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MODELING OF MASONRY INFILLED RC FRAMES FOR DYNAMIC ANALYSIS

W. A. El-Magd[1] and A. Ghobarah[2]

ABSTRACT

In the seismic design of reinforced concrete (RC) moment resisting frames, the effect of masonry infills on the response of frames is normally ignored. The assumption is that once the masonry infill fails the frame returns to the behaviour of the as designed bare frame. Observations following recent major earthquakes such as the 1999 kocaeli, Turkey and the 2004 Sumatra, Indonesia earthquakes show that the behaviour of reinforced concrete frames is very much dependent on the performance and mode of failure of the infill masonry walls. In most cases, the concrete frame fails as a consequence of the infill wall failure before reaching the bare frame condition.

An inelastic finite element model to simulate the behaviour of RC frames infilled with masonry panels subjected to static and dynamic loads is presented. 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 proposed model was incorporated in a generic nonlinear structural analysis program, for static and dynamic analysis of masonry infilled RC frames. The model is verified against the results of available models and experimental data by others. The results presented show that the model is capable of describing the dynamic behaviour of infilled reinforced concrete moment resisting frames. The model is simple and efficient as a tool for practical design of infilled frames under static and dynamic loads.

Introduction

Masonry infills are frequently used as interior partitions and exterior walls in buildings. They are usually treated as non-structural elements, and their interaction with the bounding frame is, therefore, often ignored in design. Nevertheless, the strength and stiffness of masonry infills are not negligible, and they will interact with the bounding frame when the structure is subjected to strong lateral loads induced by earthquakes. This interaction may or may not be beneficial to the performance of the structure, and it has been a topic of much debate in the last few decades (Shing and Mehrabi 2002).

There is the misconception that when a frame with infills, is subjected to an earthquake, the infills will fail first and the behaviour will be that of a bare frame. That has happened but not very often. The sequence of failure of infills affects the failure of the frames and may produce brittle failure. For example if the infills of the first floor fail first, then the structure will fail due to soft story mechanism.

On the other hand, the rigidity and strength of frames are significantly improved when masonry panels are built in line with the frames. In studies using reinforced concrete (RC) frames, the improvement in strength ranges from twice to over quadruple the strength of a frame with no infill. Stiffness improvement is still more substantial, with increase up to 60 times over that of a bare frame (Ghosh

[1]Ph.D. Candidate, Department of Civil Engineering, McMaster University, Hamilton, Ontario, Canada.
[2]Professor, Department of Civil Engineering, McMaster University, Hamilton, Ontario, Canada.

and Made 2002). 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.

The experience gained from recent earthquakes shows that irregular distribution of infills, neglecting the interaction between the frame structure and infills and weakness of structural components may cause the collapse of the entire buildings. The real capacity of these structures and their ability to withstand moderate and strong earthquakes needs to be evaluated using accurate models for predicting the behaviour of structures subjected to in-plain and out-of-plain loads.

Unfortunately, there are neither well-developed design recommendations nor well-accepted analytical procedures for infilled frames. In most of the current seismic codes, the influence of nonstructural masonry infills is ignored (Lee and Woo 2002). 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 (Shing and Mehrabi 2002).

Failure Mechanism of Masonry Infilled RC Frames

Masonry is a complex material consisting of an assemblage of bricks and mortar joints, each with differing properties. Its behaviour is made more complex by the mortar joints acting as planes of weakness due to their low tensile, shear and bond strengths. The out-of-plane stiffness of the unreinforced masonry panels is very low as compared to its in-plane stiffness. In this study only in-plane stiffness has been taken into consideration. The behaviour of an infilled frame depends upon the interaction between the infill and the frame (Shing and Mehrabi 2002).

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 frames with respect to those of the infills and the geometric configuration of the framing system (Shing and Mehrabi 2002).

