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REVIEW OF INFILL WALL MODELLING TECHNIQUES: MACRO AND MICRO MODELS

***a* Fatima Khalid*, *b* Samra Masood**

a: Department of Civil Engineering, NEDUET, Karachi fatimak@neduet.edu.com
b: Department of Civil Engineering, NEDUET, Karachi samasood@neduet.edu.com
* Corresponding author: Email ID: fatimak@neduet.edu.com

Abstract- Infilled masonry frames are integral part of reinforced concrete (RC) structures for almost 200 years. They are present in interior and exterior walls in both RC and Steel frames all around the world. The interaction of infills with the surrounding frames has a major influence on the structural response of the full composite structures. Their most influential property is that of a high initial stiffness and considerable strength. However, even today during the design process and during the assessment of the existing structures they are considered as non-structural members and their contribution in the structural response is overlooked. Numerous researchers have considered the influence of infills on the response of RC structures in the recent past and the need for inclusion of these members in the design and assessment of structures has been recognized. This study therefore aims to provide a thorough review of the work of several researchers to include the in-plane effect of infill panels in the behavior of RC frames.

Keywords- macro modelling, micro modelling, infill walls

1 Introduction

Buildings all over the world are usually designed without considering role of masonry wall enclosed within beam and columns known as infilled walls. With the advancement of research, it was found that infilled walls increase lateral strength and stiffness of the frame. However, if frames are not properly designed for aforementioned criteria, then it will eventually increase the risk of collapse. Despite of this, even today RC structures are designed without considering infill walls due to its complexity in modelling and giving the correct behavior. Therefore, still significant research considering the behavior and modelling of infill are in study[1], [2]. FEMA seismic assessment is usually carried out to see the behavior of building under earthquake loadings and considering all the aspects that are usually ignored in design.

In this study, a detailed review of existing techniques to model infill walls were conducted. Only in-plane behavior of infill walls for modelling was considered in this study. In Section 2 and 3, macro and micro models were discussed, respectively. Finally, conclusions were made in last section.

2 Macro Models

2.1 Equivalent Strut Model

Polyakov [3] has first replaced infill wall by an equivalent pin-jointed diagonal strut after conducting experiment on steel frames. The main properties required to model the diagonal strut is masonry material models in compression and the area of the strut. To find area of the strut different researchers has proposed the equivalent width of strut depending on infill aspect ratio and mode of failure of infill. The thickness for the strut is considered to be equal to the wall thickness.

Holmes [4] and Smith [5]proposed equivalent strut model with effective width of 33% of diagonal length of infill panel and different width for masonry panel ratio respectively. Smith [6] has proposed that effective width varies from $1/4^{th}$ and $1/11^{th}$ of diagonal length of infill panel for square and panels having aspect ratio of 5:1, respectively. Smith [6] further introduced stiffness parameter, λ_h which incorporate interaction between frame and infill in term of width as shown in (1) and (2), respectively.

$$\lambda_h = \sqrt[4]{\frac{E_m t \sin 2\theta}{4E_c I_c h_m}} \qquad (1)$$

$$w = 0.58\left(\frac{1}{H}\right)^{-0.445} (\lambda_h H')^{0.335 d_z \left(\frac{1}{H}\right)^{0.064}} \qquad (2)$$

Mainstone [7] proposed an empirical relation (3) based on λ_h which resulted in reduced value of effective width than proposed by [6]. Therefore it underestimated the lateral stiffness of the uncracked RC section as mentioned by Mehrabi [8].

$$w = 0.175 d_z (\lambda_h H')^{-0.4} \qquad (3)$$

Kadir [9] has introduced new parameter λg (4) that needs to be incorporated while calculating width of strut.

$$\lambda_g = \sqrt[4]{\frac{E_m t \sin 2\theta}{4E_c I_g h_m}} \qquad (4)$$

$$w = \frac{\pi}{2}\left(\frac{1}{4\lambda_h^2} + \frac{1}{4\lambda_g^2}\right) \qquad (5)$$

Hendry (1990) presented that single strut width equals to half the width proposed by [6]. Paulay [10] concluded that wider strut width make structure stiffer resulting in higher seismic forces. Therefore, the proposed width was considered same as Holmes (1961) of diagonal strut

