Send Orders of Reprints at reprints@benthamscience.org

 The Open Construction and Building Technology Journal, 2012, *6,* (Suppl 1-M2) 42-49

Open Access

Distinct Element Modeling of Masonry-Infilled Steel Frames with Openings

Amin Mohebkhah*[,1] and A.A. Tasnimi[2]

[1]*Struct. Eng. Dept., Faculty of Civil and Architectural Eng., Malayer University, Malayer, Iran;* [2]*Structural Eng. Div., Faculty of Civil & Env. Eng., Tarbiat Modares University, Tehran, Iran*

Abstract: Numerical analysis of masonry-infilled steel frames (MISFs) is one of the greatest challenges faced by structural engineers. This difficulty results from the presence of joints as the source of discontinuities and nonlinearities as well as the interaction of frame-infill panel. In spite of many studies performed on numerical modeling of solid MISFs, there are few studies on MISFs with openings. A 2D numerical model using the specialized distinct element software UDEC (2004) for the pushover analysis of MISFs with openings is developed. In this model, large displacements and rotations between masonry bricks are taken into account. A comparison between the results of distinct element modeling and the experimental results available in the literature showed a good correlation between them. Furthermore, It was found that the model has the capability to predict lateral load capacity, joint cracking patterns and explore the possible failure modes of MISFs with openings.

Keywords: Masonry-infilled steel frame, distinct element method, opening, pushover analysis, numerical modeling, micro-modeling.

1. INTRODUCTION

Steel framed buildings are usually infilled with masonry panels as partition and surrounding walls. The composite steel-masonry framed building is called masonry-infilled steel frame (MISF) which has high lateral stiffness and load capacity. Under severe lateral forces, the surrounding frame interacts with the infill masonry panel increasing lateral stiffness and load capacity of the MISF. This is because, the frame and masonry infill panel deform in a bending and shear modes, respectively. In spite of the frame-infill panel interaction, the unexpected effects of infill panels are not usually taken into account in the analysis and design of such frames. Ignoring the structural effects of infill panels may results in wrong estimation of lateral stiffness, capacity and ductility of these frames.

Since 1950's, many numerical and experimental researches have been conducted on the behavior of MISFs. Stafford Smith [1, 2], Riddington and Stafford Smith [3], Liauw and Kwan [4] and Moghadam *et al.* [5] have performed numerical and experimental studies on the lateral stiffness and load capacity of MISFs. Extensive findings of the previous studies conducted untill 1987 have been presented in the state-of-the-art report on MIFs by Moghadam and Dowling [6].

Numerical modeling strategies of infilled frames are divided into two distinct categories, *micro-modeling* and *macro-modeling*. For micro-modeling of masonry-infilled frames, both the surrounding frame and the infill panel components details are established using a numerical method such as finite element method (FEM) or distinct/discrete element method (DEM). In this method, the interaction between masonry bricks along the joints as well as the frame-infill panel interaction is taken into account. In the literature, Mehrabi and Shing [7] have proposed a smeared-crack nonlinear finite element model to study the nonlinear behavior of infilled reinforced concrete frames. Dawe and Seah [8] developed an innovative model for analyzing the interaction of frames with infill panels which includes the effects of variables such as design gapping between panel and frame, and rigid connectivity between panel and frame. Asteris [9] using a new finite element technique, investigated the influence of the masonry infill panel opening in the reduction of the infilled frames stiffness. It was found that the overall action between the frame and the infill is adversely affected as the opening position is moved towards the compression diagonal [9].

Despite the abovementioned numerical studies, it seems that the lateral load behavior of MISFs cannot be properly investigated by continuum mechanics based methods such as traditional finite element method. However, some advanced finite element programs such as DIANA (developed in Ref. [10]), include interface elements that allow the user to incorporate masonry discontinuities in the analysis properly and correctly. As an alternative to the available finite element methods, a distinct/discrete element method (DEM) can be used to investigate the nonlinear lateral load behavior of MISFs. Distinct element method has the capability to consider large displacements, shear sliding and complete joints openings between bricks as well as automatic detection of new contacts during the analysis process [11]. Mohebkhah *et al*. [12] developed a 2D distinct/discrete element model for the inelastic analysis of concrete masonry-infilled steel frames which considers both geometric and material nonlinearities.