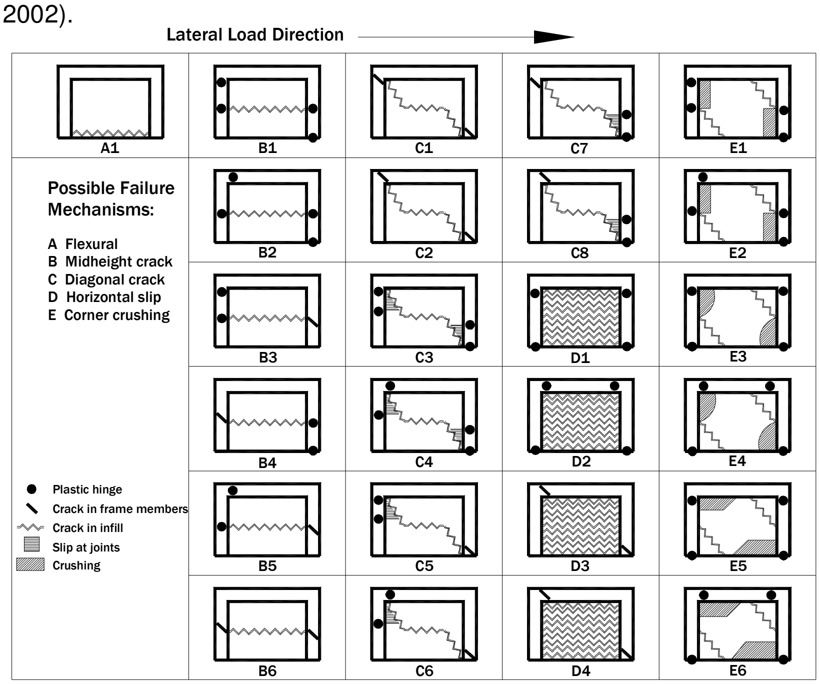


Figure 1. Failure mechanisms of infilled frames (Shing and Mehrabi 2002).

At a low lateral load level, an infilled frame acts as a monolithic load resisting system. As the load increases, the infill tends to partially separate from the bounding frame and form a compression strut mechanism as observed in many early studies. However, the compression strut may or may not evolve into a primary load-resistance mechanism of the structure, depending on the strength and stiffness properties of the infill with respect to those of the bounding frame (Shing and Mehrabi 2002).

On the basis of experimental observations, five main failure mechanisms of infilled frames are identified. They are 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. Very often, this 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.

Modeling of Masonry Infill panels in RC Frames

Equivalent diagonal strut model (Macro-Model)

Due to a multitude of highly variable parameters affecting the behaviour of infilled frames, approximate analyses are generally acceptable for this type of structure. Various approximate analytical techniques have been proposed, the simplest and most highly developed being the concept of equivalent diagonal strut. 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).

Strut models have been used to evaluate the strength as well as the stiffness of infilled frames. Even though some limited success has been achieved, 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.

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 (Weaver and Johnston 1983) and are interconnected by joint elements. The specific nature of the orthotropy of these elements is fully described by Seah (1998).

Generally, such micro-modeling is too time-consuming for analysis of large structures. Therefore, finite element analyses are useful only for small structures. Application of these methods for the analysis of an entire building of average size would be impractical. The need for practical and economical technique to provide a resolution to these difficulties is necessary.

Proposed Finite Element and Material Model

The equivalent strut model is a good approximation to study the overall behaviour of the structure but it can not simulate most of the failure mechanism of the masonry panel. While finite element method can simulate all failure modes of masonry infill panels, it is too time consuming for analysis of large structures which makes it an impractical method for use in design.

A simple new model for masonry panel is presented in this study. 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.

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 2 shows the capability of the proposed model to simulate different failure modes of masonry panel in infilled RC frames.

