher value in the shear strength reduction of the frame if the opening is upon the composed diagonal, and this explains the significance of the compressed diagonal to the shear strength of the frame. It can also be seen that at very low value of the open ratio in case C, the shear strength reduction factor tends to unity and this can be explained by the result of higher value of the column and infill contact length on the section of the frame facing the lateral force.

A reasonable regression equation can be obtain relating λ_m to β for a case of central opening on the compressed diagonal.

$$\lambda_m = 0.95e^{0.03\beta} \qquad (9)$$

The strength reduction factor λ obtained for the different cases of opening sizes in Figure 7 and 8 can be used to improve the estimation of the equivalent width of the compressed diagonal to account for effect of openings.

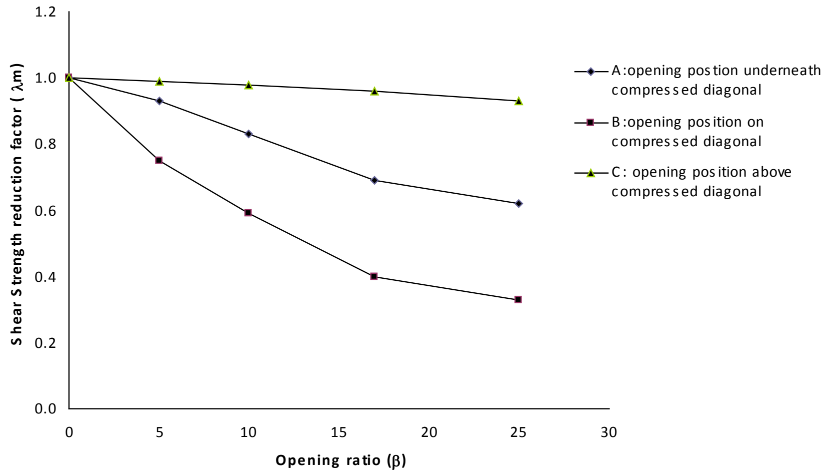


Figure 7: Variation of shear strength reduction factor λ_m of infilled frame with opening ratio for different position of opening.

6. CONCLUSION

This work presents a simple method of micro modeling of the complicated behaviour of infilled frames under lateral loads. Using the finite element analytical technique supported by a useful computer programme software developed by the author the behaviour of single-storey single-bay to multi-storey single-bay masonry infilled frames under lateral loads has been investigated. With the help to these model, the shear strength response of masonry infilled frames with varying opening ratio of the infilled panel and the different configuration of the positioning of the openings have been modeled.

The proposed finite element analytical technique is easier and very practical to apply and requires much less computational time that other techniques based on discretizing the infill panel as a series of plane stress elements interconnected by a series of springs or contact elements.

From the forgoing a study of the shear response of brick masonry infill panel on the behaviour of infill frame structure subjected to in-plane lateral load has proved the following:

- The shear strength of infilled frames is reduced with an increase in the opening ratio of the infill panel. For a frame without infill panel the decrease in the shear strength may reach 75%.
- The shear strength reduction factor may remain relatively constant as the opening ratio exceeds 0.5
- The decrease in the lateral displacements in a multi-storey structure, as masonry infill panels are introduced, suggests an increases in the shear strength of the frame.
- It is important to consider the effect the infill walls has on the shear strength response of the frame as the case of rigid frame shows about 70% decrease in the lateral displacement values obtained.

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