Lateral Stiffness of Brick Masonry Infilled Plane Frames

P. G. Asteris, M.ASCE[1]

Abstract: In a companion paper, a new finite element technique for the analysis of brickwork infilled plane frames under lateral loads has been presented. In the present paper, the influence of the masonry infill panel opening in the reduction of the infilled frames stiffness has been investigated by means of this technique. A parametric study has been carried out using as parameters the position and the percentage of the masonry infill panel opening for the case of one-story one-bay infilled frame. The investigation has been extended to the case of multistory, fully or partially infilled frames. In particular, the redistribution of action effects of infilled frames under lateral loads has been studied. It is shown that the redistribution of shear force is critically influenced by the presence and continuity of infill panels. The presence of infills leads, in general, to decreased shear forces on the frame columns. However, in the case of an infilled frame with a soft ground story, the shear forces acting on columns are considerably higher than those obtained from the analysis of the bare frame.

DOI: 10.1061/(ASCE)0733-9445(2003)129:8(1071)

CE Database subject headings: Brick masonry; Finite element method; Frames; Lateral loads; Seismic responses; Shear distribution; Stiffness.

Introduction

In multistory buildings, the ordinarily occurring vertical loads, dead or alive, do not pose much of a problem, but the lateral loads due to wind or earthquake tremors are a matter of great concern and need special consideration in the design of buildings. These lateral forces can produce the critical stress in a structure, set up undesirable vibrations, and, in addition, cause lateral sway of the structure which can reach a stage of discomfort to the occupants. In many countries situated in seismic regions, reinforced concrete frames are infilled fully or partially by brick masonry panels with or without openings. Although the infill panels significantly enhance both the stiffness and strength of the frame, their contribution is often not taken into account because of the lack of knowledge of the composite behavior of the frame and the infill. However, extensive experimental (Smith 1966; Smith and Carter 1969; Liauw 1979; Mehrabi et al. 1996) and analytical investigations (Liauw and Kwan 1984; Dhanasekar and Page 1986; Saneinejad and Hobbs 1995; Asteris 1996; Mehrabi and Shing 1997) have been made. Extensive and in-depth state-of-the-art reports can be found in Tassios (1984); Chrysostomou (1991); and Comité Euro-International du Béton (CEB 1994).

The aim of this paper is to investigate the lateral stiffness of brick masonry infilled plane frames using a recently proposed (and presented in a companion paper) finite element technique for the analysis of brick masonry infilled plane frames. Using this technique, the influence of the masonry infill panel opening in the variation (reduction) of the infilled frames stiffness has been investigated. In particular, a parametric study has been carried out using as parameters the position and the percentage of the masonry infill panel opening for the case of one-story one-bay infilled frame. The investigation has been extended to the redistribution of shear stress in the case of multi-story, fully or partially infilled frames.

[1]Visiting Assistant Professor, Faculty of Technological Applications, Technological Educational Institution of Athens, Agiou Spyridonos Str., GR 122 10 Egaleo, Greece. E-mail: asteris@teiath.gr

Note. Associate Editor: Peter W. Hoadley. Discussion open until January 1, 2004. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on July 3, 2001; approved on May 22, 2002. This paper is part of the ***Journal of Structural Engineering***, Vol. 129, No. 8, August 1, 2003. ©ASCE, ISSN 0733-9445/2003/8-1071–1079/$18.00.

Method of Analysis

A new finite element technique developed by Asteris (2003) has been used in this study to model the behavior of infilled frames under lateral loads. The basic characteristic of this 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. The method comprises the following:

1. A finite element to model the in-plane anisotropic behavior of masonry infill panel;
2. A masonry failure criterion under biaxial stress state in order to check at each step of the analysis process if the infill panel is (or not) under linear elastic behavior; and
3. A criterion for the separation of masonry panel from the surrounding frame.

A finite element computer program has been developed to implement this procedure.

Finite Element Model

For the analysis, a four-node isoparametric rectangular finite element model with 8 degrees of freedom has been used. The major assumption of modeling the masonry behavior under plane stress is that the material is homogeneous and anisotropic. In particular, the material shows a different modulus of elasticity (E_x) in the x direction (direction parallel to the bed joints of brick masonry) and a different one (E_y) in the y direction (perpendicular to the bed joints). In the case of plane stress the elasticity matrix is defined by

$$D=\begin{bmatrix} \frac{E_x}{1-\nu_{xy}\nu_{yx}} & \frac{E_x\nu_{yx}}{1-\nu_{xy}\nu_{yx}} & 0 \\ \frac{E_y\nu_{xy}}{1-\nu_{xy}\nu_{yx}} & \frac{E_y}{1-\nu_{xy}\nu_{yx}} & 0 \\ 0 & 0 & G_{xy} \end{bmatrix} \quad (1)$$

in which E_x and E_y = moduli of elasticity in the x and y direction respectively; ν_{xy}, ν_{yx} = Poisson's ratios in the xy and yx plane, respectively; and G_{xy} = shear modulus in the xy plane. It is worth noticing that in the case of plane stress in an anisotropic material the following equation holds

$$E_x\nu_{yx}=E_y\nu_{xy} \quad (2)$$

In order to model the surrounding frame we use the same constitutive relation that is used for the modeling of masonry material giving the same value for the modulus of elasticity (E_x) in the x direction and (E_y) in the y direction.

Masonry Failure Criterion Under Biaxial Stress State

Masonry is a material that exhibits distinct directional properties because the mortar joints act as planes of weakness. To define failure under biaxial stress, the derivation of a three-dimensional (3D) surface in terms of the two normal stresses and the shear stress (or the two principal stresses and their orientation to the bed joints) is required. A failure surface of this form has been recently derived by Asteris (2000) and Syrmakezis and Asteris (2001). The writers present a method to define a general anisotropic failure surface of masonry under biaxial stress, using a cubic tensor polynomial. In particular, the writers propose an analytical methodology in order to describe the masonry failure surface under plane stress via a regular surface, that is, a surface defined by a single equation of the form $f(\sigma)=0$ (Koiter 1953).