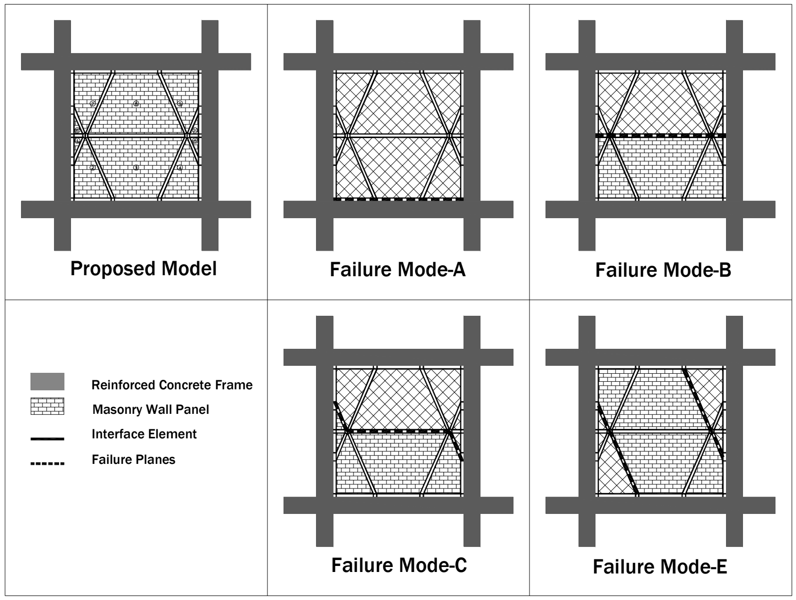
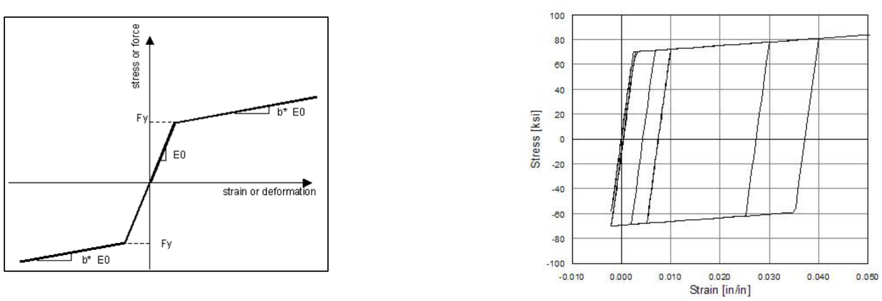


Figure 2. Capability of proposed model to simulate different failure modes of masonry panel.

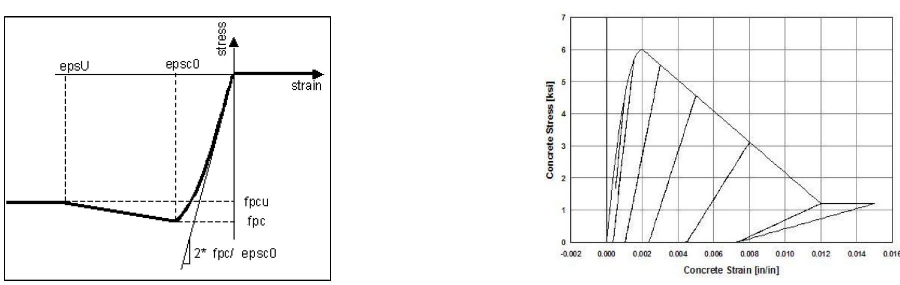
Reinforced concrete frame

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.



a- Material Parameters of Monotonic Envelope. b- Hysteretic Behavior of Model w/o Isotropic Hardening.

Figure 3. Steel material (OpenSees 2006l).



a- Material Parameters of Monotonic Envelope. b-Typical Hysteretic Stress-Strain Relation of Concrete Model.

Figure 4. Concrete material (OpenSees 2006).

Materials type Steel01 and Concrete01 are used to model reinforcing steel and concrete in RC frame members. Figures 3 and 4 illustrate material parameters of monotonic envelope and hysteretic behavior of reinforcing steel and concrete materials respectively.

