THE STATE-OF-THE-ART IN INFILLED FRAMES NUMERICAL MODELS

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ABSTRACT:
In this paper, the State-of-the-Art of the numerical models for the analysis of brickwork infilled plane frames subjected to lateral actions is reviewed. A number of distinct approaches in the field of the analysis of infilled frames since the mid-1950s, have yielded several analytical models. It has been stressed, in these analytical works, how difficult and generally unreliable the numerical simulation of infilled frame is, due to the very large number of parameters to be taken into account and the magnitude of the uncertainties associated with most of them. For a better understanding of the approach and capabilities of each model, an attempt has been made to classify them into macro- and micro- models based on their complexity, the detail by which they model an infill wall, and the information they provide to the analyst about the behavior of a structure.

1. Introduction
In many countries situated in seismic regions, reinforced concrete frames are infilled by brick masonry panels. Although the infill panels significantly enhance both the stiffness and strength of the frame, their contribution is often not considered because of the lack of knowledge of the composite behavior of the frame and the infill. However, extensive experimental (Smith [1]; Smith et al. [2]; Page et al. [3]; Mehrabi et al. [4]), and analytical investigations (Liauw and Kwan [5], [6], [7]; Dhanasekar and Page [8]; Saneinejad and Hobbs [9]; Mehrabi and Shing [10]; Asteris [11], [12]) have been made. Extensive and in-depth state-of-the-art reports can be found in Tassios [13], Moghaddam et al. [14] and CEB [15]. Recently, it has been shown that there is a strong interaction between the infill masonry wall and the surrounding frame.

Approximately 80% of the cost of damages of structures from earthquakes is due to damage of the infill walls and to consequent damages of doors, windows, electrical and hydraulic installations (Tiedeman [16]). Inspite of its broad application and its economical significance, this structural system has resisted analytical modelling; the following reasons may explain this situation:

- Computational complexity: The particulated infill material and the ever changing contact conditions along its interface to concrete, constitute additional sources of analytical burden. The real composite behavior of an in-filled frame is a complex statically indeterminate problem according to Smith [1].
Structural uncertainties: The mechanical properties of masonry, as well as its wedging conditions against the internal surface of the frame, depend strongly on local construction conditions.

The non-linear behaviour of infilled frames depend on the separation of masonry infill panel from the surrounding frame.

Attempts at the analysis of infilled frames since the mid-1950s have yielded several analytical models. For a better understanding of the approach and capabilities of each model it may be convenient to classify them into macro- and micro- models based on their complexity, the detail by which they model an infill wall, and the information they provide to the analyst about the behavior of a structure. A basic characteristic of a macro- (or simplified) model is that they try to encompass the overall (global) behavior of a structural element without modelling all the possible modes of local failure. Micro- (or fundamental) models, on the other hand, model the behavior of a structural element with great detail trying to encompass all the possible modes of failure. The following sections constitute a brief review of the most representative macro- and micro-models.

2. Macro-Models

Since the first attempts to model the response of the composite infilled frames structures, experimental and conceptual observations have indicated that a diagonal strut with appropriate geometrical and mechanical characteristics could possibly provide a solution to the problem. In 1958, Polyakov [17] suggested the possibility of considering the effect of the infilling in each panel as equivalent to diagonal bracing and this suggestion was later taken up by Holmes [18] who replaced the infill by an equivalent pin-jointed diagonal strut made of the same material and having the same thickness as the infill panel and a width equal to one third of the infill diagonal length. The ‘one-third’ rule was suggested as being applicable irrespective of the relative stiffnesses of the frame and the infill. Stafford Smith [1] and Stafford Smith and Carter [2] related the width of the equivalent diagonal strut to the infill/frame contact lengths using an analytical equation which has been adapted from the equation of the length of contact of a free beam on an elastic foundation subjected to a concentrated load (Hetenyi [19]). Based on the frame/infill contact length, alternative proposals for the evaluation of the equivalent strut width have been given by Mainstone [20] and Kadir [21].

Stafford Smith and Carter [2], and Mainstone [20] used the equivalent strut approach to simulate infill wall in steel frames and study the behavior of infilled structures subjected to monotonic loading. They also developed equations by which the properties of these struts, such as initial stiffness and ultimate strength, were calculated. For example, the following relationship was suggested for brick infills prior to cracking:

\[
\frac{w}{d} = 0.175(\lambda_h h)^{0.4} \sin 2\theta
\]  
(1)

in which \( w \), \( d \) and \( h \) is the effective width of diagonal strut, panel diagonal length and height of column respectively and

\[
\lambda_h = \frac{E_b t \sin 2\theta}{4E_s I h}
\]  
(2)

in which \( E_b \), \( t \) and \( h \) are the elastic modulus, thickness and height of the brick masonry infill respectively; \( E_s \) and \( I \) are the Young’s modulus and moment of inertia of the surrounding
frame member; and \( \vartheta \) is the angle between the infill diagonal and the horizontal. This approach proved to be the most popular over the years because of the ease with which it can be applied.