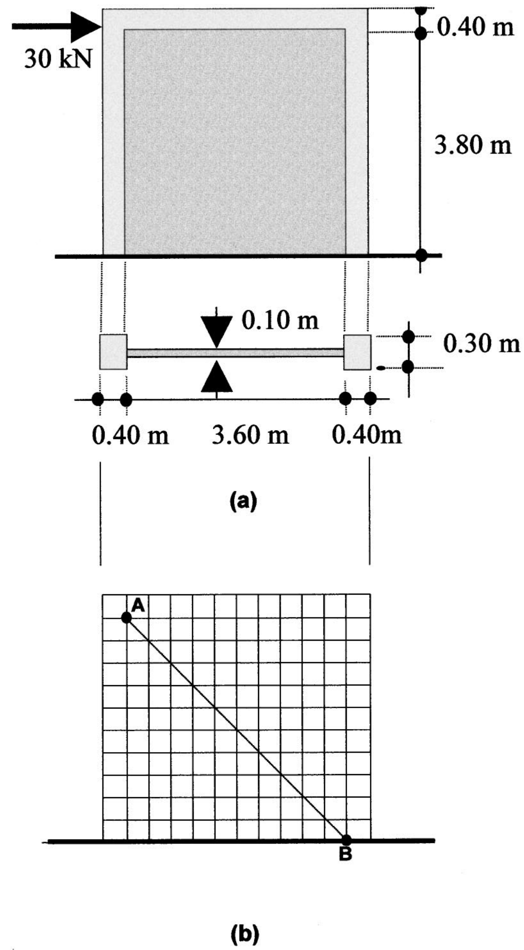

Fig. 1. One-story one-bay brickwork infilled frame: (a) geometry and loading; (b) mesh

Criterion for Frame–Infill Separation

In order to model the complicated behavior of the infilled 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 infilled frame under certain loading conditions, given that the real overall behavior of an infilled frame is a complex statically indeterminate problem according to Smith (1966). The analysis has been performed on a step-by-step basis along the following lines:

1. 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.
2. 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.

According to Asteris (2003) the proposed finite element procedure can be summarized in the following five steps:

1. 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 [points A and B in Fig. 1(b)]. (When the load is applied, the infill and the frame 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).
2. Compute the nodal forces and displacements [deformed mesh in Fig. 2(a)], and the stresses at the Gauss points of the elements.
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.
4. When the infill model points overlap the surrounding frame finite elements, the neighboring points (to the previous linked) are linked [Fig. 2(b)] and the procedure continues from step 2.
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 the 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 and the derived deformed

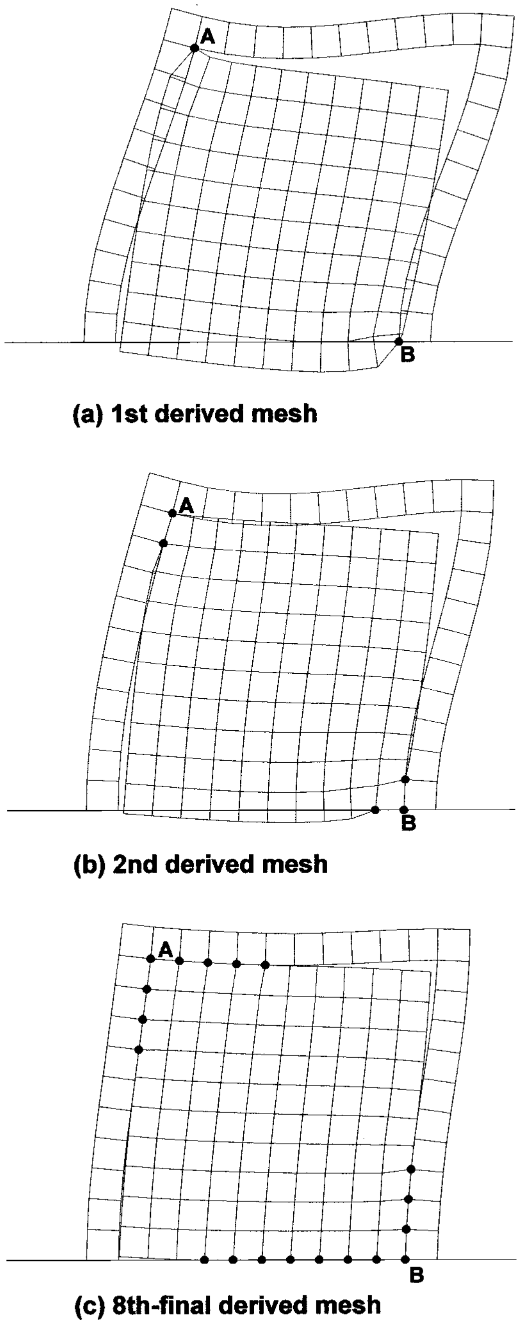

Fig. 2. Deformed meshes of one-story one-bay infilled frame using method of contact points

mesh is the one searched [Fig. 2(c)]. If the answer is positive, the linked points become unlinked and the procedure continues from step 2.

In order to implement the method, a specific computer program for a 2D linear elastic analysis of infilled plane frames under lateral static loads has been developed. The code has been developed using the *FORTRAN* programming language and has the capability of automatic mesh generation. The *Auto-Cad* plot software package has been integrated to the computer program by means of macro language commands.

Effect of Openings on Lateral Stiffness of Infilled Frames

Although infill walls usually have oversized openings, recent research has focused mainly on the simple case of infill wall without openings. Research of the infill wall with openings is mostly analytical and limited, and bears no comparison due to the different materials used and the different types of openings. It is worth noticing that the contribution of the infill wall to the frame lateral stiffness is greatly reduced when the structure is subjected under reversed cyclic loading, as in real structures under earthquake conditions. The relevant experimental findings (Vintzeleou and Tassios 1989) showed a considerable reduction in the response of infilled frames under reversed cyclic loading.

Previous Research

The effect of openings on the lateral stiffness of infilled frames has been experimentally investigated by several researchers. Benjamin and Williams (1958) measured a 50% reduction of the ultimate strength in infilled frames having an opening at the center of the infill with dimensions proportional to the infill dimensions by a ratio of one third.

As mentioned in Mallick and Gorg (1971), Coull's seminal 1966 work tested a few infilled frames having central openings with and without reinforcement around the openings. He observed that these openings reduce the stiffness and strength of infilled frames by about 60–70% and by 45%, respectively, as compared to a solid infill panel. The failures occurred due to crushing of one of the loaded corners of the infill. Considerable cracking of the infills had occurred before the failure. He predicted theoretically the values of lateral stiffnesses based on the theories of Holmes (1961) and Smith (1962), but the values differed from the experimental results by as much as 300%.

