11 WCEE

Paper No. 1675. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

EFFECT OF GEOMETRICAL CONFIGURATION ON THE SEISMIC RESPONSE OF INFILLED FRAMES

K. M. Mosalam[I], P. Gergely[I], R. N. White[I] and A. G. Ayala[II]

[I] School of Civil and Environmental Engineering, Cornell University,
Ithaca, N.Y. 14853, USA.
[II] Institute of Engineering, National Autonomous University of Mexico,
Mexico D.F. 04510, MEXICO.

ABSTRACT

The seismic performance of infilled frames was investigated using quasi-static and pseudo-dynamic experimentation. In these experiments, several geometrical parameters were varied. An analytical study was conducted using the finite element method to investigate the effect of the size of wall openings in the form of windows on the lateral stiffness of infilled frames. Based on the results of the experimental study and the finite element analysis, an approximate yet practical strut model of the infill walls was evaluated.

KEYWORDS

Infill walls; steel frames; masonry; semi-rigid connections; wall openings; quasi-static experimentation; pseudo-dynamic experimentation; finite elements.

INTRODUCTION

Reliable evaluation of the seismic behavior of new and existing frames with infills requires that available computational tools be capable of predicting the seismic performance in the nonlinear range of behavior. Some efforts have been directed towards the definition of mechanical models to simulate the seismic behavior of infill walls. Inappropriate considerations of material nonlinearities and frame/wall interface conditions have led to only a partial success of these efforts. A complete review of research activities on infilled frames through 1987 has been reported in (Moghaddam and Dowling, 1987).

The validation of numerical models for infill walls requires measured results obtained from realistic experiments designed for accurate representation of the structural configuration (i.e. geometrical and material properties and boundary conditions). Unfortunately, most previous experiments on frames with infills have concentrated on static monotonic load tests performed on the simplest structural configuration, i.e. single-bay, single-story infilled frame. The infill walls in most of these frames were solid panels, i.e. without openings.

In this paper, the results obtained from quasi-static cyclic and pseudo-dynamic experiments are discussed. The models used in these experiments were Semi-Rigidly Connected Steel (SRCS) frames infilled with UnReinforced concrete block Masonry (URM). These frames were Gravity-Load Designed (GLD) to represent construction in the eastern and central United States. Because openings increase the difficulty in defining a simple model, finite element analysis was used as a reliable means to predict the detailed characteristics of the response. Based on the experimental and the finite element results, the definition and validation of a simple accurate model to represent the seismic behavior of infill walls was investigated. The proposed model for a wall element accounts for the *material* and *geometrical* nonlinearities introduced by the change of frame/wall interface conditions during the loading.

EXPERIMENTAL INVESTIGATION

Description of Experiments

Several reduced-scale experiments have been carried out at Cornell University to study the performance of infilled GLD frames under earthquake like loading. The parameters varied in these experiments include: (1) number of bays and stories and (2) different openings (door versus window and symmetric versus asymmetric arrangements). The characteristics of the tested specimens are summarized in Table 1. All specimens consist of SRCS frames infilled with URM non-integral walls (i.e. without shear connectors between the frame members and the walls).

Table 1. Experimental Program

Test	Openings	# of bays	# of stories	$f_b^{\square}$(psi)	$f_m^{\triangle}$ (psi)	f_b/f_m
IF1	None	1	1	1000	1700	0.59
IF2	None	2	1	1000	2500	0.40
IF3	None	2	1	1500	1700	0.88
IF4	Symmetric$^{\bullet}$	2	1	2100	2500	0.84
IF5	Asymmetric*	2	1	1500	2000	0.75
IF6	Symmetric†	2	2	2100	2700	0.72

• windows ⋆ window and door † in the 2nd story only

□ block compressive strength based on gross area

△ mortar cube compressive strength

The single-story specimens were subjected to quasi-static cyclic lateral displacements of increasing amplitude applied at the top of the central column. To investigate the effect of repeated load on strength and stiffness degradation, three cycles of the same displacement amplitude were applied. The applied displacement pattern consisted of two sets of displacement histories as illustrated in Fig. 1(a), for the specimens with solid panels, and Fig. 1(b), for the specimens with panels including openings. The second set of displacement cycles (Set (B)) was used to study the performance of the structure with previously cracked walls. Displacements were applied in small increments (0.006 *in*) as long as the corresponding load changes were large ($\geq$ 300 *lb*). These increments were increased to 0.012 *in* and sometimes 0.018 *in* when load changes were small ($<$ 100 *lb*). The application of the smallest displacement increments was very important for Set (A) where small changes of applied displacement led to large changes of load, i.e. stiff behavior. Another advantage of this *dual* control technique is to capture the abrupt changes of behavior due to the opening and closing of frame/wall interface gaps and wall cracks without the application of an excessive number of displacement increments.