Liauw [11] studied that openings present in infill will affects the stiffness and strength of infills. Experimental and analytical study have been done to study the response of non-integral infilled frames incorporating material nonlinearities and proposed strut width as (6). FEMA has provision that infill wall with 25% opening do not need to be considered for equivalent compressive strut behavior.

$$w = \frac{0.95 h \cos\theta}{\sqrt{\lambda_h H'}} \qquad (6)$$

Decanini [12] provide several expressions for calculating effective strut width and concluded that with an increase in load, the strut width decreases significantly. Dawe [13] have proposed the formula based on Smith's and Kadir [9] λ_h and λ_g parameters. (7)

$$w = \frac{2\pi}{3}\left(\frac{\cos\theta}{\lambda_h} + \frac{\sin\theta}{\lambda_g}\right) \qquad (7)$$

Durrani [14] provided an equivalent strut width semi-empirical formula (8) based on geometry of frame without considering relative stiffness parameter.

$$\frac{w}{d} = \gamma \sin 2\theta \qquad (8)$$

$$\gamma = 0.32\sqrt{\sin 2\theta}\left((h^4 E_w t_w)/m E_c I_c h_w\right)^{-0.1} \qquad (9)$$

Where

$$m = 6\left(1 + \frac{6E_b I_b h}{\pi E_c I_c L}\right) \qquad (10)$$

E, *I* and *h* represents Elastic modulus, second moment of mass and height. The subscripts *b*, *c* and *w* denote beam, column and wall, respectively.

Amato [15] proposed initially single concentric strut element that does not consider the local effects. Further, to incorporate local effects eccentric element was used. It also considers the influence of masonry dilation on the strut width. [16]has proposed the effective width formula as shown in (11)

$$w = 1.414 \frac{\pi}{2\lambda_h} \qquad (11)$$

Yekrangnia [17] proposed a single strut model to incorporate both local and global behavior of infill panels. Kumar [18] proposed single strut model for structures present in Pakistan with effective width equals 18% of diagonal length of infill wall.

2.2 Multiple Strut Model or Eccentric Model

Single strut model is not capable of producing the correct bending moment and shear force diagram. Increasing number of struts give better representation of internal forces as proved by Crisafulli et al. (2007). Zarnic [19] proposed an equivalent strut model based on their experimental results of 28 specimens of masonry infilled frames subjected to lateral cyclic loading. In this model, the diagonal strut is not connected to the beam-column joint to show the damage in the upper zone of masonry panel which behaved as a captive column i.e. more free to deform. Syrmakezis et al. [20] proposed multiple struts model and Schmidt (1989) proposed 2 struts which are not parallel to each other. Whereas Chrysostomou [21] proposed a 6 strut model, 3 parallel struts for compression and 3 parallel strut for tension as shown in Figure 1. The off diagonal struts are positioned by parameter α that represents the fraction of the length or height of the panel. San Bartolomé [22] proposed 9-strut model for the infilled frame structure. El-Dakhakhni [23] proposed macro-model for concrete masonry infilled steel frames with 3 struts (one diagonal and two off-diagonal) for masonry panel as shown in Figure 2. The total area for the three struts is shown in (12).

$$A = \frac{(1-\propto_c)\propto_c ht}{\cos\theta} \qquad (12)$$

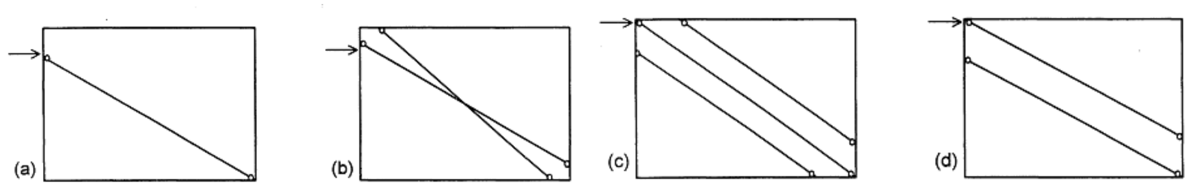

Figure 1 a) Zarnic et al. [19] *b) Schmidt (1989) c) Chrysostomou* [21] *d) Syrmakezis et al.* [20]

Thiruvengadam [24] proposed a complex model for dynamic analysis of infilled frame. In this model, infill was replaced by set of equivalent multiple struts which accounts for both frame-infill separation and infill openings. Fiorato [8] proposed "knee braced frame" to represent the masonry infilled behavior.