Masonry panel

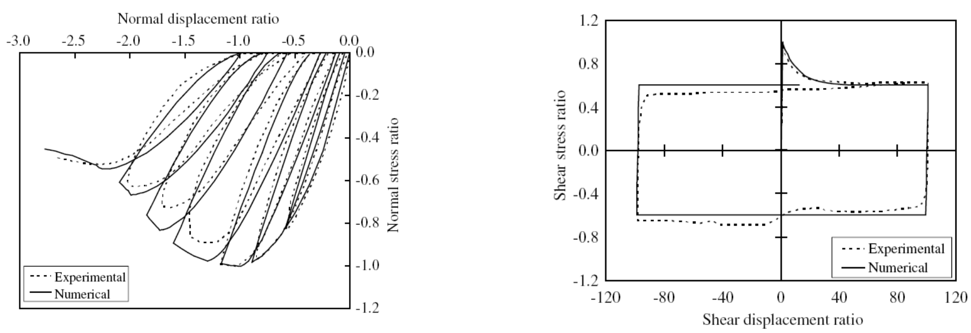
The four-noded isoparametric element was used to model the infill panel. Drucker-Prager failure criterion was used to simulate the behaviour of masonry. Tensile strength is assumed to be 10% of the compressive strength for un-reinforced masonry (Kappos et al. 2002).

Interface elements

Mortar joints

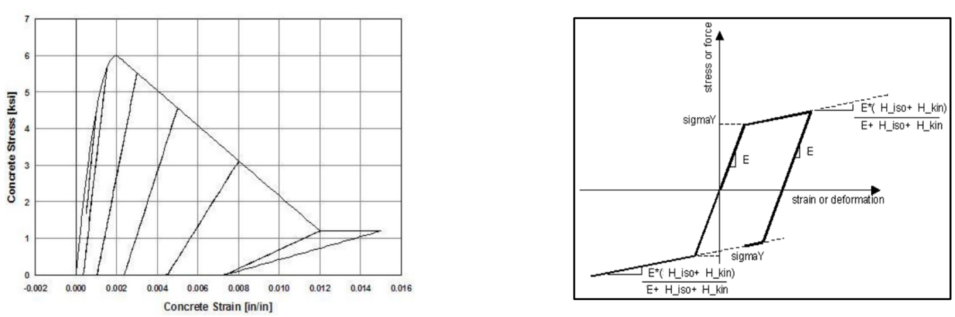
Mortar joint elements are modeled using Zero-Length Element. This element accepts specifying two different material types (or relations) in any two arbitrary directions. First material type is used to describe the behaviour of mortar joint in normal direction, and the second type is used to describe behaviour of mortar joint in shear direction.

Typical behaviour of mortar joint under both uniaxial compression cyclic loading and direct shear tests are shown in Figure 5. 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 as shown in Figure 6.



a- Uniaxial compressive test under cyclic loading. b- Direct shear test under cyclic loading.

Figure 5. Behaviour of mortar joint under uniaxial compress and direct shear (Oliveira et al. 2004).



a- Hysteretic Stress-Strain Relation of Concrete01. b- Hardening Material.

Figure 6. Modeling of mortar joint in normal and shear directions (OpenSees 2006).

Interface elements on cracked inclined planes

It is known that when quasi-brittle materials cracks such as concrete, ceramics or masonry, they exhibit considerable roughness, usually due to small-size heterogeneities. The roughness is the result of sand or stone aggregates in concrete. Roughness should not be neglected in any damage model for quasi-brittle materials. François and Royer-Carfagni (2005) presented an attempt to model the demand of a damage model involving rough fractures. The proposed approach is based upon structured deformation theory and it is built within the irreversible process framework, following the generalized standard-material theory (Halphen and Nguyen 1975). The model structure assures easy numerical implementation and allows a straightforward extension to contemplate other approaches in the field of damage models (François and Royer-Carfagni 2005). Figure 7 shows Hysteretic loop in the *(γ, τ)* plane for compressed specimens with saw-tooth cracks.

The use of 60% of the uncracked shear stiffness after closing of a crack, were decided on the basis of a sensitivity analysis performed for a half-scale un-reinforced masonry building tested by Benedetti et al. (1998).