The two-story infilled frame was tested pseudo-dynamically using the method and scheme described in (Mosalam *et al.*, 1996). In this method, on-line computations are conducted to determine an appropriate displacement pattern where both dynamic effects and progressive damage of the tested specimen are included in the statically imposed displacements.

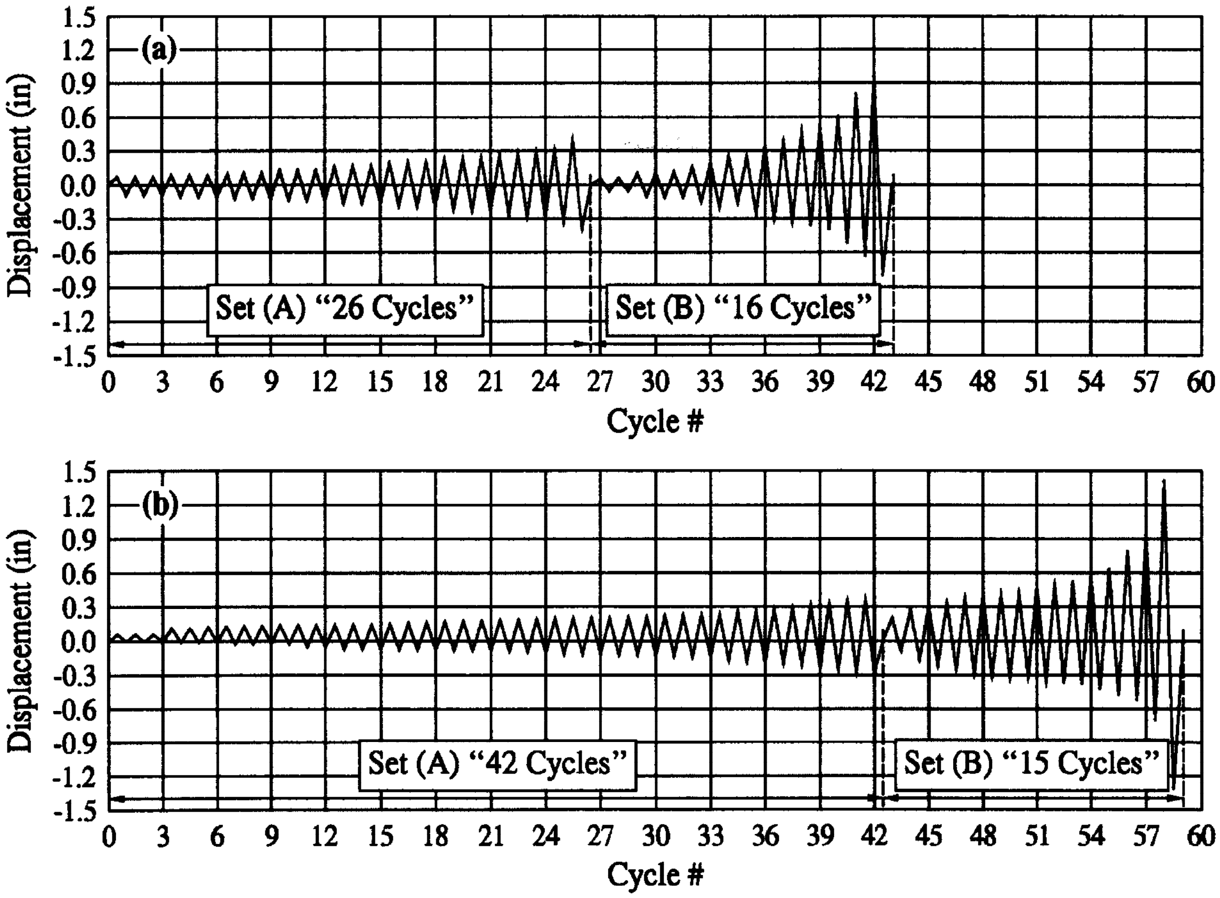

Fig. 1. Displacement patterns applied quasi-statically. (a) Test IF3; (b) Test IF5.