Mallick and Garg (1971) investigated the effect of opening positions on the behavior of infilled frames with or without shear connectors. They found that an opening at either end of the loaded diagonal of an infilled frame without connectors reduces its lateral strength about 75% and its lateral stiffness about 85–90% as compared to that of a similar infilled frame with solid panel (without opening). For infilled frames with shear connectors, the presence of an opening on either end of the loaded diagonal reduces its stiffness by 60–70% as compared to that of similar infilled frame with a solid panel. For both types of frames the loss of strength and stiffness due to a centrally loaded square opening having side dimensions one fifth those of the panel is about 50–25% compared to similar frames without openings.

Liauw and Lee (1977) and Liauw (1979) report on the results of monotonic tests on four-story single-bay steel frames infilled with reinforced microconcrete walls. One of the parameters investigated was the dimensions of openings located at mid-span of infill. The authors state that a change in the mode of failure was observed in the case where there were openings in the infills. In particular, according to the writers, in infill panels with openings, initial cracks appeared on the lowest windward side wall. As the load was increased, cracks spread to the first story windward side wall and appeared on the leeward side wall as well on the ground story lintel beam. At higher load, the spread of cracks followed a similar pattern, indicating the transfer of compression from one side to the other through the lintel beams on the upper stories. At the ultimate stage, the two diagonal cracks in the lowest infills divided the infills into three separate parts and compression failure occurred at the bottom level of the lintel beam and the bottom corner of the windward side wall. On the other hand, when the panels are solid, failure takes place in the infill and it is either a diagonal compression or a shear failure. According to the writers the results could be summarized as follows: (1) the openings in the infills produce large reductions in the strength and the stiffness of infilled frames; and (2) when the opening extends above

Table 1. Materials Elastic Properties

Material	Moduli of elasticity E_x (kN/m^2)	E_y (kN/m^2)	Poisson's ratios ν_{xy}	ν_{yx}
Concrete	2.9×10^7	2.9×10^7	0.20	0.20
Masonry[a]	4.5×10^6	7.5×10^6	0.19	0.32[b]

[a]The values of this masonry material have been estimated experimentally by Page (1981).

[b]$\nu_{yx}=(E_y/E_x)\nu_{xy}$ according to Eq. (2).

the compression diagonal, then the infill is under bending, shear, and compression, and the action of the infill is different in nature from the action of a diagonal strut.

Utku (1980) investigated the effect of openings parameters (such as aspect ratio, position, and area) on the stiffness and strength of one-story walls with single openings under earthquake loads. The walls were analyzed as plane stress problems assuming linearly elastic isotropic material and small deformations. Considering the largest magnification factor in the wall as the maximum magnification factor, the variation of this factor with the opening parameters was investigated and presented. According to this analytical research work, the following were observed: (1) the maximum stress magnification factor increases as the opening percentage increases; (2) the maximum stress magnification factor increases as the opening moves upward; and (3) the maximum stress magnification factor increases as the aspect ratio of the opening changes from 1/1 to 2/1.

A representative analytical work on the influence of the openings to the elastic stiffness of infill walls has been presented by Giannakas et al. (1987). The writers use the finite element method to model the infill walls, assuming that the masonry is a material homogeneous, elastic, and isotropic. They model the surrounding frame by means of suitable boundary condition and investigate the effect of openings parameters (such as position and area) on the elastic stiffness of infill panels. According to the authors, the openings reduce the stiffness of infilled frames by about 70–80% for an opening percentage of 20–30%. However, they also observe that the effect of the opening position on the infill panel is insignificant.

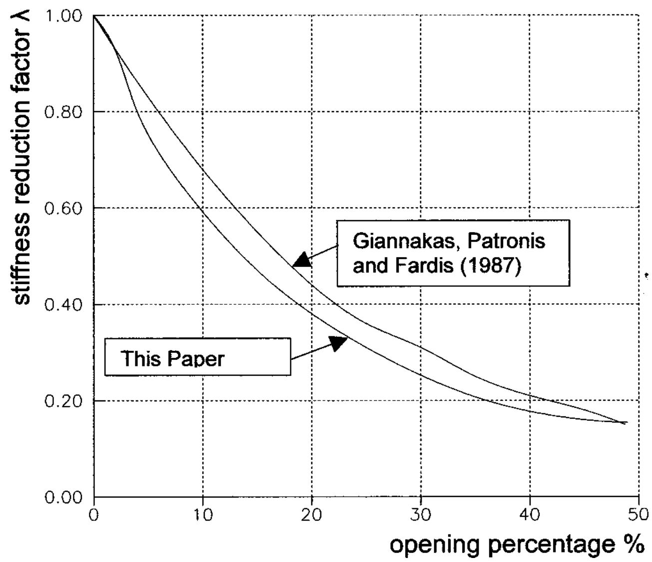

Fig. 4. Stiffness reduction factor λ of infilled frame in relation to opening percentage (case B: opening upon compressed diagonal)

Analytical Investigation

In this section, we present analytical results on the influence of the opening size and its position on the infill wall in seismic response of masonry infilled frames, based on the method of contact points described above. The problem is studied in the elastic region for monotonic loading. In addition, the estimated stiffness reduction ratio λ (defined as the stiffness with wall opening to the stiffness without a wall opening) is used for comparison with bibliographical data.

A number of one-story one-bay infilled structures with different configurations has been analyzed using the above-mentioned computer program. Typical data have been considered as shown in Fig. 1(a). The structure has been studied under a 30 kN horizontal loading with a similar uniform load distribution in the surrounding frame and infill wall surface. The mechanical character-

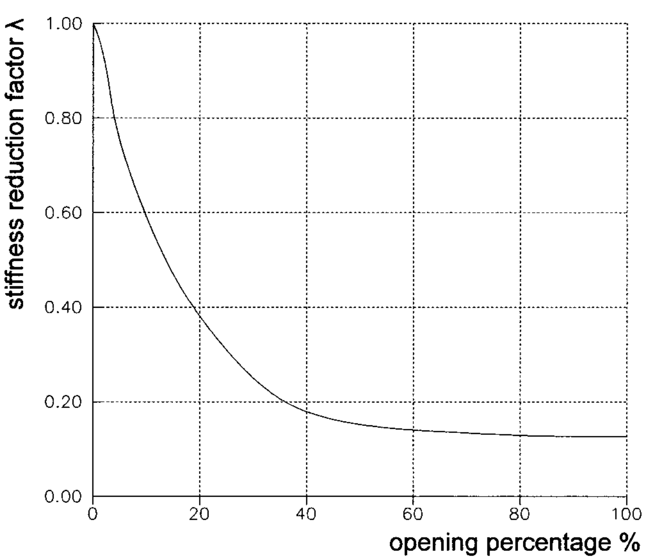

Fig. 3. Stiffness reduction factor λ of infilled frame in relation to opening percentage (case B: opening upon compressed diagonal)

