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A FINITE ELEMENT TECHNIQUE FOR THE ANALYSIS OF INFILLED R/C FRAMES

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Abstract

This paper presents a new finite element technique for the analysis of brickwork infilled plane frames subjected to lateral actions. The basic characteristic of this new method of analysis is that the infill/frame contact lengths and the contact stresses are estimated as an integral part of the solution, and are not assumed in an ad-hoc way. Using this technique, the response of multi-story fully or partially infilled frames under lateral static loads has been investigated. In particular, the redistribution of the action-effects of lateral loads on the infilled frames has been studied. It is shown that the presence and continuity of the infill panels critically influence the redistribution of shear forces and leads, in general, to decreased shear forces on the frame columns. However, in case the infilled frames are built with a soft ground story, the shear forces acting on the frame columns are considerably higher than those obtained from the analysis of the bare frame. The large variation of the contact lengths between the infill and the frame members for each frame condition and between different frame stories is clearly demonstrated.

Introduction

In many countries situated in seismic regions, the 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, mainly because of the lack of knowledge of the composite behavior of the frame and the infill. Infilled frame behavior has been the focus of investigation for many years, but the system has not received successive analytical modeling, mainly due to its computational complexity.

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The particulated infill material and the ever changing contact conditions along its interface with the surrounding frame, constitute additional sources of analytical burden. The real composite behavior of an infilled frame is a complex, statically indeterminate problem [Smith 1966]. However, extensive experimental [Smith 1966; Page 1985; Mehrabi 1996], and semi-analytical investigations [Asteris 1996; Dhanasekar 1986; Liauw 1983; Mehrabi 1997] have been performed recently.

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 modeling of infilled R/C plane frames is presented in this paper. According to this, in order to model the complicated behavior of the in-filled frames under lateral loads, a realistic criterion, in terms of physical meaning, is used to describe the frame-infill separation. 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.

Method of analysis

The objective of the present study is to find a valid geometrical equilibrium condition for the composite structure of the infilled frame under certain loading conditions, given that the real overall behavior of an infilled frame is a complex, statically indeterminate problem. The analysis has been performed on a step-by-step basis, according to the following conditions:

- The major "physical" boundary condition between the infill and the frame is that the infill panel cannot get into the surrounding frame; the only accepted "natural" conditions between the infill and the frame are either the contact or the separation condition.
- 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 summarized as follows:

Step 1. Initially, the finite elements of the infill models are considered to be linked to the elements of the surrounding frame at two corner points (only); i.e., at the ends of the compressed diagonal of the infill. (When the load is applied, the infill and the frame are getting separated 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, 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, continue to Step 5 of the procedure.

Step 4. If the infill model points overlap the surrounding frame elements, the neighboring points to the previous linked points are linked, and the procedure is repeated from

Step 2.

Step 5. This final step is a further check on the acceptability of the derived deformed mesh. This check will determine if at any point of the derived contact area, tension has occurred. In particular, what is checked is whether the normal stresses along the x-axis (for the linked points on the vertical part of the interface) and along the y-axis (for the linked points on the horizontal part of the interface) are tensile. If the answer is negative, the procedure is stopped. If the answer is positive, the linked points are considered to be unlinked and the procedure is repeated from Step 2.

Numerical example

In this section, the proposed finite element technique has been used to study the response of the one-story one-bay infilled frame (shown in Figure 1) to a lateral static load acting at the beam level. The frame material is reinforced concrete with section dimensions of 30x40 cm, for both the columns and beams. The mechanical characteristics of the reinforced concrete and the infill masonry material are given in Table 1.

Figure 2 shows the successive deformed meshes of the studied one-story / one-bay infilled frame generated by the proposed method. In particular, Figure 2a depicts the deformed mesh based on the assumption that the infill and the frame are linked only at the points A and B. According to this deformed mesh, two neighboring points of B and one neighboring point of A of the infill model points overlap the surrounding frame elements. Thus, according to the fourth step of the procedure, these three neighboring points to the previous linked points are considered to be linked, and the procedure is repeated. The process continues (see intermediate solutions in Figs. 2b to 2d) until a final equilibrium condition is reached (Fig. 2d).