Experimental Results and Discussions

The test specimen, designated IF3 in Table 1, was subjected to the displacement pattern illustrated in Fig. 1(a). The load/displacement relationships corresponding to the imposed lateral displacement Sets (A) and (B) are shown in Fig. 2. From Set (A) of this figure, the following three distinctive zones may be observed:

1. *Zone of non-active walls*: Represents the behavior of the frame without the interaction of the infills. Its extent is defined by the pre-existing gaps between the frame columns and the walls. These gaps are due to shrinkage of the mortar and blocks.
2. *Zone of walls with non-degrading strength*: Walls interact with the bounding frame showing some stiffness degradation and small energy dissipation due to hysteresis.
3. *Zone of walls with degrading strength*: Initiates immediately after wall cracking when the response starts to show degradation of both stiffness and strength with large energy dissipation due to hysteresis.

For Set (B), similar zones to those of Set (A) may also be identified. In this case, however, the corresponding first zone has become larger due to sliding along the pre-existing cracks especially those along the mortar bed joints. As initial cracking of the walls (due to Set (A)) was stable, the second and third zones showed large stiffness degradation without further strength deterioration.

In Fig. 3, the envelopes of the load/displacement relations obtained from test IF3 are compared with those obtained from test IF5. It can be observed that infilled frames including openings show less

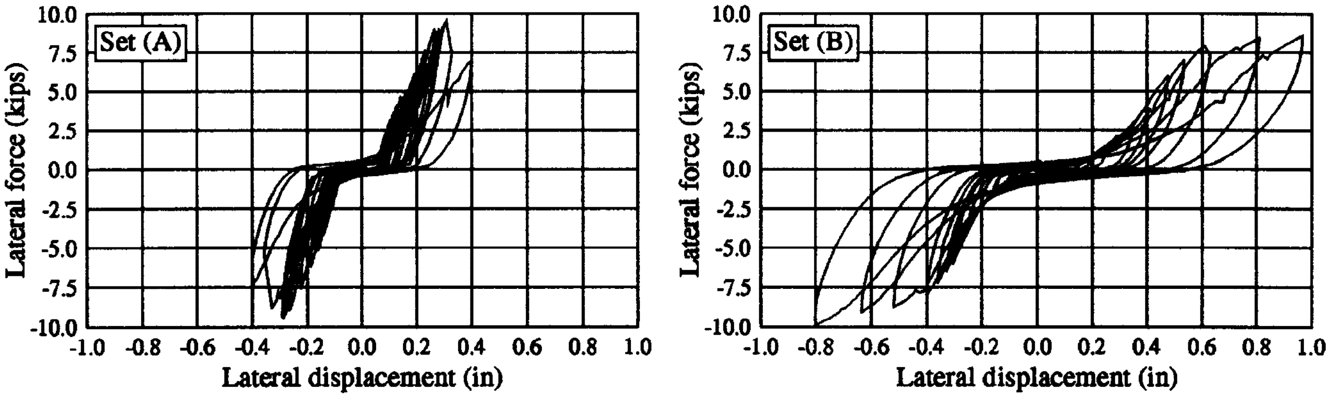

Fig 2. Load/displacement relations obtained for test IF3.