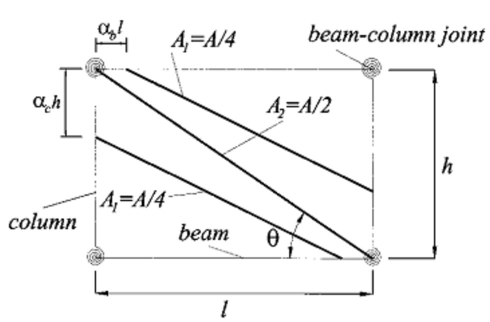

Figure 2 El-Dakhakhni [23] *macro model*

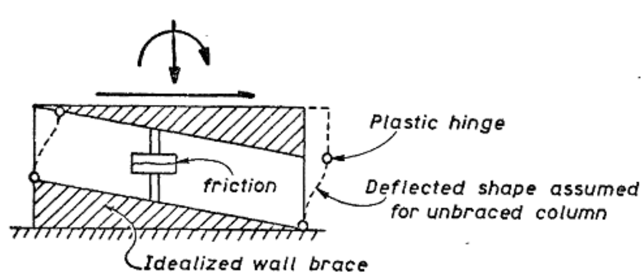

Figure 3 Leuchars et al. [8] *model*

2.3 Strut Model with Friction Element

Leuchars [8] proposed a double strut model with a friction element as shown in Figure 3. This model was portraying the internal forces including bending moment and shear in columns as well the friction mechanism along the cracks. This was just a hypothetical model that was never implemented.

Crisafulli [19] researched on three models as shown in Figure 4; single strut, double strut and three strut models. It was concluded that single strut model is not capable of capturing the local effects whereas multiple strut models can overcome this problem. Single strut model provides an adequate estimation of stiffness of the frame. But for refined analysis, multi strut models should be used without significant increase in the complexity.

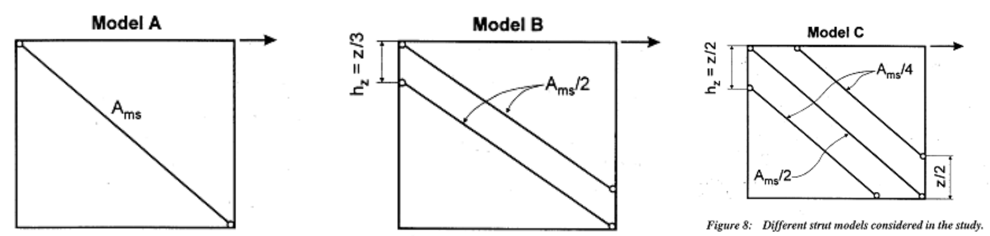

Figure 4 Proposed model for study by [19]

Further [19] proposed a new multi-strut model with shear spring as shown in Figure 5. This model accounts separately for compressive and shears behavior of masonry panel. This model depicts better the shear failure along mortar joints or diagonal tension failure when expected. The stiffness for whole masonry panel is divided into shear and axial compressive strut. This model is implemented in Ruaumoko (Carr, 2002) and SeismoStruct [25] software

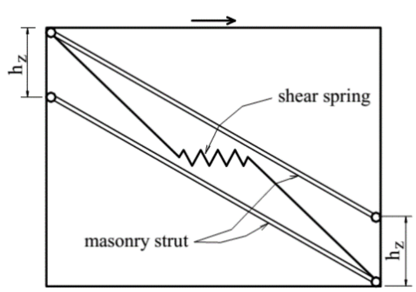

Figure 5 Crisafulli & Carr (2007) model

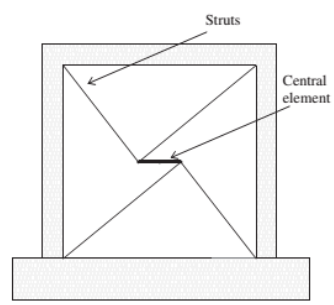

Figure 6 Rodrigues et al. (2010) model

Rodrigues [26] proposed an improved equivalent bi-diagonal compression strut model with a central strut element for representation of hysteretic behavior of masonry infill panels (Figure 6). Masonry panel is defined by 4-strut elements having rigid behavior and a central element where nonlinear hysteretic behavior is concentrated. This central element has purely compressive or tensile nature. The proposed model considers hysteretic behavior, strength and stiffness degradation, pinching, damage evolution and function of deformation demands, and implemented in Open Sees [27].