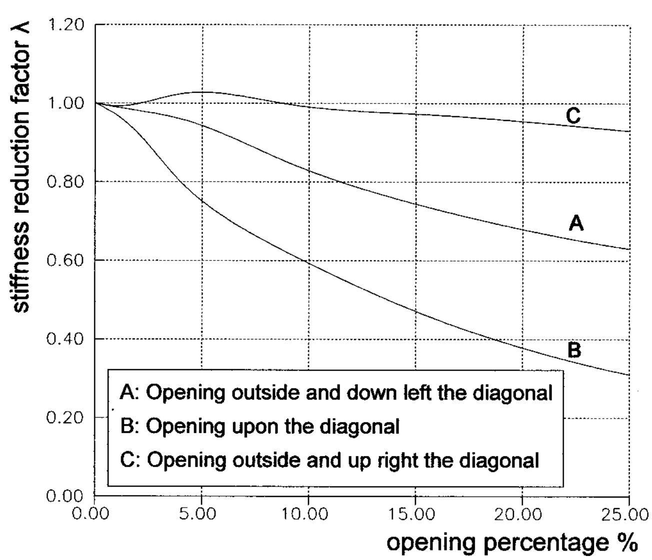

Fig. 5. Stiffness reduction factor λ of infilled frame in relation to opening percentage for different positions of opening

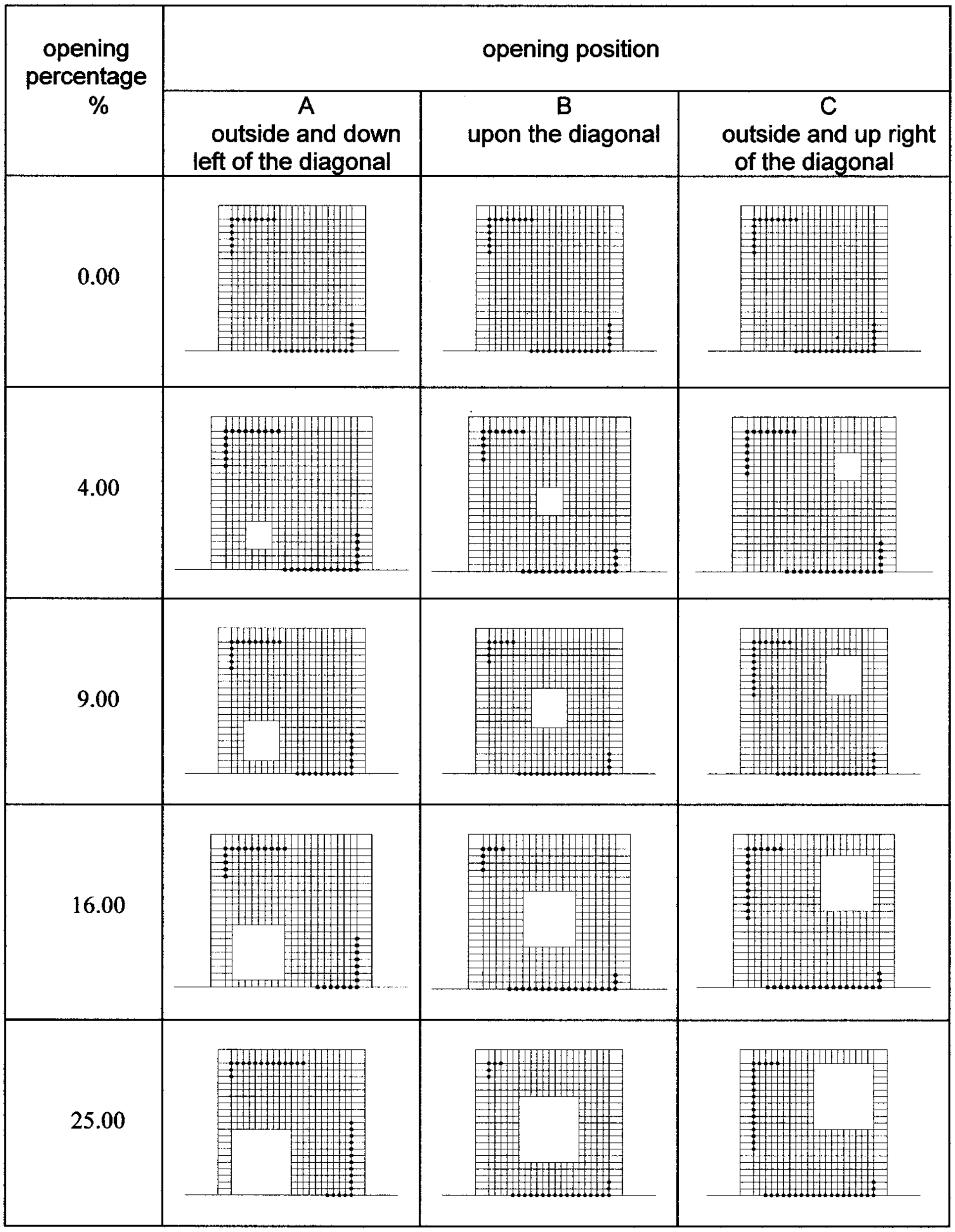

Fig. 6. Contact/interaction areas between infill masonry wall and surrounding frame for different opening percentages

istics for both the reinforced concrete and the infill masonry walls are shown in Table 1.

In order to thoroughly understand the effect of openings on the lateral stiffness/behavior of infilled plane frames under lateral loading the following parameters and cases have been considered:

1. The presence (or not) of opening in the infill panel;
2. The percentage of opening (area of opening to the total infill panel area): opening percentages of 4.00, 9.00, 16.00, and 25.00 have been studied; and
3. The position of opening to the compressed diagonal. Opening percentages of 4.00, 9.00, 16.00, and 25.00 have been studied for the following three cases:
   - Case A: opening is underneath the compressed diagonal,
   - Case B: opening is upon the compressed diagonal, and
   - Case C: opening is above the compressed diagonal.