*Address correspondence to this author at the Struct. Eng. Dept., Faculty of Civil and Architectural Eng., Malayer University, Malayer, Iran;
Tel: +98 0851 2232346; Fax: +98 0851 2221977;
E-mail: amoheb@malayeru.ac.ir

1874-8368/12

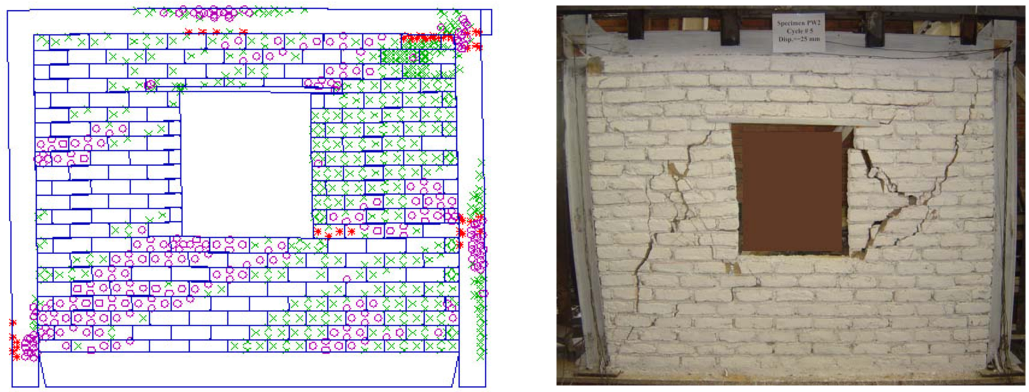

Fig. (7). Elements' failure points and crack patterns of the joints for specimen PW2 (numerical and experimental [19] results).

predicted by the DEM is compatible with laboratory experimental findings. The diagonal tension failure points have been distinguished from the others by the symbol O. As it can be seen in the test failure pattern in Fig. (**7**), masonry side piers undergo sudden diagonal brittle failures (localized fracture through bricks) which cannot be properly captured by finite element-based plasticity models such as Mohr-coulomb failure criterion. That's why the extent of DEM failure seems slightly different compared to the test. These kinds of failures can be simulated properly using fracture mechanics principles. As an alternative, the failure can be simulated in future DEM studies using the potential brick cracks as proposed by Lourenco in his PhD dissertation [10].

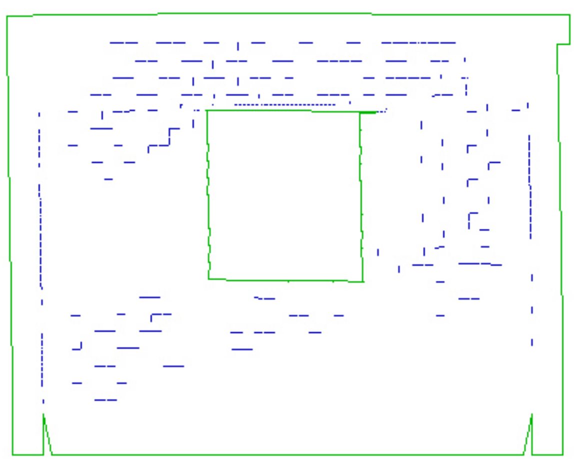

Fig. (8). Plot of joints with zero normal or shear stresses (joint sliding).

Figs. (**8**) and (**9**) show the plot of joint sliding and joint openings in the infill panel, respectively. As can be seen, the nonlinear behavior comes from the bricks than the joints.

Fig. (**10**) shows the magnified picture of the deformed geometry of specimen PW2. The separations and geometry distortions of the bricks (indicating cracking and crushing of the bricks) is clearly observed in the figure. Therefore, the obtained results reveal the capacity of the DEM to model masonry infill walls behavior.