Samoilă [28] investigated several formulations for width of equivalent diagonal strut present in literature to find the best model. It has been concluded that the Paulay [10] formulation is the most appropriate choice, due to its consistency and simplicity.

Islam [29] used an open source computer program, STERA 3D to model infill frame with macro-element masonry (IFM2). They also discretized using a combination of nonlinear bending and shear springs together with axial and shear spring for frames and infills, respectively. A good match in the dataset was observed as the model was validated with existing literature.

Saneinejad and Hobbs [30] developed an inelastic analysis and design method using an equivalent diagonal strut for infill steel frames. Kakaletsis and Karayannis [31], also used equivalent strut model to assess the lateral resistance of masonry infilled RC frames with openings. Thiruvengadam [24] and Chrysostomou [32] introduced multiple struts to model infill walls and Klingner and Bertero [33] studied the behavior of RC block infilled reinforced concrete frames under cyclic loading. El-Dakhakhni [34] suggested the stiffness and the ultimate load capacity of concrete masonry infilled steel frames failed by corner crushing using an analytical approach. Mohyeddin [35] showed that even for same infill frames the strut properties can change for different values and location and number of struts can vary from infill to infill. Kareem and Panto [36] compared existing strut model and introduced 2D discrete macro model.

Srechai [37] developed a multistrut model based on experimental tests. Fiber-section truss elements are used for struts and equivalent stress-strain parameters were used to incorporate all potential failure modes. Empirical formulas were developed and calibrated based on experimental and statistical analysis. Their reliability was assessed through blind validation tests of empirical formulas and proposed model. Monotonic and cyclic load simulations of the infilled RC frames for single and multiple bays were conducted and compared with experimental results.

3 Micro Models

In micro-modeling, infill panels are modeled at different levels in detail using finite elements: mortar, bricks, and mortar/brick interface (Figure 7). It shows the behavior at local level so all possible modes of failure can be observed. It is the most accurate representation of infill panel behavior. But the computation time is high for large structures and numerous parameters need calibration.

Micro modeling can be further divided into three levels. The basic idea behind these levels is the variation in computational effort and accuracy [38].

1. Detailed Micro Modeling: In this approach, the continuum elements are used to model brick and mortar joints whereas interface between the brick and mortar is modelled by an interface discontinuous element.
2. Simplified Micro Modeling: In this approach, the continuum elements also known as expanded units are used to model bricks and joint and brick mortar interface is modeled using an interface element at mid thickness of mortar layer.
3. Homogenized Modeling: In this method, brick, mortar, and their interface is modeled as a homogenous continuum.

The level of micro modeling depends on level of refinement required in the research. The detailed micro-modeling approach is the most comprehensive approach in all modeling. It is precise for studying the local behavior of infill panels for both linear and non-linear behavior. But its modeling requires high level of knowledge of different parameters which require large number of tests. Apart from this, its computation time is highly consuming. On the other hand, the simplified micro-modeling or homogenized modeling is accurate for computing linear behavior of infills.