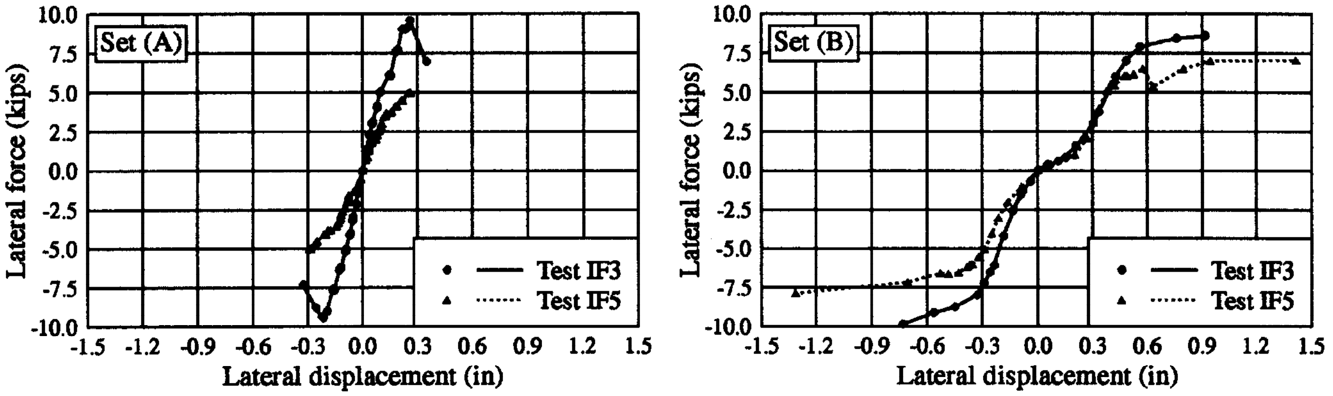

Fig 3. Load/displacement envelopes obtained for tests IF3 and IF5.

strength and more ductile behavior than the frames with solid infills. In these envelopes, the zones of non-active walls are eliminated as their sizes are uncertain because they depend on the shrinkage characteristics of the masonry and also on the level of workmanship.

Close to the end of Set (A), several cracks appeared along the mortar bed and head joints in test IF3. Horizontal cracks appeared first in the center of the rectangular solid infill walls, subsequently propagating diagonally towards the loaded corners. This crack pattern is illustrated in Fig. 4(b), where thick lines indicate fully open cracks and thinner lines indicate pre-existing closed cracks. For IF1 and IF2, however, failure was by corner crushing only, as shown in Fig. 4(a) and reported in (Zawilinski, 1994). The difference in modes of failure between IF2 and IF3 may be attributed to the difference in the relative strength between the block strength (f_b) and the mortar strength (f_m) as reported in Table 1.

Cracks in masonry infill walls tend to *dilate*, i.e. cracks widen due to shear along crack surfaces. This phenomenon is illustrated in Fig 4(b), where shearing in the X-direction along the crack, marked H, causes the crack to widen in the Y-direction. Therefore, the wall tends to swell and push towards the

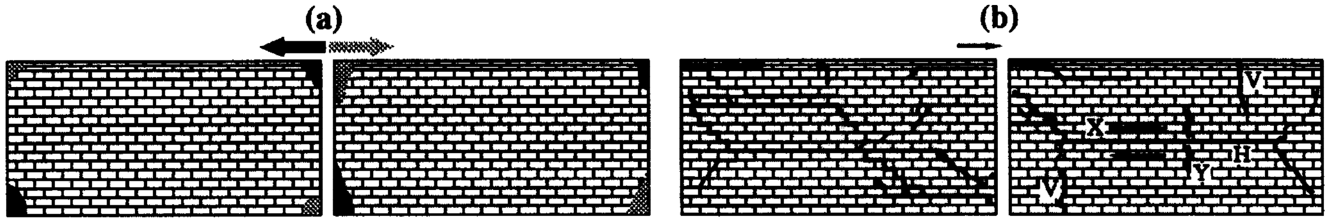

Fig. 4. Modes of failure after Set (A). (a) Test IF2; (b) Test IF3.

frame beams producing the vertical cracks, marked V. This observation explains the tight fit of the infill wall inside the frame after the completion of Set (A). On the contrary, in IF1 and IF2, because of the absence of mortar cracking, after Set (A), the wall became loose and Set (B) could not be applied.

Crack patterns were affected by the presence of openings, either door or window. An example of them is shown in Fig. 5. It should be noted that openings forced the cracks to initiate at their corners. Subsequently, these cracks propagated towards the loaded corners, as in the case of solid panels.