Fig. 3 shows, for the case (B) of an opening upon the compressed diagonal of the infill wall (with dimensions ratio equal to the infill wall dimensions ratio), the variation of the λ factor as a function of the opening percentage (opening area/infill wall area). As is expected, an increase in the opening percentage leads to a decrease in the frame's stiffness. The decrease is 87% for a bare frame (100% opening). For openings exceeding 50%, the stiffness factor λ remains practically constant. Fig. 4 shows the results of the present investigation on the effect of opening percentage (Case B: opening upon the compressed diagonal) in the reduction of infilled frames stiffness in comparison with previous analytical results (Giannakas et al. 1987). The good agreement of the present and previous analytical results is apparent for this case.

Fig. 5 shows the opening influence in the reduction infilled frames stiffness for the three different positions studied. The variation of the stiffness reduction factor λ of the infilled frame is depicted as a function of the opening percentage. The higher value of stiffness reduction of the frame occurs when the opening

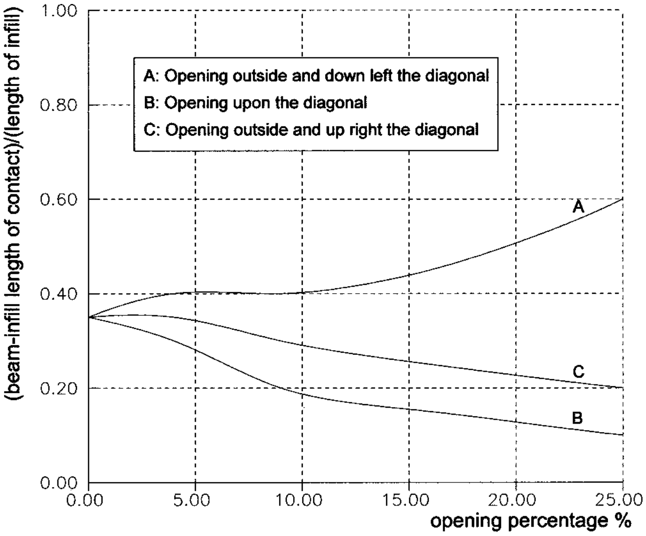

Fig. 7. Beam/infill length of contact as function of opening percentage

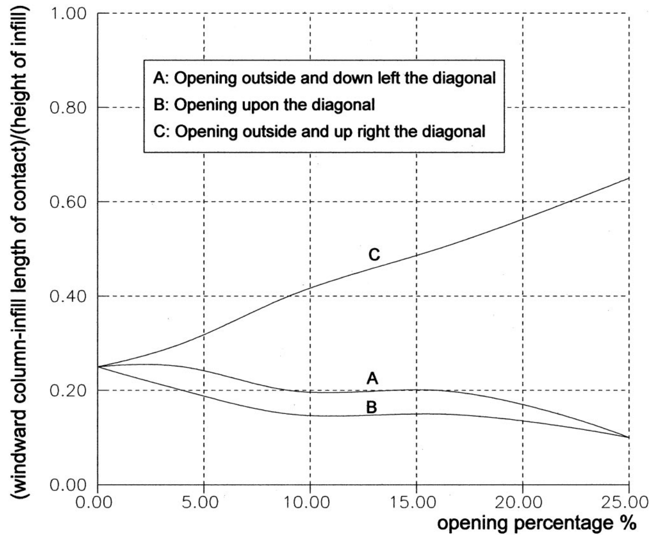

Fig. 8. Windward column/infill length of contact as function of opening percentage

is upon the diagonal. This is explained due to the action of the compressed diagonal of the infill wall, which is abolished in this case.

The presence of a 5% opening percentage for Case C in Fig. 5 leads to a "reduction" factor greater than 1 due to the fact that both the windward column/infill and base/infill lengths of contact are greater than these of a 0% opening percentage (Fig. 6).

The values of the stiffness reduction factor λ obtained from these diagrams (Figs. 3, 4, and 5) can be used to improve the estimation of the "equivalent width" of the compressed diagonal strut. For practical design purposes, based on the Mainstone's formula (Mainstone 1971), we suggest the estimation of the "equivalent width" by means of the following simplified formula:

$$(w/d) = 0.175\lambda(\lambda h)^{-0.4} \tag{3}$$

where λ = stiffness reduction factor (Figs. 3, 4, and 5), and

$$\lambda h = h\sqrt[4]{\frac{E_b t \sin 2\theta}{4E_s I h}} \tag{4}$$

in which E_b, t, and h = elastic modulus, thickness, and height of the brick masonry infill respectively; E_s and I = Young's modulus and moment of inertia of the surrounding frame member; and θ = angle between the infill diagonal and the horizontal.

In Fig. 6, dots depict the contact/interaction areas between the infill masonry wall and the surrounding frame for different opening percentages, for the same three opening positions A, B, and C. The changes to the contact lengths between infill wall and the surrounding frame are observed from case to case. The large magnitude of the variation of the contact lengths between infill and different frame members is clearly shown. Figs. 7 and 8 show the opening influence to the variation of the contact length between infill and different frame members for the three different positions studied of openings. In particular, Fig. 7 shows variations of the contact length α_b between infill and the beam. It is observed that the contact length α_b is critically dependent on the opening position. The increase of the opening percentage leads to a decrease in contact length for cases B and C but to an increase for the case A. Fig. 8 shows variation of the contact length α_c between infill and the windward column. It is also observed that the contact length α_c is critically dependent on the opening position. The increase of the opening percentage leads to a decrease in contact length for Cases A and B but to an increase for Case C.

Redistribution of Action Effects in Multistory 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 damages. The most usual case of a soft story in a building is the ground soft story (pilotis) where, opposite to the higher stories, infill walls do not exist. In this case, the stiffness of the ground story appears drastically decreased due to the decrease of infill walls. In these buildings severe damage during an earthquake appears in the vertical carrying elements of the ground story, whereas most of the other building elements remain usually undamaged. For example, after the 1978 Thessaloniki (Greece) earthquake only 16.4% of the buildings with infill walls in the ground story showed damages (in the frame or the shear walls), while the same happened to 29.8% of the buildings with a nonrigid ground story (Penelis et al. 1988).