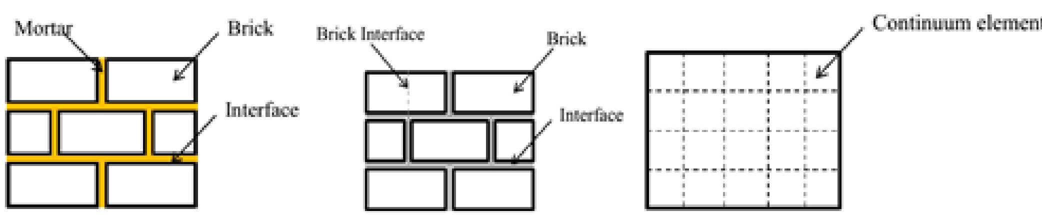

Figure 7 a) Detailed Micro Modeling b) Simplified Micro Modeling c) Homogenized Modeling

Several researchers worked on finite element modeling and presented different constitutive models to represent each unit of masonry wall. Firstly, Mallick [39] applied finite element approach as a micro modeling to address the issue of representing interface between frame and infill. It was modeled by contact elements but was not able to transfer tensile forces. Liauw [40] proposed a plastic approach in which three separate types of elements were used to study the behavior of infill frames. Three failure modes were identified which captures the corner crushing with failure in columns, beams and diagonal crushing of the infill. A very close agreement has been observed between experimental and analytical results. Achyutha [41] investigated the elastic behavior of single storey infilled frame with opening. Slip, separation and contact conditions were modeled by single link elements at interface. The opening was also modeled by using very low value of thickness and modulus of elasticity of masonry. It was found that larger the opening, lesser will be the lateral stiffness of the structure. Dhanasekar [42] developed a model for brick masonry wall in which non-linear isotropic six-node elements were used for both the mortar and the bricks . The mortar joints are modeled as one-dimensional joint elements between infill and frame. Ali [43] proposed a finite element model similar to [42] having 4-node quadrilateral elements with a finer mesh near the loading point. This proposed model can be used for any brick mortar combination with any bond pattern. Mehrabi [8] proposed a complex constitutive model for modeling masonry joints interfaces. Compressive hardening behavior, the reversal of shear dilatancy, and the normal contraction of cementitious interfaces can be accounted in the proposed constitutive model. They used smeared cracked finite element model. It was concluded that the model can capture failure mechanisms and can approximate the lateral resistance of the frame. Syrmakezis [44] proposed a new finite element technique in which the frame-infill separation criterion is used to find the geometrical equilibrium condition. The basic difference of the analysis was that the contact lengths and stresses were estimated as an integral part of the solution. Stavridis presents a FEM scheme for assessing the nonlinear load-deformation behavior and failure mechanisms of masonry infilled RC frames through combination of the discrete and smeared-crack modeling approaches. Dorji [45] used gap element to model the interface between infill and frame. Mohyeddin [35] proposed a simplified micro-model where brick and mortar were modeled as a single smeared material and the mortar joints were modeled as zero-thickness interfaces or contact joints. Bhagyashri [46] studied two types of micro modelling techniques i.e. gap and link element method that were earlier proposed by Dorji [47] and Achutya [41]. It was concluded that both method give same results so they can be used in any FE software. Mohammad [42] proposed micro model parameters that were incorporated in ATENA software and were verified with existing results proposed by [6] for variant configuration of infill walls.

4 Research Significance

The significance of this work holds in the fact that although infills are not considered structural members they affect the structure's mass and lateral rigidities. Hence, to fully understand the behavior of the free vibration of the structure under seismic loads their contribution towards the behavior of frame shall not be neglected. Previously modeling infills and incorporating their contribution within the frame was a rather complex method. Studying the literature reveals that there are less complicated ways to include the effect of infills without compromising much on the overall behavior of the frames under dynamic loads. Thus, it is important to understand how these modeling methods are applied and which behavioral aspect of infilled frame can be covered by a certain technique. This research study gives an insight into all the modeling techniques which shall be included within the design in near future.

5 Conclusion

Extensive review of the existing studies that were proposed to model masonry infills to depict its behavior properly has brought following conclusions:

- Masonry infill significantly increase lateral strength and stiffness of the structures changing their time periods and mode shapes, consequently increasing the risk of collapse. Hence, they shall be incorporated in analysis to fully comprehend the behavior of masonry infilled RC frames;
- Despite of significant research, still infill walls are not considered while designing, though now researchers have started incorporating them into analysis. And it is revealed that incorporating them can be done at Macro, Micro or Meso levels, each having their own level of complexity;
- Macro modelling approach is easier and simpler as compared to micro modelling. However, it depicts only global behavior. Whereas, micro-modelling is time consuming and require large computations, but it captures failure modes and infill- frame interaction effects.

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