MODELING OF MASONRY INFILL PANELS FOR DYNAMIC ANALYSIS

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ABSTRACT:

The performance of reinforced concrete (RC) infilled frames during earthquakes shows that the behaviour is very much dependent on the performance and mode of failure of the infill masonry walls. The concrete frame may fail as a consequence of the infill wall failure before reaching the bare frame load resistance levels. Even though frame-infill interaction has sometimes led to undesirable structural performance, recent studies have shown that a properly designed infilled frame can be superior to a bare frame in terms of stiffness, strength, and energy dissipation. The objective of this paper is to present a new finite element model based on prescribed failure planes in the infill panels, where Drucker-Prager failure criterion is used to simulate the behaviour of masonry. Interface elements are used to describe the behaviour of masonry panel along the prescribed failure planes. The elasto-plastic behaviour of mortar and cracked masonry along the failure planes are considered in the analysis. The proposed model was incorporated in a generic nonlinear structural analysis program for static and dynamic analysis of masonry infilled reinforced concrete frames. Simulations of experimental force-deformation behaviour of large scale infilled frame are performed to validate the proposed model.

KEYWORDS: Infilled frames, Masonry, Reinforced concrete, Frames, Modeling, Finite element

1. INTRODUCTION

The moment resisting frame is one of the most commonly used lateral load resisting system in modern structures because it is suitable for low and medium rise buildings and industrial structures. It can be designed to behave in a ductile manner under seismic loads. Many existing RC frame buildings were not designed for seismic resistance or detailed for ductile behaviour. Masonry infills have traditionally been used in buildings as partitions and for architectural or aesthetic reasons. They are normally considered as non-structural elements, and their effect on the structural system has been ignored in the design. However, even though they are considered non-structural elements, there is mounting evidence that they interact with the frame when the structures are subjected to lateral loads (Lee and Woo, 2002). This interaction may or may not be beneficial to the performance of the structure, and it has been a topic of much recent debate (Shing and Mehrabi, 2002).

Infill walls have been identified as a contributing factor to catastrophic structural failures during earthquakes. Frame-infill interaction can induce brittle shear failures of reinforced concrete columns by creating a short column. Furthermore, infills can over-strengthen the upper stories of a structure and when they fail a soft first storey is created, which is highly undesirable from the earthquake resistance standpoint. If properly designed, detailed and constructed masonry infill can improve the earthquake resistance of a frame structure. The increase in strength is also associated with increase of the initial stiffness of the structure and may result in adverse increase of the inertia force. The damage to the structure may be reduced by dissipating a considerable portion of the input energy in the masonry infills or at the interface between the infills and the frame.

In most of the current seismic codes, the influence of non-structural masonry infills is ignored. In spite of the numerous studies in past years, many of the controversial issues still remain. The main difficulty in evaluating the performance of an infilled structure is to determine the nature of interaction between the infill and the frame, which has a major impact on the structural behaviour and load-resisting mechanism.

2. FAILURE MECHANISMS

The behaviour of masonry-infilled reinforced concrete frames subjected to in-plane lateral loads was investigated by a number of researchers. Studies have shown that infilled frames can develop a number of possible failure mechanisms, depending on the strength and stiffness of the bounding frame with respect to those of the infill and the geometric configuration of the framing system (Shing and Mehrabi, 2002).

On the basis of experimental observations, five main failure mechanisms of infilled frames are identified as illustrated in figure 1, and can be summarized as following (Shing and Mehrabi 2002); ***Mode-A*:** is a purely flexural mode in which the frame and the infill act as an integral flexural element. This behaviour can occur at a low load level, where the separation of the frame and the infill has not occurred; it rarely evolves into a primary failure mechanism, except for tall slender frames that have very low flexural reinforcement in the columns; ***Mode-B:*** is a failure mechanism that is characterized by a horizontal sliding crack at the mid-height of an infill. This introduces short-column behaviour and is therefore highly undesirable; ***Mode-C:*** diagonal cracks propagate from one loaded corner to the other; and these can sometimes be jointed by a horizontal crack at mid-height. In this case, the infill can develop a diagonal strut mechanism that can eventually lead to corner crushing and plastic hinges or shear failure in the frame members; ***Mode-D:*** is characterized by the sliding of multiple bed-joints in the masonry infill. This often occurs in infills with weak mortar joints, and can result in a fairly ductile behaviour, provided that the brittle shear failure of the columns can be avoided. In Mechanism-D, the frame and the infill are considered as two parallel systems with displacement compatibility at the compression corners; ***Mode-E:*** exhibits a distinct diagonal strut mechanism with two distinct parallel cracks. It is often accompanied by corner crushing. Sometimes, crushing can also occur at the centre of the infill.