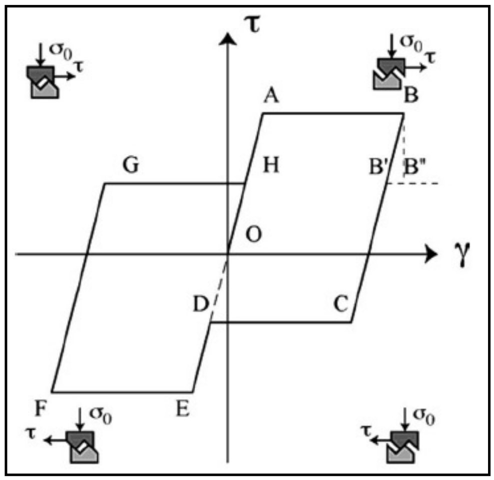
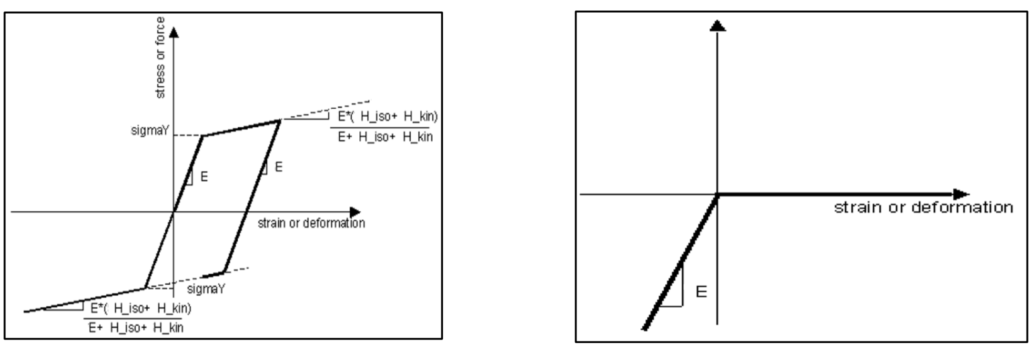


Figure 7. Hysteretic loop in the *(γ, τ)* plane for compressed specimens with saw-tooth cracks (François and Royer-Carfagni 2005).

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 as shown in Figure 8.



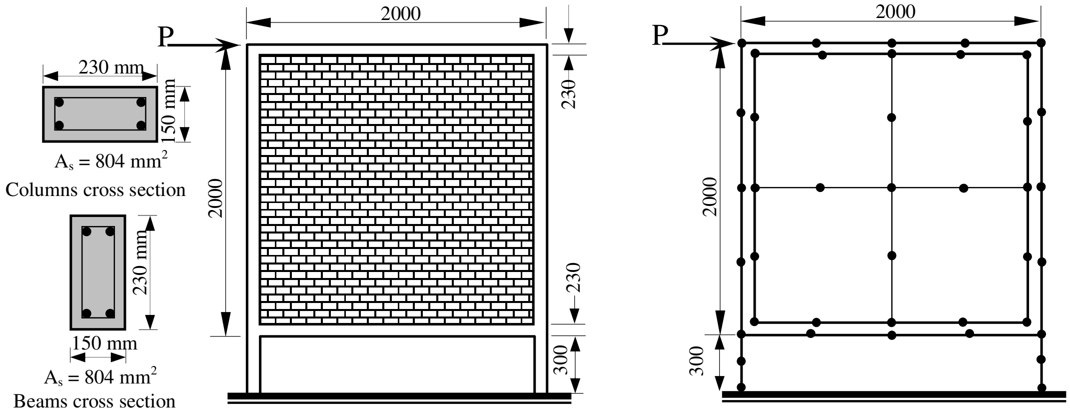
a- Hardening Material. b- Elastic-No Tension Material.

Figure 8. Modeling of inclined cracks of masonry panel in normal and shear directions (OpenSees 2006).

Results of Finite Element Analysis

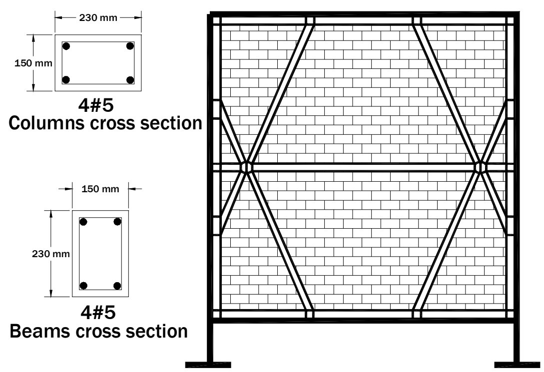
Application: 1

A single storey one-bay infilled RC frame shown in Figure 9, was investigated experimentally and analytically by Choubey (1990) and analytically by Singh et al. (1998). The same infilled RC frame was analyzed using the proposed model. Physical and material properties and other details of the structure are given in the figure. The structure has been discretized as shown in Fig 9(c).