The significance of the above finding provided the prime motive for our investigation of the shear stress distribution along the columns of infilled frames. In particular, we investigated the aseismic behavior of multistory infilled frames, compared to partially infilled frames (soft ground story, soft interim story etc.). The method of contact points was applied to the case of a three-story one-bay frame, loaded with the vertical and horizontal seismic loads simultaneously, with the value $\varepsilon = 0.30$ for the seismic coefficient. In particular, at each joint of the mesh both a vertical load is applied, which is equal to self weight and a horizontal load equal to the vertical load multiplied by the value ε of the seismic coefficient. The frame is constructed with reinforced concrete 30/50 cm sections for both columns and beams, whereas the infill wall is rectangular with a 4 m side in all three stories. The mechanical characteristics for both the reinforced concrete and the infill masonry walls are shown in Table 1.

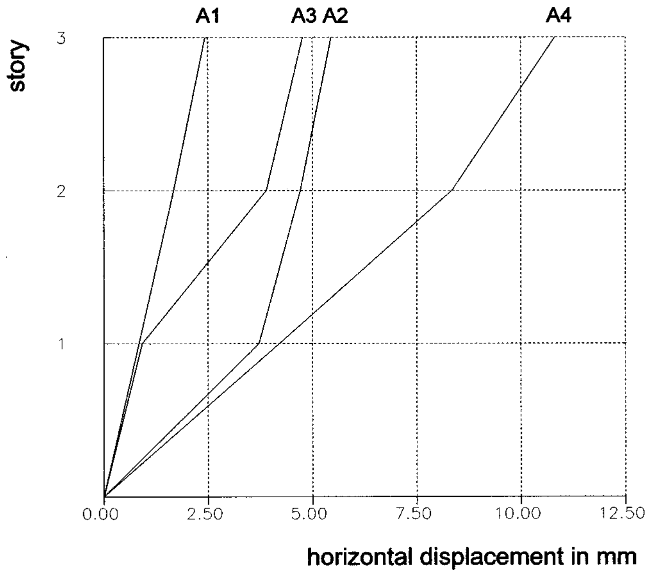

Fig. 9. Story displacements for different arrangements of infill wall

Fig. 9 shows in comparison the story displacements of a three story one bay frame infilled frame for the following four different cases:

1. Case A1: fully infilled frame,
2. Case A2: infilled frame with a soft ground story (pilotis),
3. Case A3: infilled frame with a soft second story, and
4. Case A4: the well-known bare frame.

It is observed that the infill wall (Cases A1, A2, and A3) has a considerable contribution to the stiffness and lateral resistance of the frame. In particular, the case of infilled frame with infill walls in all three stories (case A1) contributes up to a 77% decrease of the lateral displacements. Sobaih and Abdin (1988) used a method based on the concept of equivalent struts to study the behavior of multistory one-bay fully or partially infilled plane frames. According to the writers, the reduction of the lateral displacements due to the presence of infill panels in all stories of a ten-story one-bay may reach 65.8%.

In Fig. 10, contact areas between surrounding frame and infill walls for four different cases of the infill wall arrangement are depicted with dotted lines. The large magnitude of the variation of the contact lengths between infill and different frame members as well as between different frame stories is clearly shown.

As described in the previous section, when a frame is laterally loaded, a separation between frame elements and infill wall occurs at early loading stages. 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. 11 and 12 shown the shear stress distribution for two of the four cases studied in the above. According to these diagrams the main results can be summarized as follows:

1. As is expected (Tassios 1984; CEB 1994), the presence of infills leads (Cases A1 and A3) to decreased shear forces on the frame columns, since a considerable part of the seismic forces is resisted by the so-called ''nonstructural'' infill.
2. 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. 11).

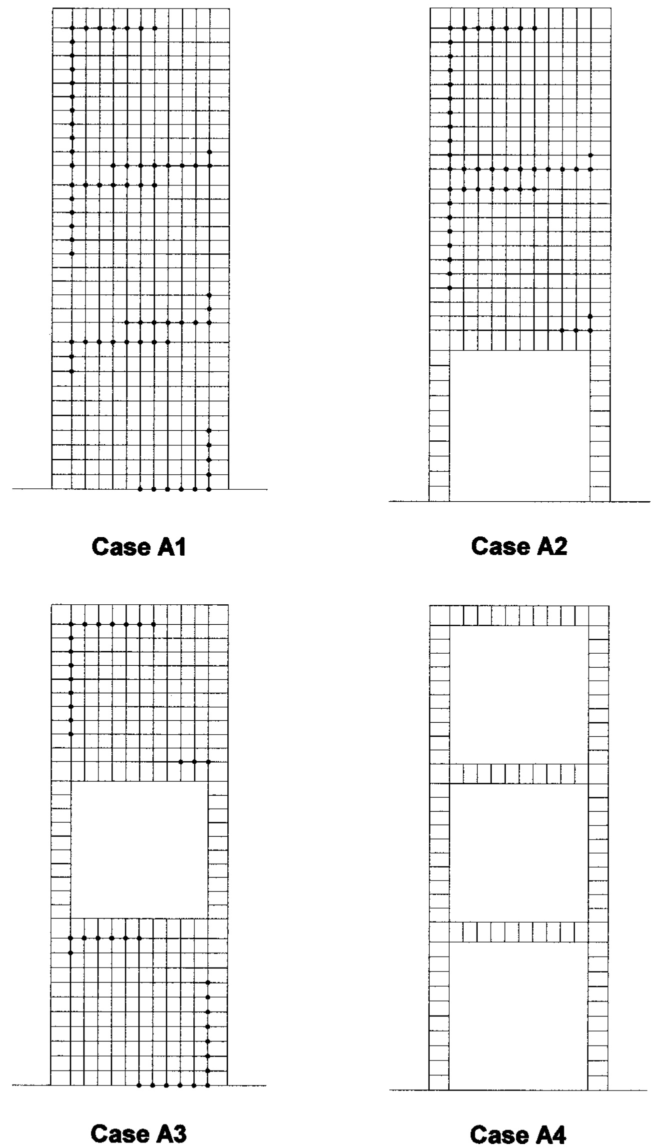

Fig. 10. Contact areas between surrounding frame and infill walls for four different cases of infill wall arrangement

3. The presence of a soft story in an infilled frame leads to a considerable change in 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 and White at Cornell University (Buonapane and White 1999) clearly state that the available methods for estimating shear strength that neglect infill–frame interaction were found to largely underestimate measured shear strength. In addition, trying to explain how a column at the top of a structure has shear higher than in the base story, they propose a possible strut mechanism that seems to be in good agreement with our results. In particular, Buonapane and White highlight the possibility of shear forces to change sign, and indicate how a column at the top of a structure has shear higher than in the base story.