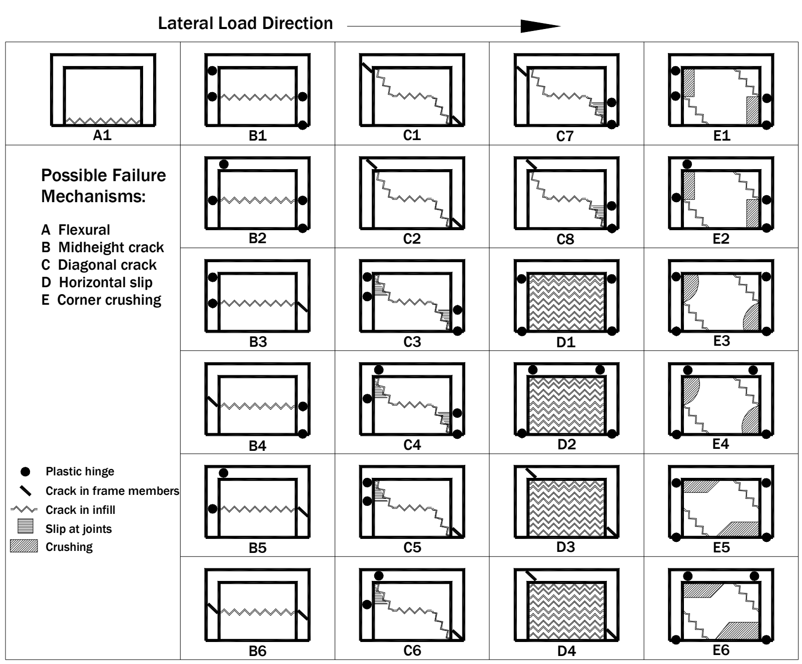


Figure 1 Failure mechanisms of infilled frames (Shing and Mehrabi, 2002).

3. MODELING OF MASONRY INFILL PANELS IN RC FRAMES

3.1. Equivalent Diagonal Strut Model (Macro-Model)

In this method, an infilled frame structure is modeled as an equivalent braced frame system, with a compression diagonal replacing infill panels. The diagonal strut concept may be used to predict behaviour prior to panel cracking but cannot predict nonlinear load-deformation behaviour and ultimate strength (Dawe et al. 2001). The use of an equivalent strut model to calculate the strength of an infilled frame is rather inadequate for a number of reasons. Most importantly, an infilled frame has a number of possible failure modes caused by the frame-infill interaction, and a compression strut type failure is just one of many possibilities.

3.2. Finite Element Model (Micro-Model)

A masonry infilled panel was modeled as an assemblage of rectangular elastic zones separated by joints with limited shear and tensile capacity. The elastic zones are modeled by rectangular orthotropic plane stress elements and are interconnected by joint elements. The specific nature of the orthotropy of these elements is described by Seah (1998). The use of micro-modeling is too time-consuming for analysis of large structures. Therefore, finite element analyses are useful only for small structures.

4. PROPOSED MODELING OF MASONRY INFILLED RC FRAMES

A simple new model for masonry panel is presented. This model can simulate most of the masonry panel failure modes with small number of elements. The proposed model will avoid the disadvantages of both Equivalent strut and Finite element models. Details of the model are shown in figure 2.