(a) Infilled one story frame. (b) Model presented by Singh et al. (1998).

Concrete material	*Steel Material*	*Panel Material*
$E_c = 10E9$ N/m^2	$E_s = 2E11$ N/m^2	$E_m = 0.7E9$ N/m^2
$v_c = 0.2$	$v_s = 0.3$	$v_m = 0.2$
$f_{cu} = 40E6$ N/m^2	$\sigma_{sy} = 4E8$ N/m^2	$\sigma_u = 4.5E6$ N/m^2



(c) Proposed model.

Figure 9. Geometry and material properties of infilled RC frame.

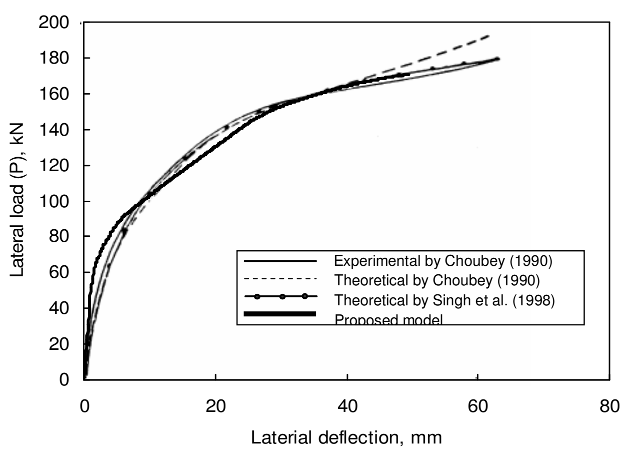
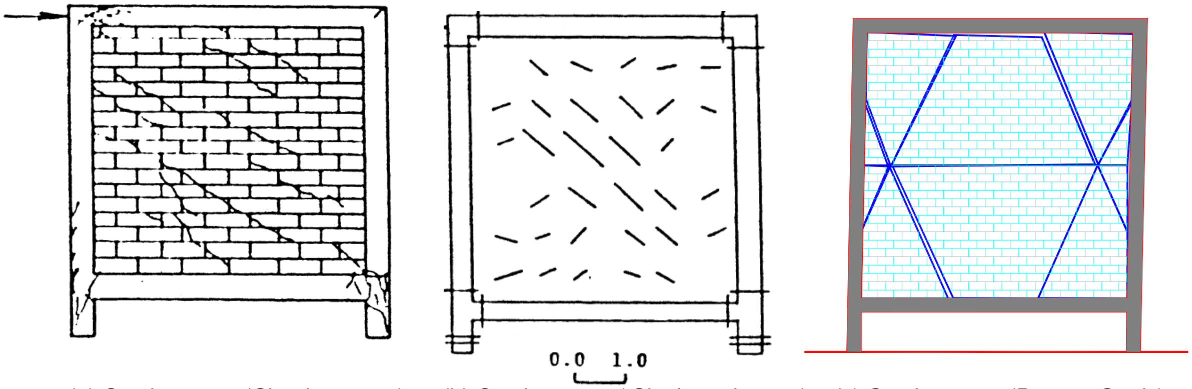


Figure 10. Load deflection behaviour of the infilled RC frame.

The load deflection curve obtained by using the proposed model has been compared with that reported by Choubey (1990) and Singh et al. (1998) in Figure 10. Good agreement with the experimental results was observed. The failure load of 170.68 kN as predicted by the proposed model is close to that obtained experimentally of 175.38 kN by Choubey (1990). The crack patterns in the infill at failure predicted by the proposed model, as well as those obtained experimentally by Choubey

(1990) and analytically by Singh et al. (1998) are presented in the Figure 11. A good comparison between the predicted and the reported results has been obtained.