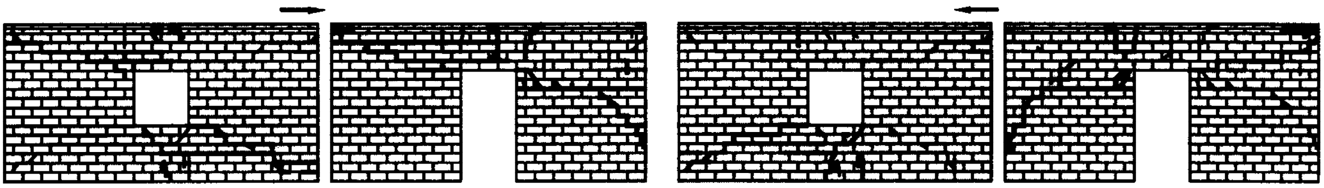

Fig. 5. Crack patterns obtained for test IF5 after Set (A)

In the pseudo-dynamic experiment, specimen IF6 was subjected to a sequence of scaled records of the S69E component of the 1952 Taft earthquake. The scaling was based on the Peak Ground Acceleration (PGA). Up to a PGA of $0.15g$, no visible damage was detected. The observations on the load/displacement relationships and the crack patterns obtained from the quasi-static experiments are also applicable for this experiment. The story shear/story drift relationships and the corresponding crack patterns for a record with a PGA of $0.275g$ are illustrated in Figs. 6 and 7, respectively.