6. CONCLUSION

A 2D distinct element model developed for the inelastic nonlinear analysis of masonry-infilled steel frames. A micro-modeling approach was used to model masonry infill wall in which the joint is modeled as a zero thickness interface element. The bricks are joints are assumed fully deformable to simulate bricks failure points and joints sliding.

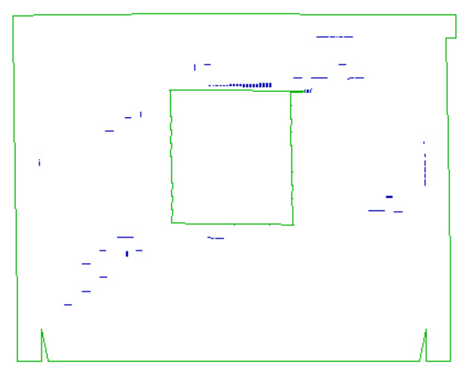

Fig. (9). Plot of joint opening.

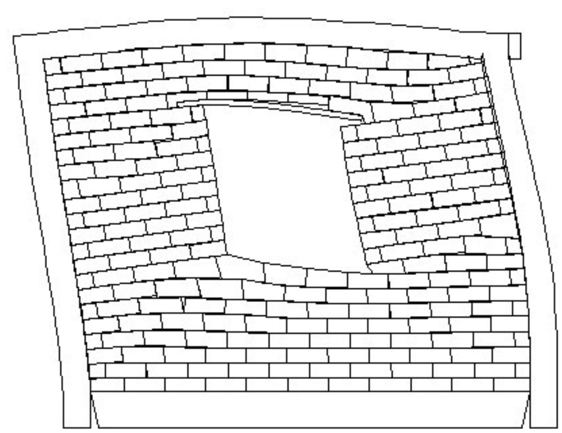

Fig. (10). Magnified deformed geometry for specimen PW2 (magnification factor = 10).

The developed model was used herein to simulate the lateral load behavior of some tested masonry-infilled steel frames with openings reported in the literature. It was found that the DEM model is applicable to a detailed simulation of the nonlinear behavior of such frames throughout the loading process leading to failure. The prediction of lateral load capacity and the evolution of the deformations were both in agreement with the experiments. It was shown that the method can simulate confidently the failure mechanisms based on joint separation and sliding.

NOMENCLATURE

E_b	=	Young's modulus of brick masonry
E_m	=	Young's modulus of mortar
G_b	=	Shear modulus of brick masonry
G_m	=	Shear modulus of mortar
F_y	=	Yield stress of steel material
h_m	=	Thickness of the mortar
k_n	=	Normal joint stiffness ($N/mm^2/mm$)
k_s	=	Shear joint stiffness ($N/mm^2/mm$)
c	=	Brick masonry cohesion strength
ϕ	=	Brick masonry angle of internal friction
f_c'	=	Brick masonry compressive strength
c_j	=	Mortar joints cohesion strength
ϕ_j	=	Mortar joints angle of internal friction
ψ_j	=	Mortar joints angle of dilatancy

CONFLICT OF INTEREST

The author confirm that this article content has no conflicts of interest.

ACKNOWLEDGEMENT

Declared none.

REFERENCES

[1] B. Stafford-Smith, “Lateral stiffness of infilled frames”, *J. Struct. Div. ASCE*, vol. 88, no. ST6, pp. 183-199, 1962.

[2] B. Stafford-Smith, “Behavior of square infilled frames”, *J. Struct. Div. ASCE*, vol. 92, no. ST1, pp. 381-403, 1966.

[3] J.R. Riddington, and B. Stafford Smith, “Analysis of infilled frames subjected to racking with design recommendations”, *Struct. Eng.*, vol. 55, no. 6, pp. 263-268, 1977.

[4] T.C. Liauw, and K.H. Kwan, “Unified plastic analysis for infilled frames”, *J. Struct. Eng.*, vol. 111, no. 7, pp. 1427-1448, 1985.