(a) Crack pattern (Choubey 1990). (b) Crack pattern (Singh et al. 1998). (c) Crack pattern (Present Study).

Figure 11. Crack patterns for the infilled RC frame.

Application: 2

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 chosen 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 and strong frames are shown in Figure 12. The infill panels 100 ×100 × 200 mm hollow and solid concrete masonry blocks, as shown in Figure 13, were used in specimens to represent weak and strong infill panels, respectively.

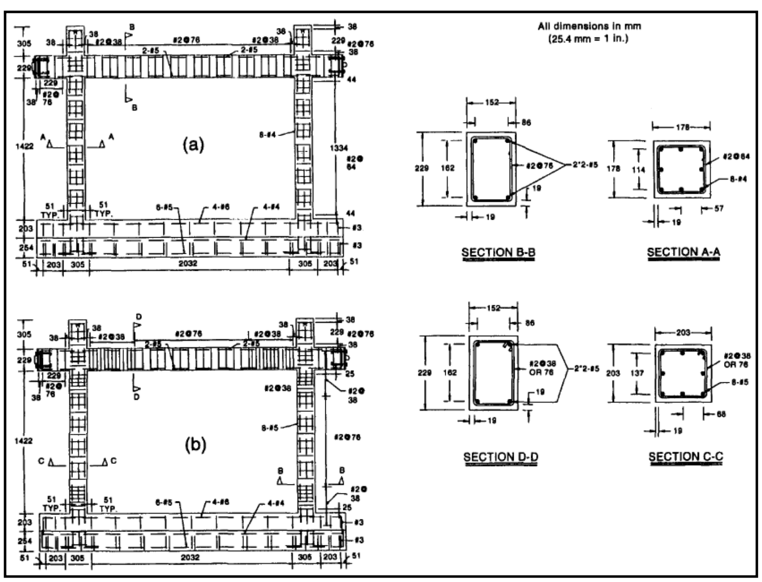


Figure 12. Design details of test specimens: (a) weak frame; (b) strong frame Mehrabi et al. (1997).

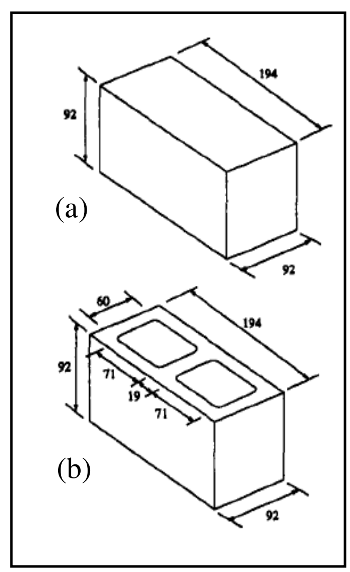


Figure 13. Concrete masonry units: (a) solid block; (b) hollow block

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.

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		
1	21,930	30.9	0.0018	6.76	3.29	--	--	--	--	--
6	19,960	25.9	0.0024	4.91	3.14	4,200	10.14	0.0032	16.48	16.76
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

A weak bare frame (specimen number 1) was subjected to a monotonically increasing lateral load up to failure. It exhibited a fairly flexible and ductile behaviour. The other three specimens are infilled RC frames. For the case of infilled frames, infill panels increased the strength and stiffness of the RC frame by a substantial amount. Three specimens previously investigated experimentally and analytically by Mehrabi and Shing (1997), are analyzed using the proposed model. The first frame number 6 is strong frame with weak infill panel. The second frame number 8 is weak frame with weak infill panel. The third frame number 9 is a weak frame with strong infill panel. The three specimens were monotonically loaded up to failure.

The load deflection curve obtained by using the proposed model was compared with experimental and analytical results reported by Mehrabi and Shing (1997). Good agreement with the experimental results were obtained as shown in Figures 14, 15, 16 and 17.