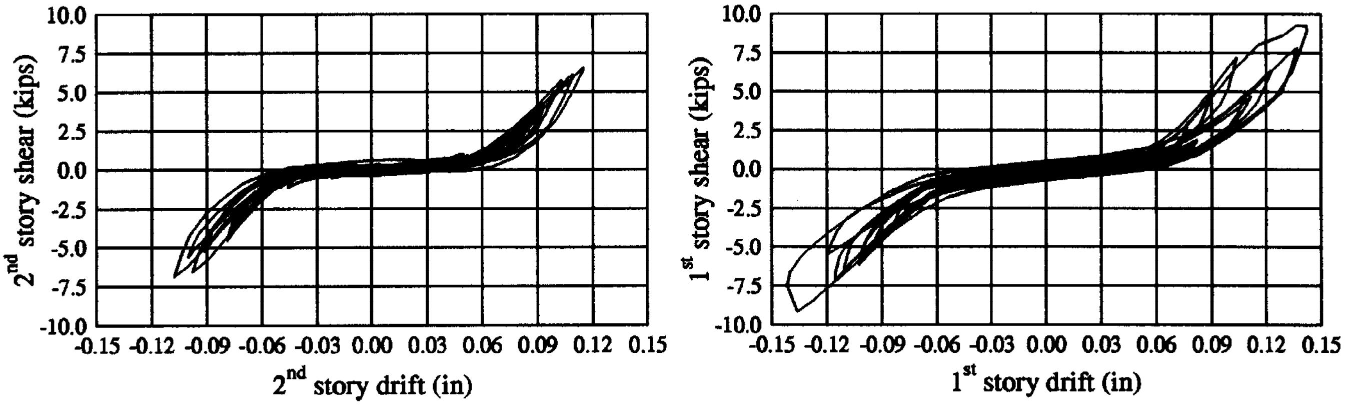

Fig. 6. Story shear/story drift relationships for the $0.275g$ Taft earthquake

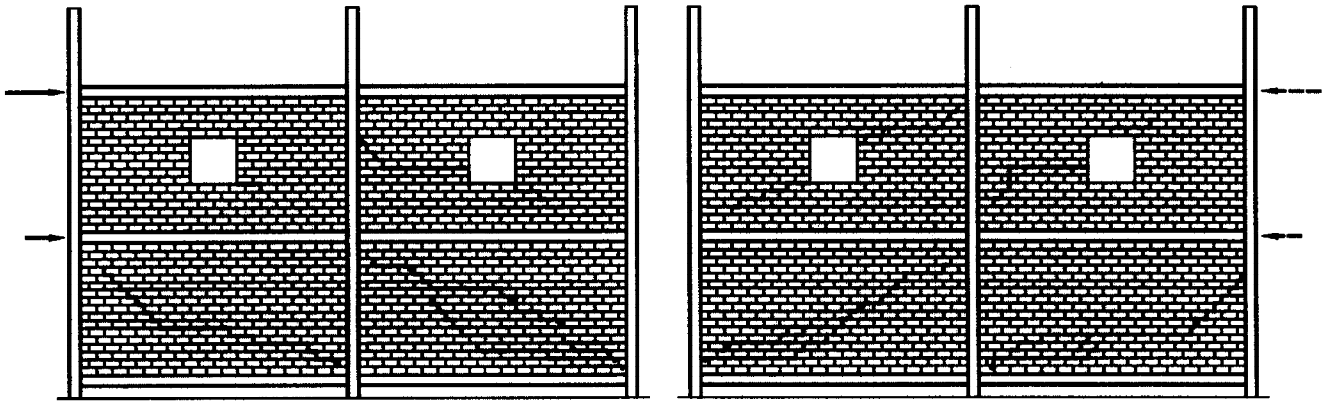

Fig. 7. Crack patterns under the $0.275g$ Taft earthquake

FINITE ELEMENT ANALYSIS

Several researchers have used Finite Elements (FE) to analyze frames with filler walls. Mallick and Severn (1967) pioneered this approach by accounting for interface conditions between the frame and the infill wall. In this paper, a smeared crack finite element model is adopted to characterize the effect of opening size on the stiffness of test IF4 listed in Table 1. The FE code DIANA (1993), developed at TNO Building and Construction Research in the Netherlands, is used in this numerical investigation. The FE analysis was intended to complement the experimental data as for the complicated case of panels with openings, the properties and arrangements of equivalent struts are difficult to select. The used FE model together with the used material parameters are shown in Fig. 8. The results of these FE analyses are shown in Fig. 9. It may be observed that for either uncrcaked or cracked walls, the variation of the wall stiffness ratio is *linear* function of the opening area. Between the uncracked and cracked states, there is a transition zone which is a function of the intensity of the applied displacement.