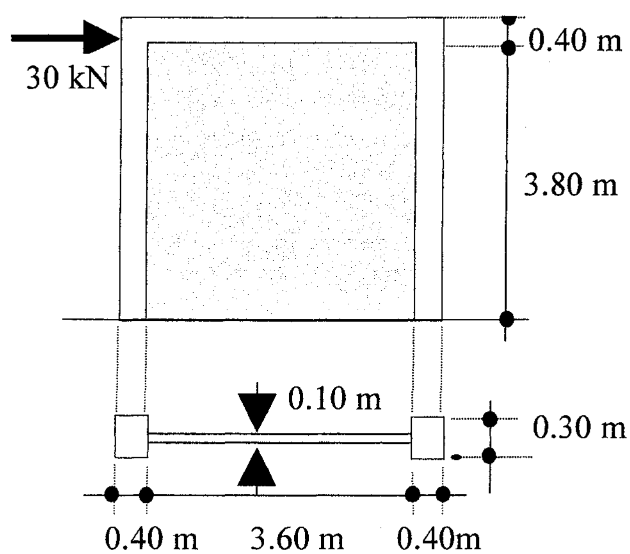


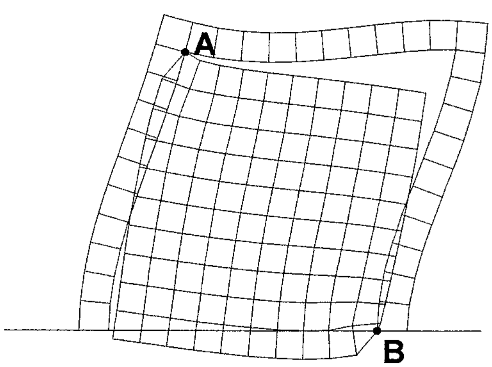
Fig. 1. Geometry and loading of the one-story / one-bay brick masonry infilled frame

Table 1. Material's Elastic Properties

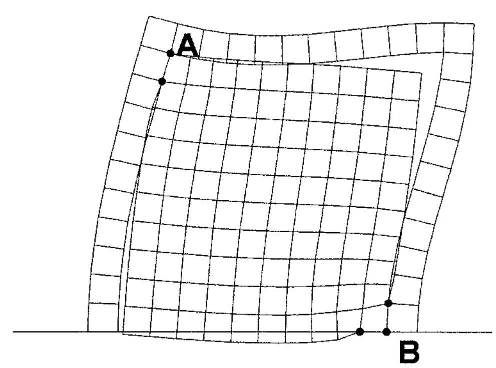
Material	Moduli of elasticity		Poison's ratios	
	E_x (kN/m^2)	E_y (kN/m^2)	ν_{xy}	ν_{yx}
(1)	(2)	(3)	(4)	(5)
Concrete	2.9×10^7	2.9×10^7	0.20	0.20
Masonry*	4.5×10^6	7.5×10^6	0.19	0.32**

* The values of the masonry material have been estimated experimentally by Page [Page 1981].