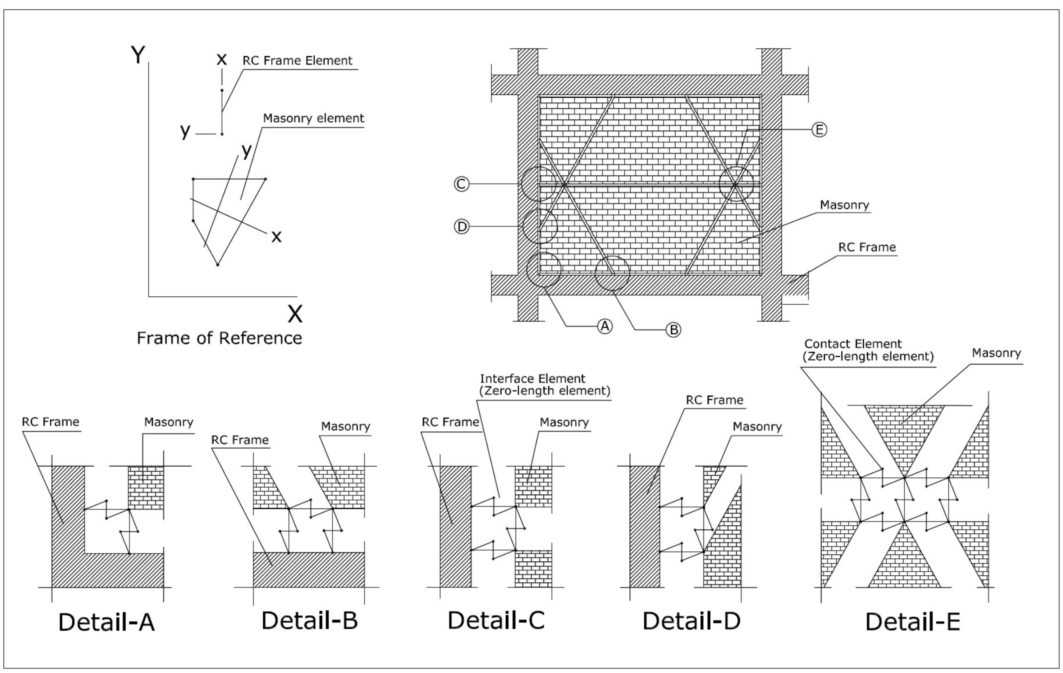


Figure 2 Details of the proposed model.

The model consists of 10 2-D elements with two degrees of freedom per node to represent the masonry material, joint elements to connect among the 2-D elements, and interface elements to connect between 2-D elements and the surrounding RC frames. Figure 3 shows the capability of the proposed model to simulate different failure modes of masonry panel in infilled RC frames.

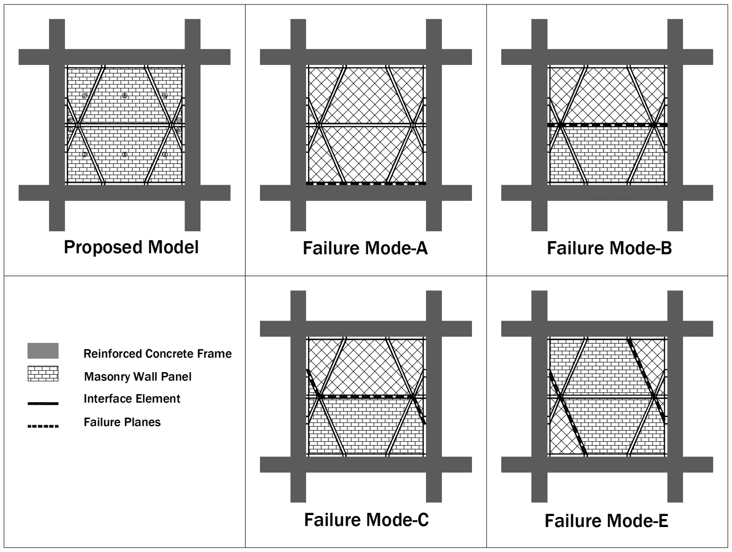


Figure 3 Capability of proposed model to simulate different failure modes of masonry panel.

The Open System for Earthquake Engineering Simulation (OpenSees) code (OpenSees, 2006) was selected to verify the proposed model against numerical and experimental results.