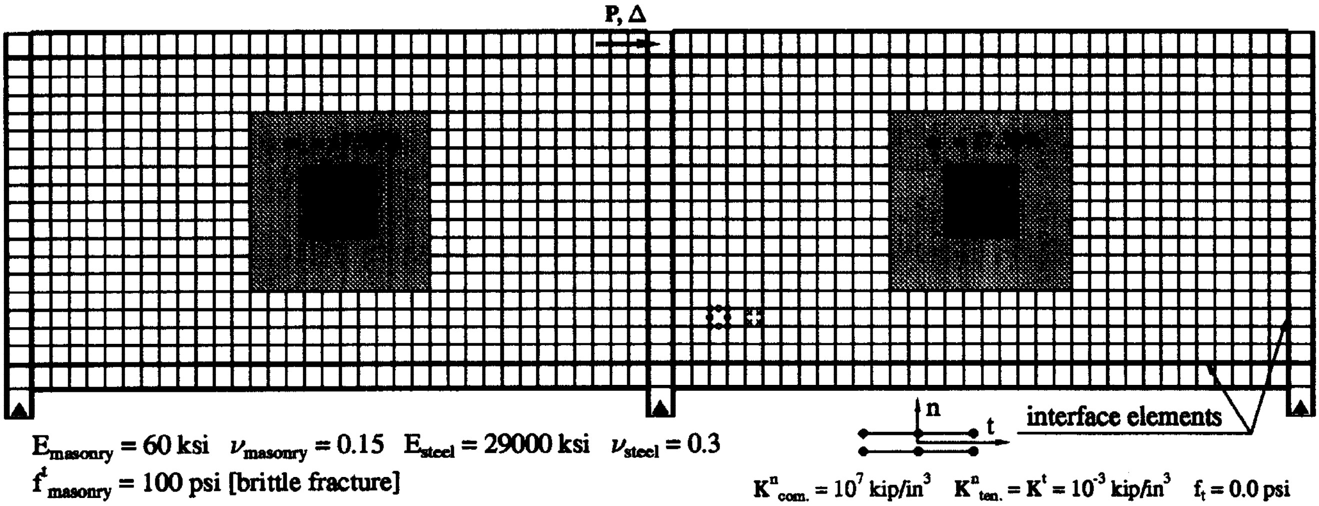

Fig. 8. FE model and material parameters

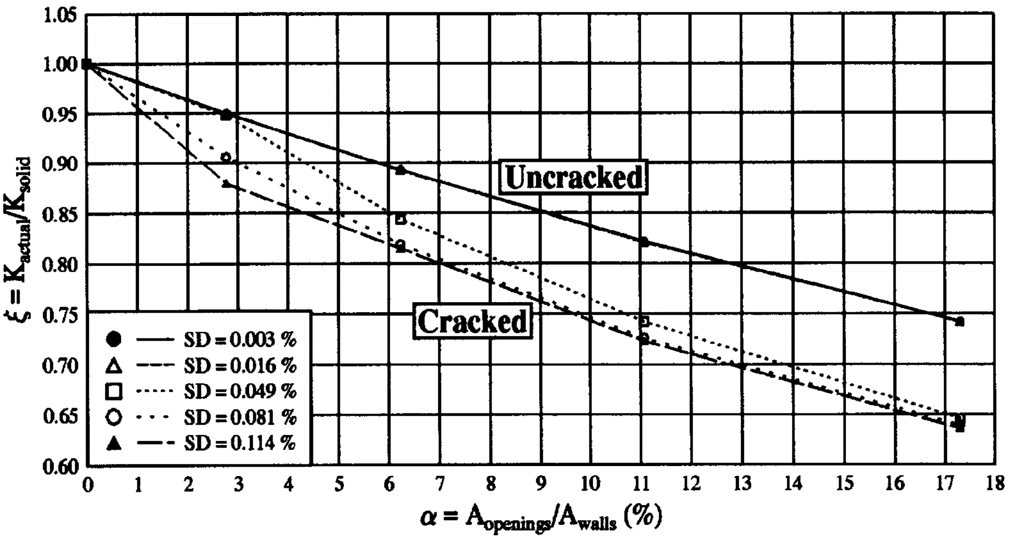

Fig. 9. Effect of opening size on infilled frame lateral stiffness (SD = Story Drift)

EQUIVALENT STRUT MODEL

The composite action between the infill wall and the bounding frame depends on the area of contact between these two components and on the interface conditions (i.e. existence or absence of shear

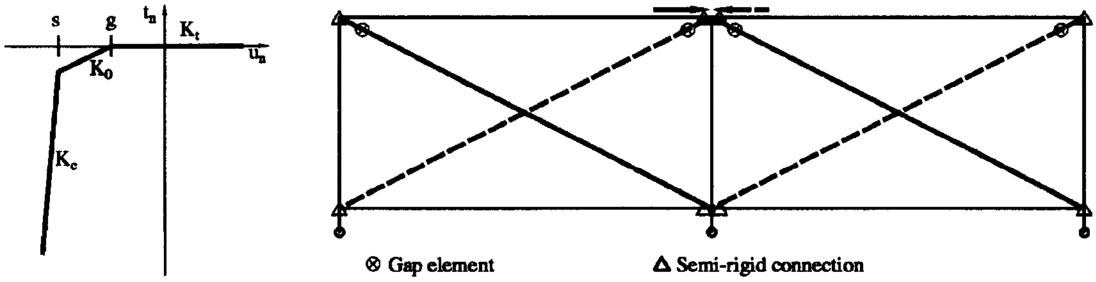

FIG. 10. Compression-only equivalent strut model for infilled SRCS frame

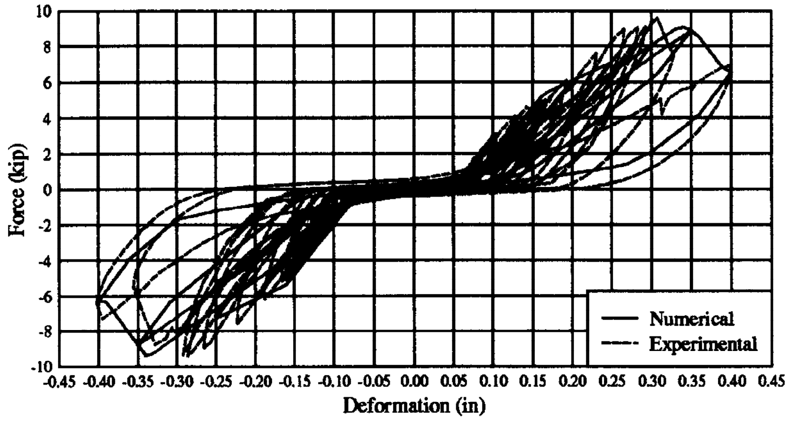

FIG. 11. Load/displacement for two-bay, single-story infilled SRCS frame

connectors). The present research focuses on non-integral infill walls where *partial* composite action between the wall and the surrounding fames occurs. From this perspective, compression-only struts are used to represent the contribution of the infill panel to the stiffness and strength of the infilled frame. The first researcher to introduce the concept of *equivalent strut* was Holmes (1961) who estimated the effective width of the strut to be one-third of the steel frame diagonal length. This was later modified by Stafford-Smith and Carter (1969) where the strut width was found to be inversely proportional to the frame/infill relative stiffness. However, slippage along the steel frame/wall interface was neglected which led to an overestimation of the equivalent strut stiffness. Barua and Mallick (1977) proposed a simple expression for the equivalent strut stiffness which yields a lower value than the formulae given by Stafford-Smith and Carter (1969).