Fig. 13 presents the derived deformed mesh for a three-story one-bay infilled frame with a soft second story (Case A3). The large magnitude of the variation of the contact lengths between infill and different frame members as well as between different

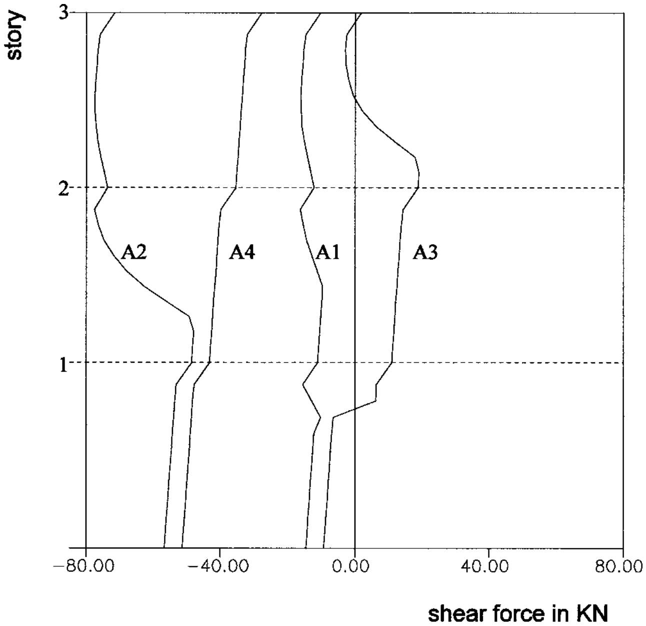

Fig. 11. Shear force diagram for windward column of three-story one-bay infilled frame (see Fig. 10). Positive shear force indicates clockwise shear force

frame stories is clearly shown. The deformed mesh in Fig. 13 shows large displacement of structure due to illustrative reasons (that is, to better show the separation of infill and surrounding frame). This is achieved by multiplying the computed displacements by a scale factor.

It should be mentioned that our future research work will focus on identifying the main areas of higher vulnerability of infilled frame, such as the ones delineated by circles in the deformed mesh of Fig. 13.

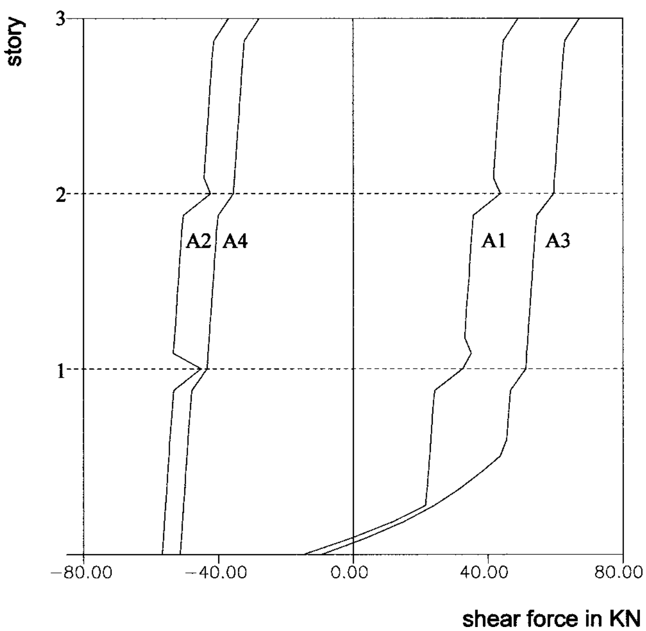

Fig. 12. Shear force diagram for right column of three-story one-bay infilled frame (see Fig. 10). Positive shear force indicates clockwise shear force

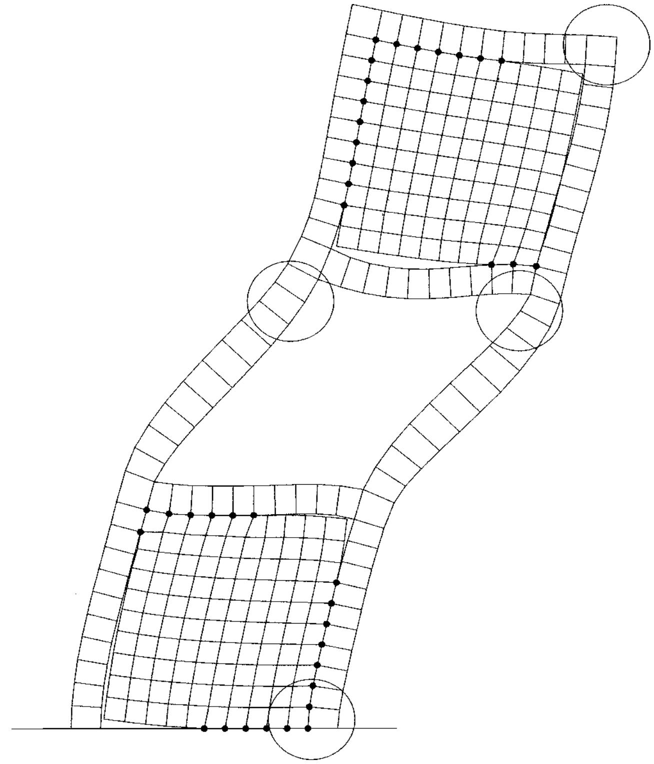

Fig. 13. Deformed mesh and main areas of higher vulnerability in three-story one-bay infilled frame with soft second story

Conclusions

A detailed parametric study of the influence of brick masonry panel on the behavior of infilled frames subjected to in-plane loads using the method of contact points for the analysis has shown the following:

1. The increase in the opening percentage leads to a decrease on the lateral stiffness of infilled frames. This decrease can reach 87% for a bare frame (100% opening). For openings exceeding 50%, the stiffness factor λ remains practically constant.
2. The overall action between the frame and the infill is adversely affected as the opening position is moved towards the compression diagonal.
3. The infill walls in multistory buildings have a considerable contribution to the stiffness and lateral resistance of frame. In particular, the case of infilled frame with infill walls in all three stories contributes to up to a 77% decrease of the lateral displacements.
4. The presence of infills leads, in general, to decreased shear forces on the frame columns. However, in the case of infilled frame with a soft ground story, the shear forces acting on columns are considerably higher than those obtained from the analysis of the bare frame.