In the last two decades it became clear that one single strut element is unable to model the complex behavior of the infilled frames. More complex macro-models were then proposed, but they were still usually based on a number of diagonal struts.

Thiruvengadam [22] suggested the equivalent multiple strut model. The infill is discretized into a grid of shear panels. Each panel, considered under the state of pure shear, is replaced by two diagonals, once acting in compression and the other in tension.

Syrmakezis and Vratsanou [23] suggested a distribution of multiple equivalent diagonal struts to have a better estimation of the compressed zone, both in the infill panel and in the frame members. It was stressed how different compressed lengths have a significant effect on the bending moment distribution in the frame members.

Chrysostomou, Gergely and Abel [24] had the objective of simulating the response of infilled frames under earthquake loading by taking into account stiffness and strength degradation of the infills. They proposed to model each infill panel by six compression-only inclined struts as shown in Figure 1. Three parallel struts are used in each diagonal direction and the off-diagonal ones are positioned at critical locations along the frame members. At any point during the analysis of the non-linear response only three of the six struts are active, shown in Figure 1 with solid lines. The struts are switched to the opposite direction whenever their compressive force reduces to zero. The parameter \( \alpha \) represents a fraction of the length or height of a panel and is associated with the position of the formation of a plastic hinge in a beam or a column. Theoretical values for this parameter are given by Liaw [5], [6], [7].

\[ \Phi = \frac{U}{h} \]

\[ \alpha L \]

\[ \alpha h \]

\[ \alpha L \]

\[ \alpha h \]

**Fig. 1 Six-strut idealization of infill walls [24]**

The hysteretic behavior of the six struts is defined by a hysteretic model, which consists of two equations. The first equation defines the strength envelope of a structural element and the second defines its hysteretic behavior. The shape of the envelope and the hysteretic loops (Figure 2) is controlled by six parameters, all of which have physical meaning and can be obtained from experimental data. More details about the model are presented by Chrysostomou [25].
The proposed model was implemented in a three-dimensional non-linear analysis programme and used and tested on simple and multi-storey multi-bay infilled frames to study the effects of infill walls on the non-linear dynamic behaviour of infilled steel frames. The advantage of this strut configuration over the single diagonal strut is that it allows the modelling of the interaction between the infill and the surrounding frame.

3. Micro-Models

All models described in this section are based on the Finite Element Method, using three different kinds of elements to represent the behavior of infilled frames subjected to lateral loading. According to these models the frame is constituted by plane or beam element, the infill by plane elements, and the interface behavior by interface elements or by one-dimensional joint elements.

Mallick and Severn [26], and Mallick and Garg [27] suggested the first finite element approach to analyse infilled frames, addressing the problem of an appropriate representation of the interface conditions between frame and infill. The infill panels were simulated by means of linear elastic rectangular finite elements, with two degrees of freedom at each four nodes, and the frame was simulated by beam element ignoring axial deformation. This was a consequence of the assumption that the interaction forces between the frame and the infill along their interface consisted only of normal forces. In this model, the slip between the frame and the infill was also taken in account, considering frictional shear forces in the contact regions. Several single storey rectangular infilled frames under static loading were analysed and the results were in a good agreement with experimental results if the height to span ratio was not greater than two.

Liauw and Kwan [7] used three different types of elements to study the behavior of infilled frames subjected to monotonic loading. The infill-frame interface was modelled by simple bar type elements capable of simulating both separation and slip. The infill panel was modelled by triangular plane stress elements. In tension, the material was idealized as a linear elastic brittle material. Before cracking, the material was assumed to be isotropic and after cracking was assumed to become anisotropic due to the presence of the crack. It was assumed that for an open crack the Young’s modulus perpendicular to the crack and the shear modulus parallel to the crack were zero. When the crack was closed, the Young’s modulus was restored, and the shear force is assumed to be taken over by friction. In compression, the panel was
assumed to exhibit extensive nonlinearity in the stress-strain relationship. Although the material was subjected to bi-axial stress, it was assumed that the panel was under uniaxial stress based on experimental results, which show that one of the principal stress is much smaller than the other. Using an iterative procedure with incremental displacement, several four-story one-bay model frames infilled with micro-concrete were analysed. Close agreement between experimental and analytical results has been observed.