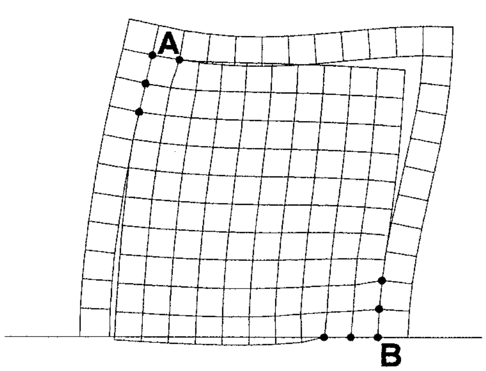
** $\nu_{yx} = \frac{E_y}{E_x}\nu_{xy}$



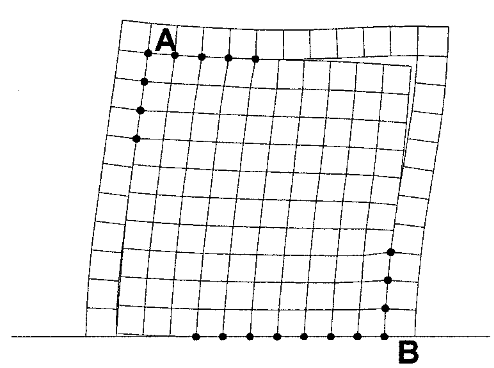
(a) 1st deformed mesh



(b) 2nd deformed mesh



(c) 3rd deformed mesh



(d) 8th (final) deformed mesh

Fig. 2. Successive deformed meshes of the one-story / one-bay infilled frame

According to the derived deformed mesh (Fig. 2d), different contact lengths between the infill wall and surrounding frame members are observed, as is expected. In particular, the infill frame contact lengths are varied between the windward column and the infill, the beam and the infill, and the infill and the rigid base; thus, demonstrating how unrealistic and inadequate is the modeling of the infill panel by a number of parallel compression inclined struts, a method widely preferred to date for the analysis.

Redistribution of the action-effects in multi-story infilled frames

Soft stories often appear due to a stiffness decrease in a story compared to the adjacent ones. This fact results in a concentration of high stresses to the carrying elements of the soft story leading, in most cases, to extensive damage. The most usual case of a soft story in a building is the ground soft story (pilotis) where infill walls do not exist. In such cases, the stiffness of the ground story is drastically decreased due to the absence of the infill walls. In these buildings, severe damage appears during an earthquake in the vertical carrying elements of the ground story, whereas most of the other elements in the building usually remain undamaged. For example, after the 1978 Thessaloniki earthquake in Greece, only 16,4% of the buildings with infill walls in the ground story showed damage (in the frame columns or the shear walls); while this happened to 29,8% of the buildings with a non-rigid ground story (Penelis 1988).

The significance of the above finding was the prime motive for our investigation on the shear stress distribution along the columns of the infilled frames. In particular, the aseismic behavior of multi-story infilled frames compared to the behavior of partially infilled frames (soft ground story, soft interim story, etc.) has also been investigated. The method of contact points was applied to the case of a three story / one bay frame loaded with vertical and horizontal seismic loads simultaneously, with the value ε=0.30 for the seismic coefficient. At each node of the mesh, both a vertical load (which equals the self-weight) and a horizontal load (equal to the vertical load multiplied by the value ε of the seismic coefficient) were applied. The frame material was reinforced concrete with section dimensions of 30x50 cm for both columns and beams, whereas the infill wall was rectangular with a four (4) meters side in all three stories. The mechanical characteristics of the reinforced concrete and the infill masonry material are those given in Table 1.

In Fig. 3, contact areas between the surrounding frame and the infill walls for four different cases of the infill wall arrangement are depicted with dot lines for the following four different cases:

- Case A1: Fully infilled frame
- Case A2: Infilled frame with a soft ground story (pilotis)
- Case A3: Infilled frame with a soft second story
- Case A4: The (wellknown) bare frame

The large magnitude of the variation of the contact lengths between the infill and different frame members, as well as between different frame stories, is clearly shown.