Notation

The following symbols are used in this paper:

d = diagonal length of infill;
E_b = elastic modulus of brick masonry infill;
E_s = elastic modulus of surrounding frame;

E_x, E_y = moduli of elasticity in x and y direction, respectively;
G_{xy} = shear modulus in xy plane;
h = height of frame (on center lines of beams);
h' = height of brick masonry infill;
I = moment of inertia of frame member;
t = thickness of brick masonry infill;
w = effective width of infill;
α_c = infill/column contact length;
α_b = infill/beam contact length;
θ = angle between infill diagonal and horizontal;
λ = stiffness reduction factor of infilled frames (defined as stiffness with wall opening to stiffness without wall opening);
λh = relative stiffness parameter as defined in Eq. (4); and
ν_{xy}, ν_{yx} = Poisson's ratios in xy and yx plane respectively.

References

Asteris, P. G. (1996). ''A method for the modelling of infilled frames (method of contact points).'' *Proc., 11th World Conf. on Earthquake Engineering*, Acapulco, Mexico.

Asteris, P. G. (2000). ''Analysis of anisotropic nonlinear masonry.'' PhD thesis, National Technical Univ. of Athens, Athens Greece.

Asteris, P. G. (2003). ''Analysis of masonry infilled frames using a finite element technique.'' *J. Struct. Eng.*, in press.

Benjamin, J. E., and Williams, H. A. (1958). ''The behavior of one story brick shear walls.'' *J. Struct. Div., ASCE*, 84(4).

Buonopane, S. G., and White, R. N. (1999). ''Pseudodynamic testing of a masonry infilled reinforced concrete frame.'' *J. Struct. Eng.*, 125(6), 578–589.

Chrysostomou, C. Z. (1991). ''Effects of degrading infill walls on the nonlinear seismic response of two-dimensional steel frames.'' PhD thesis, Cornell Univ., Ithaca, N.Y.

Comité Euro-International du Béton (CEB). (1994). ''Behavior and analysis of reinforced concrete structures under alternate actions inducing inelastic response: Volume 2: Frame members.'' *Bulletin D'Information No 220*.

Dhanasekar, M., and Page, A. W. (1986). ''Influence of brick masonry infill properties on the behaviour of infilled frames.'' *Proc., Inst. Civ. Eng., Struct. Build.*, 81, 593–605.

Giannakas, A., Patronis, D., and Fardis, M. (1987). ''The influence of the position and the size of openings to the elastic rigidity of infill walls.'' *Proc., 8th Hellenic Concrete Conf.*, Xanthi, Kavala, Greece, 49–56.

Holmes, M. (1961). ''Steel frames with brickwork and concrete infilling.'' *Proc., Inst. Civ. Eng., Struct. Build.*, 19, 473–478.

Koiter, W. T. (1953). ''Stress–strain relations, uniqueness and variational theorems for elastic-plastic materials with a singular yield surface.'' *Q. Appl. Math.*, XI, 350–354.

Liauw, T. C. (1979). ''Tests on multistory infilled frames subject to dynamic lateral loading.'' *J. Am. Concr. Inst.*, 76(4), 551–560.

Liauw, T. C., and Kwan, K. H. (1984). ''Nonlinear behaviour of non-integral infilled frames.'' *Comput. Struct.*, 18, 551–560.

Liauw, T. C., and Lee, S. W. (1977). ''On the behaviour and analysis of multi-story infilled frames subject to lateral loading.'' *Proc., Inst. Civ. Eng., Struct. Build.*, 63, 641–656.

Mainstone, R. J. (1971). ''On the stiffnesses and strengths of infilled frames.'' *Proc. Inst. Civ. Eng., Struct. Build.*, (iv), 57–90.

Mallick, D. V., and Garg, R. P. (1971). ''Effect of openings on the lateral stiffness of infilled frames.'' *Proc., Inst. Civ. Eng., Struct. Build.*, 49, 193–209.

Mehrabi, A. B., and Shing, P. B. (1997). ''Finite element modeling of masonry-infilled RC frames.'' *J. Struct. Eng.*, 123(5), 604–613.

Mehrabi, A. B., Shing, P. B., Schuller, M., and Noland, J. (1996). ''Experimental evaluation of masonry-infilled RC frames.'' *J. Struct. Eng.*, 122(3), 228–237.

Page, A. W. (1981). ''The biaxial compressive strength of brick masonry.'' *Proc., Inst. Civ. Eng., Struct. Build.*, 71, 893–906.

Penelis, G., Sarigiannis, D., Stayrakakis, E., and Stylianidis, K. (1988). ''A Statististical evaluation of damage to buildings in the Thessaloniki Greece earthquake of June 20, 1978.'' *Proc., 9th World Conf. on Earthquake Engineering*, Tokyo-Kyoto, Japan.

Saneinejad, A., and Hobbs, B. (1995). ''Inelastic design of infilled frames.'' *J. Struct. Eng.*, 121(4), 634–650.

Smith, B. S. (1962). ''Lateral stiffness of infilled frames.'' *J. Struct. Div., ASCE*, 88(6), 183–199.

Smith, B. S. (1966). ''Behavior of square infilled frames.'' *J. Struct. Div., ASCE*, 1, 381–403.

Smith, B. S., and Carter, C. (1969). ''A method of analysis for infilled frames.'' *Proc. Inst. Civ. Eng., Struct. Build.*, 44, 31–48.

Sobaih, M., and Abdin, M. M. (1988). ''Seismic analysis of infilled reinforced concrete frames.'' *Comput. Struct.*, 30(3), 457–464.

Syrmakezis, C. A., and Asteris, P. G. (2001). ''Masonry failure criterion under biaxial stress state.'' *J. Mater. Civ. Eng.*, 13(1), 58–64.

Tassios, T. P. (1984). ''Masonry infill and R. C. walls (An invited state-of-the-art report).'' *Proc., 3rd Int. Symp. on Wall Structures*, Warsaw, Poland.

Utku, B. (1980). ''Stress magnifications in walls with openings.'' *Proc., 7th World Conf. on Earthquake Engineering*, Vol. 4, Istanbul, Turkey, 217–224.

Vintzeleou, E., and Tassios, T. P. (1989). ''Seismic behaviour and design of infilled R.C. frames.'' *Proc., J. European Earthquake Eng.*, 2, 22–28.