Dhanasekar and Page [8], using one-dimensional joint elements to model the mortar joint between the infill and the frame, have shown that the behavior of the composite frame not only depends on the relative stiffness of the frame and the infill and the frame geometry, but is also critically influenced by the strength properties of the masonry (in particular, the magnitude of the shear and tensile bond strengths relative to the compressive strength).

A simpler and much quicker finite element technique (Axley and Bertero [28]) consists in reducing, by condensation, the stiffness of the infill to the boundary degrees of freedom. It is assumed that the frame constrains the form (but not the degree) of deformation on the infill. Separate stiffnesses are formed. A constraint relation is assumed between the 12 frame degrees of freedom (DOF) and the boundary degrees of freedom. Thus, a congruent transformation of the separate systems to a composite approximate frame-infill system (with only 12 DOF) is possible.

To overcome the problem of the ever-changing contact conditions between the brick masonry infill and the surrounding frame, a new finite element technique for the modelling of infilled frames has been recently proposed by Asteris [11], [12]. According to this in order to model the complicated behavior of the in-filled plane frames under lateral load similar to an earthquake load, a criterion for the frame-infill separation is used. The main goal of this criterion is to describe the evolution of the natural response of these composite structures subjected to seismic lateral loads as a boundary condition problem. The objective of the present study is to find a valid geometrical equilibrium condition for the composite structure of the in-filled frame under certain loading conditions, given that the real overall behavior of an in-filled frame is a complex statically indeterminate problem according to Smith [1]. The analysis has been performed on a step-by-step basis based on the following:

The major “physical” boundary condition between infill and frame is that the infill panel cannot get into the surrounding frame; the only accepted “natural” conditions between infill and frame are either the contact or the separation.

The frame, while directly carrying some of the lateral loads, serves primarily to transfer and distribute the bulk of the loads to the infill. The stiffness response of the infill is influenced, to a considerable extent, by the way in which the frame distributes the load to it. Simultaneously, the frame’s contribution to the overall stiffness is affected by the change in its mode of distortion, as a result of the reaction of the infill.

The proposed finite element procedure can be summarised as follows:

Step 1. Initially, the infill finite element models are considered to be linked to the surrounding frame finite element models at two corner points (only), at the ends of the compressed diagonal of the infill. (When the load is applied, the infill and the frame are getting separate over a large part of the length of each side and contact remains only adjacent to the corners at the ends of the compression diagonal).

Step 2. Compute the nodal forces and displacements, and the stresses at the Gauss points of the elements.
Step 3. Check whether the infill model points overlap the surrounding frame finite elements. If the answer is negative, step 5 of the procedure will be followed. If the answer is positive, step 4 will, instead, be followed.

Step 4. When the infill model points overlap the surrounding frame finite elements, the neighbouring points (to the previous linked) are linked and the procedure continues from step 2.

Step 5. This final step is a further check on the acceptance (or not) of the derived deformed mesh. This check will determine if at any one point of the derived contact area tension is occurring. In particular, what is checked is whether the normal stresses along to x-axis (for the linked points on vertical part of the interface) and along the y-axis (for the linked points on horizontal part of the interface) are tensile. If the answer is negative, the procedure is stopped. If the answer is positive, the linked points become unlinked and the procedure continues from step 2.

Fig. 3 Successive deformed meshes of an one-story one-bay infilled frame using the Method of Contact Points [12]

Fig. 3 shows the successive deformed meshes of the studied one-story one-bay infilled frame generated by the proposed method of contact points. In particular, Fig. 3a depicts the deformed mesh based on the assumption that infill and frame are linked only at the two points A and B. According to this deformed mesh, two neighbouring points of B and one neighbouring point of A of the infill model points overlap the surrounding frame finite elements. Thus, according to the fourth step, these three neighbouring points (to the previous linked) are linked (Fig. 3b) and the procedure continues. The process is iterated, until a final equilibrium condition is reached (Fig. 3d).
According to the derived deformed mesh (Fig. 3d), different contact lengths between infill wall and surrounding frame members are observed, as is expected. In particular, the infill/frame contact lengths are varied between windward column and infill, beam and infill, and between infill and rigid base, thus demonstrating how unrealistic and inadequate is the modelling of the infill panel by a number of parallel compression inclined struts.

4. Conclusions
The brief review of existing analytical models for the analysis of brick masonry infilled frames, which has been presented in this paper, suggests that a computational procedure must be sought along the following directions:

- the infill/frame contact lengths and the contact stresses should be considered as an integral part of the solution, and are not assumed in an ad-hoc way, and
- new finite element and associated computer code to model the anisotropic behavior of brick masonry infill panel must be developed, since none of the available ones appear to be able to take into account this anisotropic and composite behavior.

REFERENCES