5. MATERIAL MODELING

5.1 Reinforced Concrete Frame

Different sections of RC frame members will be modeled using Fiber Section object. A fiber section has a general geometric configuration formed by subregions of simpler, regular shapes called patches. Nonlinear Beam-Column element is used to model members of RC frame.

Materials type Steel01 and Concrete01 (OpenSees, 2006) are used to model reinforcing steel and concrete in RC frame members. Pinching4 material was used to include the pinching, stiffness degradation and strength deterioration effects to the behaviour of the moment resisting RC frame. Cyclic degradation of strength and stiffness occurs in three ways: unloading stiffness degradation, reloading stiffness degradation, strength degradation.

5.2 Masonry Panel

The four-noded isoparametric element was used to model the infill panel. Drucker-Prager failure criterion was used to simulate the behaviour of masonry. Tensile strength is assumed to be 10% of the compressive strength for un-reinforced masonry.

5.3 Interface Elements

Mortar joint elements are modeled using Zero-Length Element. This element accepts specifying two different material types (or relations) in any two arbitrary directions. First material type is used to describe the behaviour of mortar joint in normal direction, and the second type is used to describe behaviour of mortar joint in shear direction. Material type Concrete01 is used to simulate the behaviour of mortar joints under uniaxial compression and cyclic loading. Hardening Material model is used to represent the behaviour of mortar joint under direct shear.

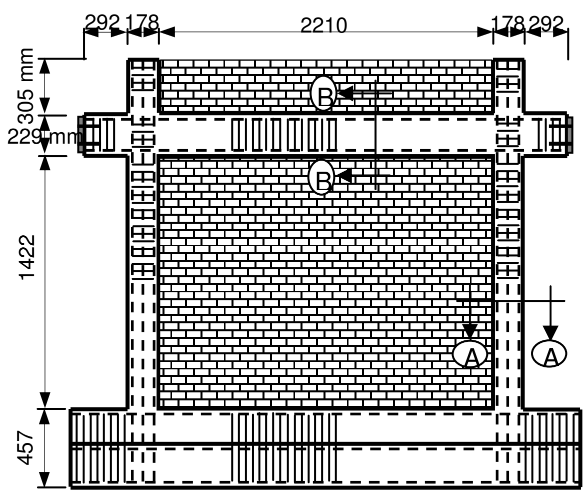
Material type Hardening is used to simulate the behaviour of inclined cracks of masonry panels under direct cyclic shear load. While Elastic-No Tension Material is used to model the behaviour of inclined cracks of masonry panels under compression or tension load.

6. MODEL VERIFICATIONS

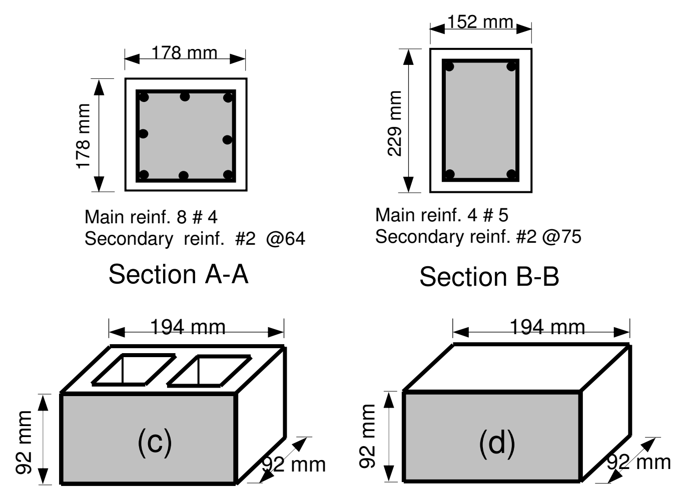
Performance of masonry-infilled RC frames under in-plane lateral loading was investigated experimentally and analytically by Mehrabi and Shing (1997). The prototype frame selected in this study was a six-story three-bay, moment resisting RC frame, with a 13.5 m by 4.5 m tributary floor area. The design gravity loads complied with the provisions of the Uniform Building Code (UBC, 1991). Two types of frames were considered with respect to lateral loading. One was a "weak" frame design, which was based on a strong wind load, and the other was a "strong" frame design, which was based on the equivalent static load force stipulated for Seismic Zone 4 in the UBC. In the design of the frames, the contribution of infill panels to the lateral load resistance was not considered. The frames were designed in accordance with the provisions of ACI 318-89 (1989).