The model used for the case of a two-bay, single-story steel frame with solid infill walls and equivalent strut width as in (Barua and Mallick, 1977) is illustrated in Fig. 10. The struts work only in compression as indicated by drawing the acting strut with the same line type as the loading direction. This feature is provided by adding a *gap element* in the direction of the strut (n-direction) which is governed by the shown constitutive model. The zone characterized by the slope, K_0, represents the transition from zero stiffness in tension, K_t, to very high stiffness in compression, K_c. The size of the initial gap (g) defines the beginning of this transition zone. The end of this zone (s) is the summation of the gap size and the amount of deformation required to crush the roughness of both the wall and the frame along the interface. The semi-rigid connections are modeled using rotational springs which behave in elastic/perfectly plastic manner. The strut itself is governed by the *Von Mises* yield criterion with strain hardening/softening. As discussed previously, Set (A) included several levels of displacement magnitudes. These different magnitudes were repeated in groups of three cycles each. In the present analysis, only one cycle of each group was applied. The obtained load/displacement relationship is plotted in Fig. 11. Experimental results are shown for comparison. It may be concluded that the model captures the basic characteristics of the behavior, i.e. the three zones mentioned above.

CONCLUSIONS

Results of current experimental and analytical research activities at Cornell University on infilled frames have been briefly presented. From their analyses, the following conclusions may be drawn:

1. Cracking in masonry infills under seismic loading initiates in and mostly propagates along the mortar bed and head joints aligned with the compressed diagonal.
2. Cracks initiate at the center of the solid panels and, when openings exist, at their corners and subsequently, propagate towards the loaded corners of the wall.
3. The mode of failure of concrete block masonry infills may change from mortar cracking to corner crushing due to changes of the relative strength between the blocks and the mortar.
4. Finite element analyses can provide useful information on the effect of openings on the lateral stiffness of infilled frames.
5. The global behavior of infilled frames can be accurately captured using the equivalent strut model modified to account for the changes of stiffness due to interface conditions and the effect of openings.

ACKNOWLEDGEMENTS

This research is sponsored by the National Center for Earthquake Engineering Research (NCEER). Opinions and findings expressed herein are those of the authors, and do not necessarily represent those of the NCEER. Special thanks to Mrs. A. Ayala for neat editorial revision of this paper.

REFERENCES

Barua, H. K. and S. K. Mallick (1977). Behavior of mortar infilled steel frames under lateral load. *Building and Environment*, **12**, 263-272.

DIANA-Finite Element Analysis (1993). User's manual, release 5.1. TNO Building and Construction Research, Department of Computational Mechanics, Delft, The Netherlands.

Holmes, A. W. (1961). Steel frames with brickwork and concrete infilling. *Proc. Instn of Civ. Engrs*, **19**, 473-478.

Mallick, D. V. and R. T. Severn (1967). The behavior of infilled frames under static loading. *Proc. Instn of Civ. Engrs*, **38**, 639-656.

Moghaddam, H. A. and P. J. Dowling (1987). The state of the art in infilled frames. *ESEE research report no. 87-2*, Imperial College of Science and Technology, Civil Engrg. Dept., London.

Mosalam, K. M., R. N. White, P. Gergely and G. Ayala (1996). Seismic performance of infilled frames using on-line computer controlled experiments. *Proc. Cairo 1st inter. conf. on concrete structures*, Cairo, Egypt, 283-292.

Stafford-Smith, B. and C. Carter (1969). A method for the analysis of infilled frames. *Proc. Instn of Civ. Engrs*, **44**, 31-48.

Zawilinski, D. J. (1994). Experimental investigation of infilled frames under lateral loading. *M.Sc. thesis*, Cornell University, Ithaca, NY.