[5] H.A. Moghaddam, M.G.H. Mohammadi, and M. Ghaemian, “Experimental and analytical investigation into crack strength determination of infilled steel frames”, *J. Construct. Steel Res.*, vol. 62, no. 12, pp. 1341-1352, 2006.

[6] H.A. Moghaddam, and P.J. Dowling, “The state-of-the-art in infilled frames”, ESEE Res. Rep. No. 87-2, Imperial College of Science and Technology, Civil Engineering Department, London, England, 1987.

[7] A.B. Mehrabi, and P.B. Shing, “Finite element modeling of masonry-infilled RC frames”, *J. Struct. Eng.*, vol. 123, no. 5, pp. 604-613, 1997.

[8] J.L. Dawe, C.K. Seah, and Y.A. Liu, “Computer model for predicting infilled frame behavior”, *Can. J. Civ. Eng.*, vol. 28, pp. 133-148, 2001.

[9] P.G. Asteris, “Lateral stiffness of brick masonry infilled plane frames”, *J. Struct. Eng.*, vol. 129, no. 8, pp. 1071-1079, 2003.

[10] P.B. Lourenco, “Computational strategies for masonry structures”, Ph. D. Thesis, Delft University of Technology, Delft, The Netherlands, 1996.

[11] Itasca Consulting Group, Inc. UDEC- Universal Distinct Element Code, version 4.0- User's manual, Minneapolis, MN, USA, 2004.

[12] A. Mohebkhah, A.A. Tasnimi, and H.A. Moghaddam, “Nonlinear analysis of masonry-infilled steel frames with openings using discrete element method”, *J. Construct. Steel Res.*, vol. 64, no. 12, pp. 1463-1472, 2008.

[13] V.M. Sharma, K.R. Saxena, and R.D. Wood, “*Distinct Element Modeling in Geomechanics*”, Balkema: Rotterdam, 1999.

[14] L.V. Lemos, “*Discrete element modeling of the seismic behavior of stone masonry arches*”, Computer Methods in Structural Masonry-4, In Pande, Middleton and Kralj Eds., E and FN Spon: London, 1997, pp. 220-227.

[15] G.E. Sincraian, and J.J. Azevedo, “Numerical simulation of the seismic behavior of stone and brick masonry structures”, *in Proc. of the 11th European Conference on Earthquake Engineering*, Balkema, 1998.

[16] G.E. Sincraian, J.V. Lemos, and C.S. Oliveira, “Assessment of the seismic behavior of stone masonry aqueduct using the discrete element method”, *in Proc. 11th European Conference on Earthquake Engineering*, Balkema.1998.

[17] J.J. Azevedo, G.E. Sincraian, and J.V. Lemos, “Seismic behavior of blocky masonry structures”, *Earthquake Spectra*, vol. 16, no. 2, pp. 337-365, 2000.

[18] A.A. Tasnimi, and A. Mohebkhah, “Investigation on the behavior of brick-infilled steel frames with openings, experimental and analytical approaches”, *Eng. Struct.*, vol. 33, pp. 968-980, 2011.

[19] A. Mohebkhah, “A nonlinear-seismic model for brick-masonry-infill panels with openings in steel frames”, Ph. D. Thesis, Tarbiat Modares University, Tehran, Tehran, Iran, Nov. 2007.

[20] J.G. Rots, Ed, “*Structural masonry: an experimental/numerical basis for practical design rules*”, Center for Civil Engineering Research and Codes (CUR), Balkema: Rotterdam, 1997.

[21] R.H. Atkinson, B.P. Amadei, S. Saeb, and S. Sture, “Response of masonry bed joints in direct shear”, *J. Struct. Eng.*, vol. 115, no. 9, pp. 2276-2296, 1989.

[22] K.M. Mosalam, R.N. White, and P. Gergely, “Static response of infilled frames using quasi-static experimentation”, *J. Struct. Eng.*, vol. 123, no. 11, pp. 1462-1469, 1997.

Received: November 30, 2011 Revised: March 16, 2012 Accepted: April 12, 2012