The test specimens were selected to be 1/2-scale frame models representing the interior bay at the bottom story of the prototype frame. The design details for the weak frame is shown in figure 11. The infill panels 92 × 92 × 194 mm hollow and solid concrete masonry blocks, as shown in figure 4, were used in specimens to represent weak and strong infill panels, respectively.

Material tests were conducted on the reinforcing steel and concrete and masonry samples for each infilled frame specimen. The material properties are summarized in Table 1. The compressive strength of the hollow units is based on the net cross-sectional area, where as the compressive strength of the hollow prisms is based on the cross-sectional area of the face shell only.



Design details of test specimen of a weak frame



Concrete masonry units (c) Hollow block, (d) Solid block

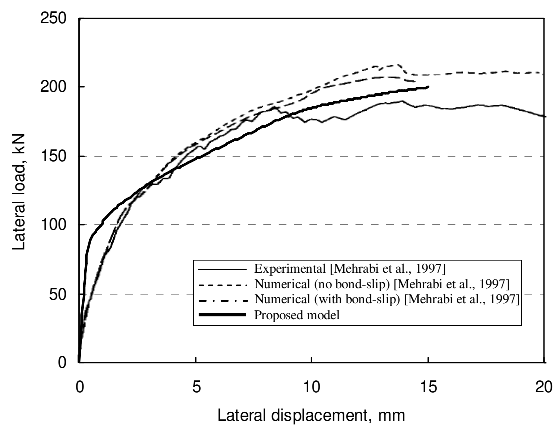
Figure 4 Design details of test specimens (weak frame), Mehrabi and Shing (1997).

TABLE 1. Average strength of concrete and masonry material Mehrabi and Shing (1997).

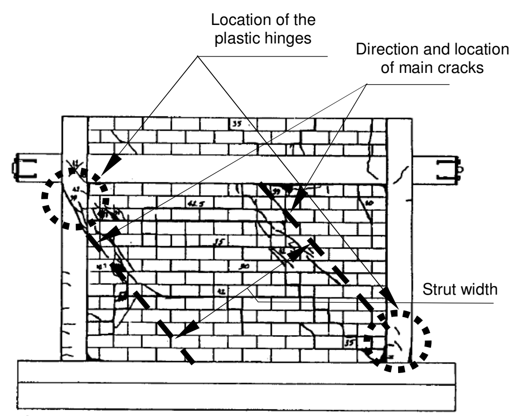
No	Frame Concrete					Three-Course Masonry Prisms			Compressive strength of masonry units (MPa)	Compressive strength of mortar cylinder (MPa)
	Secant modulus (MPa)	Compressive strength (MPa)	Strain at peak stress	Modulus of rupture (MPa)	Tensile strength (MPa)	Secant modulus (MPa)	Compressive strength (MPa)	Strain at peak stress		
8	17,240	26.8	0.0027	4.86	2.77	5,100	9.52	0.0027	16.48	15.52
9	17.240	26.8	0.0027	4.86	2.77	8,240	14.21	0.0026	15.59	12.48

Two specimens previously investigated experimentally and analytically by Mehrabi and Shing (1997), are analyzed using the proposed model. The first frame number 8 is weak frame with weak infill panel. The second frame number 9 is a weak frame with strong infill panel. The two infilled RC frames were subjected to monotonically increasing lateral load up to failure.