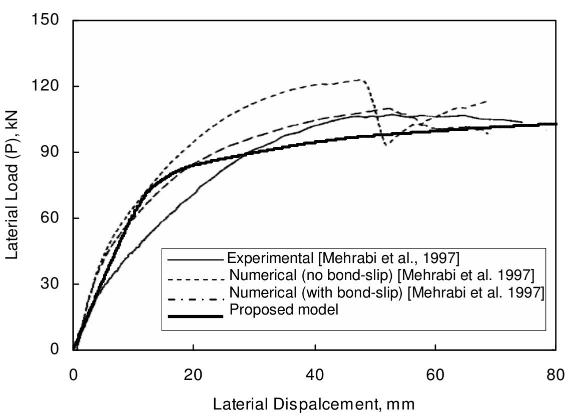


Figure 14. Lateral load- lateral displacement curve for Frame # 1.

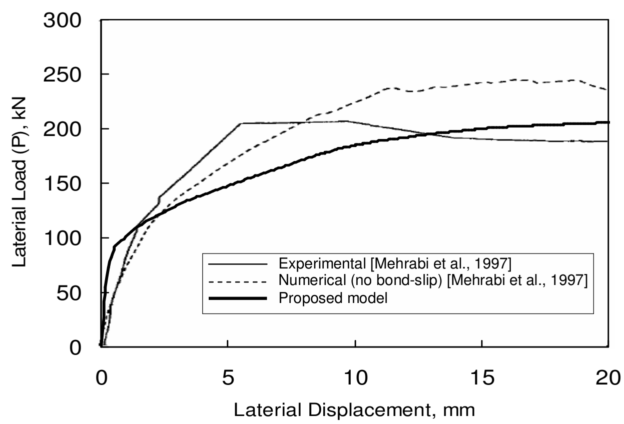


Figure 15. Lateral load- lateral displacement curve for Frame # 6.

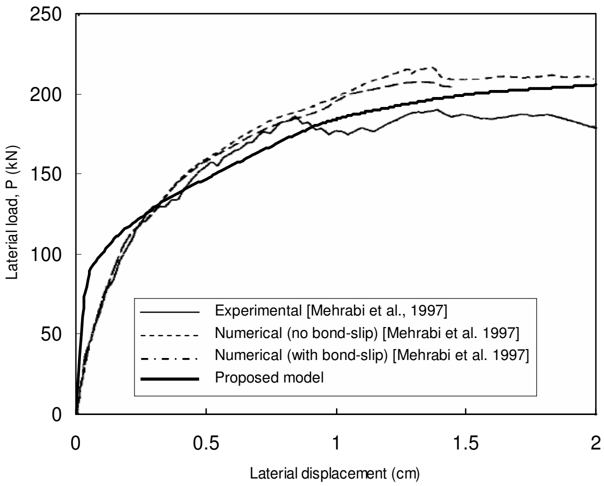


Figure 16. Lateral load- lateral displacement curve for Frame # 8.

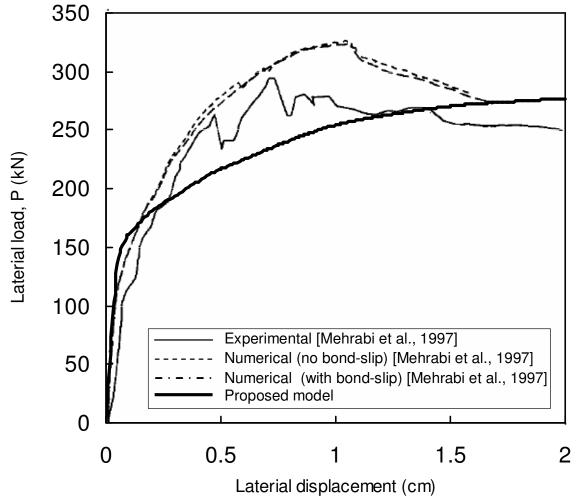


Figure 17. Lateral load-lateral displacement curve for Frame # 9.

Conclusions

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 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. Analyses were conducted on one bare frame specimen and on four masonry-infilled RC frame specimens using the proposed finite element models. The numerical results have shown that the model can capture the failure mechanisms of the infilled frame structures subjected to in-plane monotonic loading. The maximum lateral resistance of the specimens was estimated fairly accurately.

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