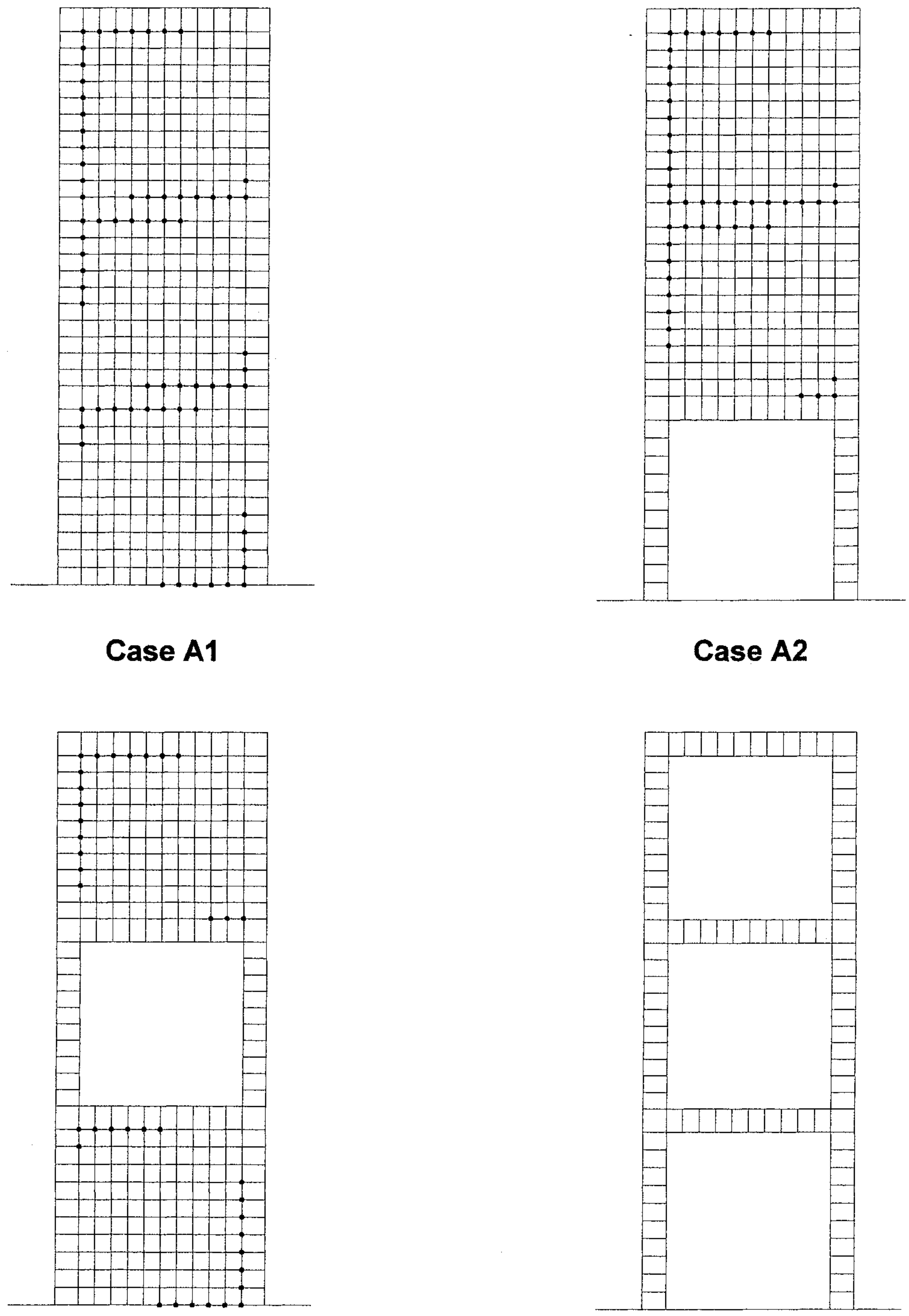


Fig. 3. Contact Areas Between Surrounding Frame and Infill Walls for Four Different Cases of the Infill Wall Arrangement

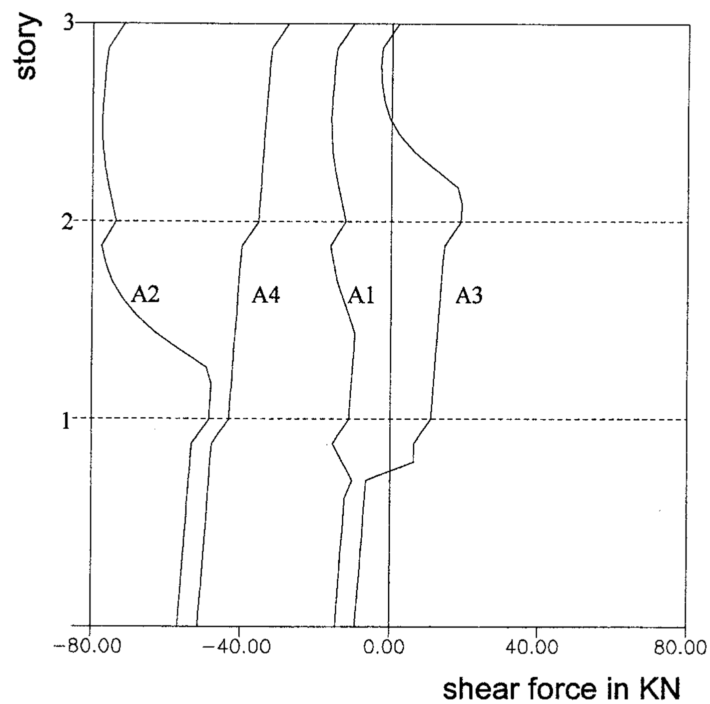


Fig. 4. Shear Force Diagram for the Windward Column of a Three-Story / One- Bay Infilled Frame (see Fig. 3)