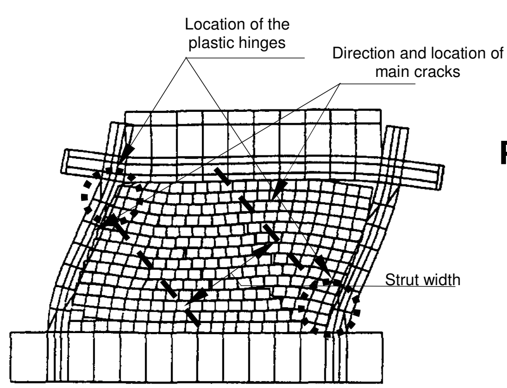
The load deflection curve obtained for specimen number 8 by using the proposed model was compared with experimental and analytical results reported by Mehrabi and Shing (1997). Result of the developed model is in close correlation with the analytical result of no bond slip model developed by Mehrabi and Shing (1997), as shown in figure 5(a).



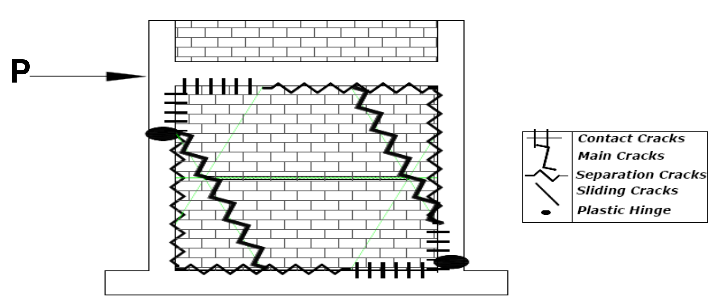
a- Lateral load-displacement curve



b- Experimental by Mehrabi and Shing (1997)



c- Analytical by Mehrabi and Shing (1997)