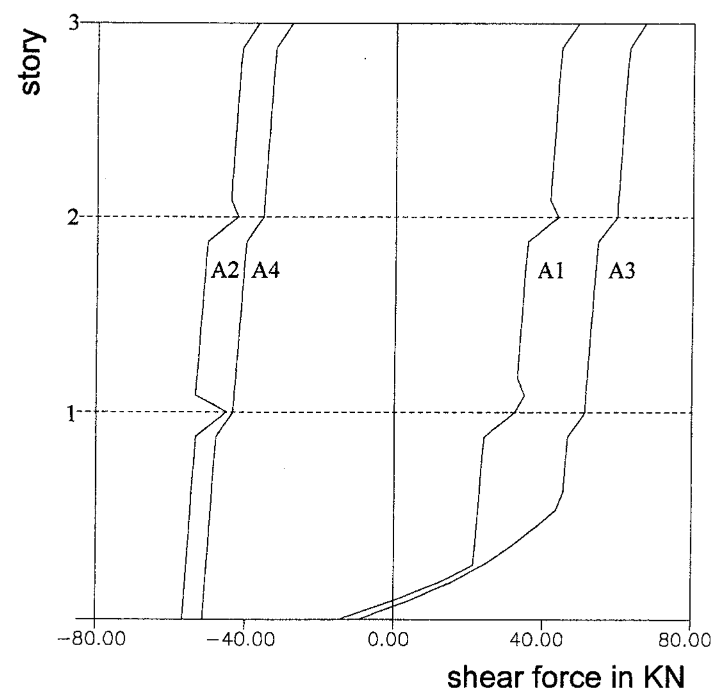


Fig. 5. Shear Force Diagram for the Right Column of a Three-Story / One-Bay Infilled Frame (see Fig. 3)

As described in the previous section, when a frame is laterally loaded, a separation between the frame elements and the infill wall occurs at an early loading stage. From this stage on, only part of the infill (the region around the compressed diagonal) is stressed, while the remaining part of the infill remains free from stresses. Thus, additional shear forces are expected to act on columns and beams adjacent to the infill. Figs. 4 and 5 show the shear stress distribution for the four cases studied. According to these diagrams, the main findings can be summarized as follows:

- As expected (Tassios 1984; CEB 1994), the presence of the infills leads, in general (Case A1 and A3), to decreased shear forces on the frame columns, since a considerable part of the seismic loads is resisted by the so-called "non-structural" infill.
- However, in the case of the infilled frame with a soft ground story (case A2), the shear forces acting on columns are considerably higher than those obtained from the analysis of the bare frame (Fig. 4).
- The presence of a soft story in an infilled frame leads to a considerable change on the distribution of the shear force diagram in the columns of this particular story. This action-effect may be particularly important for the windward column where additional tension and shear may produce catastrophic consequences.

Buonapane et al., at Cornell University (Buonapane 1999), clearly state that the available methods that neglect infill-frame interaction for estimating shear strength were found to largely underestimate the measured shear strength. In addition, in attempting to explain how a column located at the top of a structure has higher shear stress than a column located at the base story, they propose a possible strut mechanism that gives results which are in a good agreement with the results from this investigation.

Conclusions

A new finite element technique for the analysis of brick masonry infilled plane frames is presented in this paper. Using this technique, the behavior of infilled frames under lateral static loads, has been investigated. The main advantages of the method can be summarized as:

- the ability to calculate the infill/frame contact lengths as an integral part of the solution and not assuming them in an ad-hoc way (the large magnitude of the variation of the contact lengths between the infill and different frame members, as well as between different frame stories, is clearly shown), and
- the capability to model the behavior of single and multi-story infilled frames, either fully or partially infilled.

A detailed parametric study on the influence of brick masonry infill panels to the behavior of infilled frames has revealed that the presence of the infills leads, in general, to decreased shear forces on the frame columns. However, in the case of infilled frames with a soft ground story, the shear forces acting on the columns are considerably higher than those obtained from the analysis of the bare frame.

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