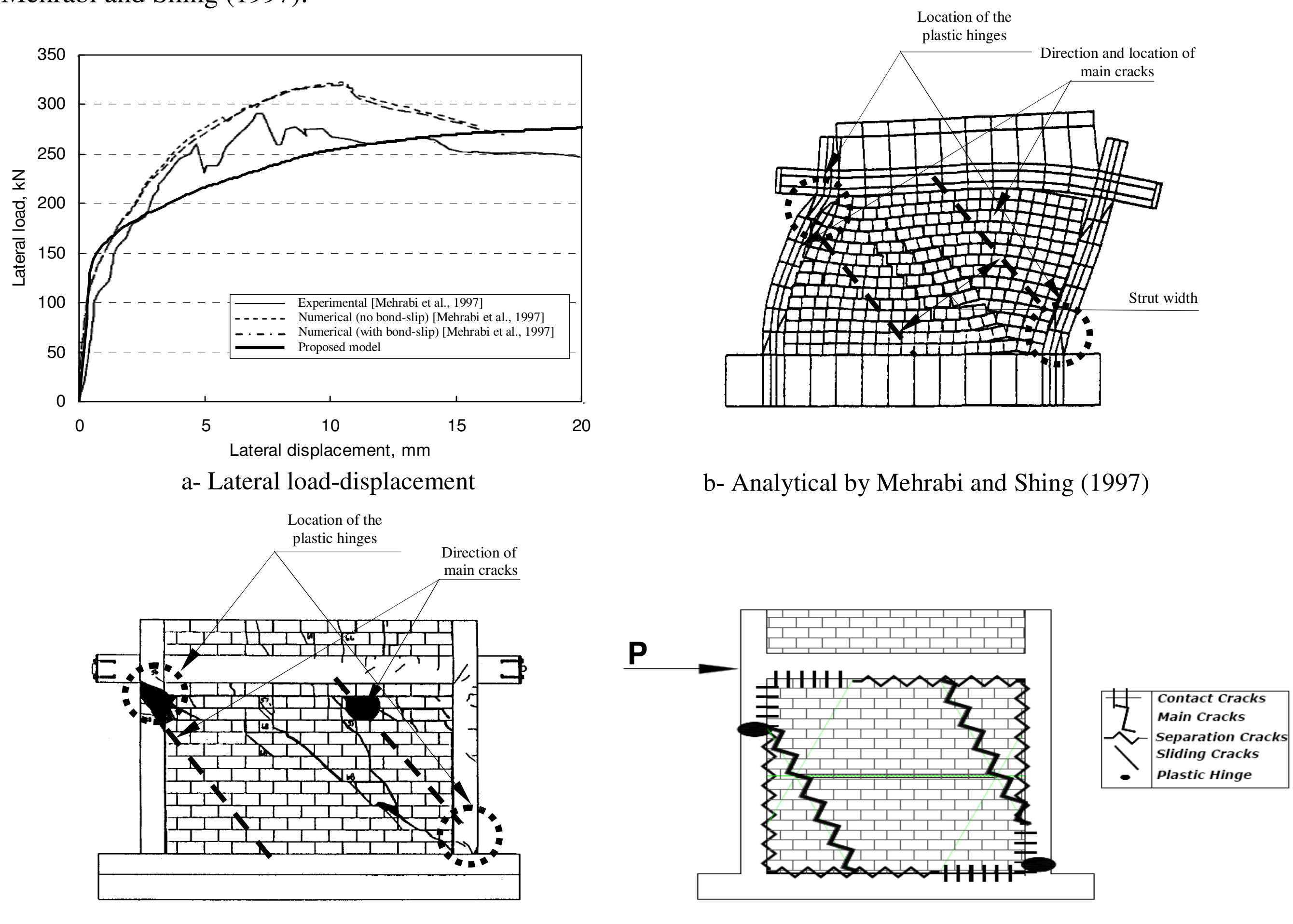
d- Analytical by proposed model

Figure 5 Load-deflection relationship and crack pattern for specimen # 8

The location and direction of inclined cracks in the infill panel as well as the strut width can be observed from experimental results of specimen 8, as shown in figure 5(b). The direction of the diagonal cracks obtained using the developed model was in good correlation with results observed experimentally and analytically by Mehrabi and

Shing (1997). The locations of the plastic hinges formed during the test were near the top of the windward column and at the bottom of the lee windward column, as shown in figure 5(b). The locations of the plastic hinges developed during the analysis using the proposed model were in the same location as obtained from the experimental results and analytical analysis by Mehrabi and Shing (1997), as shown in figure 5(b, c and d).

The behaviour of specimen 9 during experimental test by Mehrabi and Shing (1997), showed increase in the lateral resistance up to a lateral load of approximately 260 kN, followed by a sudden drop in the resistance due to start of failure in the infill panel. The strong infill panel resorted some of its resistance and started to show additional resistance to the infilled frame up to a load of approximately 290 kN. After this point, the infill panel lost its resistant and the only resisting element was the RC frame. Figure 6(a) shows the load-deflection relationship obtained using the proposed model as compared to the results obtained from experimental and finite element model by Mehrabi and Shing (1997).



a- Lateral load-displacement

b- Analytical by Mehrabi and Shing (1997)

c- Experimental by Mehrabi and Shing (1997)

d- Analytical by proposed model

Figure 6 Load-deflection relationship and crack pattern for specimen # 9

The crack pattern observed from the test and the analysis by Mehrabi and Shing (1997) was in correlation with the crack pattern predicted using the developed model. It is important to observe that the location of the plastic hinges especially in the windward column of the RC frame was the same as that observed from the experimental results, as shown in figures 6(c) and 6(d). These observations indicate that the developed model can predict the behaviour of the RC infilled frame in terms of main crack direction, crack locations, strut width, and most important, the location of plastic hinges in the RC boundary frame.

7. CONCLUSION

The behaviour of masonry-infilled RC frames was analyzed with a new finite element model. The finite element model included interface elements at the frame-infill interface as well as infill-infill interface along the proposed failure planes. The nonlinear behaviour of reinforcing steel, concrete and masonry are taken into consideration. The elasto-plastic behaviour of mortar and cracked masonry along the failure planes are also considered in the analyses. The strength and stiffness degradations are also implemented in the model. The proposed model was incorporated in a generic nonlinear structural analysis program, for static analysis of masonry infilled RC frames. The numerical model was verified by comparing the numerical solutions with experimental results and numerical analysis by others. A satisfactory agreement is obtained. The numerical results have shown that the model can capture the overall behaviour and failure mechanisms of the infilled frame structures subjected to in-plane monotonic loading.

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