Engineering Structures 82 (2015) 226–235

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Numerical study of in-plane behaviour and strength of concrete masonry infills with openings

Xi Chen, Yi Liu [*]

Department of Civil and Resource Engineering, Dalhousie University, Halifax, NS, Canada

ARTICLE INFO

Article history:
Received 3 June 2014
Revised 15 October 2014
Accepted 23 October 2014

Keywords:
Concrete masonry infills
Openings
In-plane behaviour
Stiffness and strength
Reduction factor
Finite element
Analytical method

ABSTRACT

A finite element study was conducted to investigate the in-plane behaviour and strength of concrete masonry infills bounded by steel frames with the focus on the infills with openings. The effect of the size and location of openings on the stiffness and strength of the infilled frames was studied. The results showed that the presence of opening decreased the in-plane stiffness and strength of the infill and the degree of this reduction was associated with the location of the opening. Based on regression analysis on finite element model results, a simple analytical method was proposed to define the relationship between the reduction factor in the stiffness and strength and opening size and location. The efficacy of the proposed equation and other existing analytical models was evaluated using experimental results in the available literature. The proposed method was shown to provide the best overall performance when compared with experimental data for both stiffness and strength estimate.

1. Introduction

Masonry infills built inside concrete or steel frames have been shown to contribute significantly to the lateral stiffness, strength, ductility and energy dissipation of the frame system. In the past six decades, numerous experimental tests [1–10] as well as finite element studies [11–13] have been conducted to study the stiffness and strength of infilled frames. A "diagonal strut concept" has been developed and commonly adopted for consideration of infill stiffness and strength where a strut connecting loaded corners is used to replace the entire infill. Once the diagonal strut width is determined, a simple frame analysis can be performed to calculate the stiffness and strength of the infilled frames. Most existing equations expressed the strut width as a function of some form of the infill-to-frame stiffness ratio and infill geometry [14–16]. Previous studies also found that infilled frames can develop different failure modes based on the geometric and configuration characteristics of the infill and the frame. Among several failure modes, corner crushing has been identified to be the predominant failure mode for infill frames of typical geometric and material properties.

In comparison with extensive experiments on solid masonry infills, infills with door or window openings are less researched and even within the few available studies, limited parameters were considered [17–19]. It is commonly accepted though that the presence of openings reduces the lateral stiffness and strength of the infilled system. Several analytical methods have been proposed to account for these reductions as affected by openings in infills [20–26]. However, the efficacy of these methods has not been thoroughly examined. As for the location of the infill, conflicting findings have been reported. Kakaletsis and Karayannis [19] suggested that the opening be placed near to the edge of infill to achieve best improvement in the performance whereas others indicated that the openings be located at the centre of the infill [5,17]. Due to the lack of technical information, the current Canadian and American masonry design standards [27,28] do not contain design provisions for masonry infills with openings.

In this paper, a finite element model was developed using software ANSYS and was verified with existing experimental results obtained from available literature. The main objectives of the paper are (1) to conduct a numerical study to investigate the effect of opening size and location on the in-plane behaviour and strength of masonry infills bounded by steel frames; (2) to develop an analytical method for infill opening consideration based on the finite element results; and (3) to assess the efficacy of the proposed method and other existing methods using available experimental results.

2. Existing analytical methods

Based on the diagonal strut approach for solid infills, the simple and practical way of taking into account of opening effect is to apply a reduction factor, R_F, to the width of the corresponding solid

---

[*] Corresponding author. Tel.: +1 (902) 494 1509; fax: +1 (902) 494 3108.
E-mail address: yi.liu@dal.ca (Y. Liu).

http://dx.doi.org/10.1016/j.engstruct.2014.10.042
0141-0296/

infill, w, resulting in an effective width of $R_F \times w$. The existing analytical methods adopt this approach and details of each method are summarized in the following sections. All existing methods expressed the reduction factor as some form of polynomial function of opening-to-infill area ratio. It is noted that some proposed equations are valid for only stiffness or strength reduction factors whereas others are intended for both. None of the methods considered the eccentricity of openings and all openings were assumed to be located at the centre of the infill.

2.1. Durrani and Luo (1994)

Durrani and Luo [20] proposed the following empirical equation to calculate the reduction factor for both stiffness and strength consideration based on a finite element study.

$$R_F = 1 - \left(\frac{A_d}{H \times L}\right)^2 \tag{1}$$

and

$$A_d = H \times L - \frac{[R\sin(2\theta) - R_0\sin(\theta + \theta_0)]^2}{2\sin(2\theta)} \tag{2}$$

$$R_0 = \sqrt{H_0^2 + L_0^2} \tag{3}$$

$$R = \sqrt{H^2 + L^2} \tag{4}$$

where H and L are the height and length of the infill, respectively; H_0 and L_0 are the height and length of the opening respectively; θ and θ_0 are calculated as $\tan^{-1}(H/L)$ and $\tan^{-1}(H_0/L_0)$ respectively.

2.2. Al-Chaar et al. (2003)

Al-Chaar et al. [21] developed an expression for the reduction factor as a function of the ratio of opening to infill area, A_o/A_p, to account for the effect of openings on both stiffness and strength by conducting a series of experiment tests and analytical studies.

$$R_F = 1 + 0.6(A_o/A_p)^2 - 1.6(A_o/A_p) \tag{5}$$

2.3. New Zealand Society for Earthquake Engineering (2006)

Based on the work of Dawe and Seah [5], the New Zealand Society for Earthquake Engineering (NZSEE) recommends a simplified expression for R_F to account for reduction on stiffness and strength due to openings.

$$R_F = 1 - \frac{1.5 \times L_0}{L} \tag{6}$$

This formula calculate the R_F factor solely based on the ratio of the length of opening to length of the infill. When the length of opening exceeds 2/3 of the length of infill, the contribution of infill can be ignored.

2.4. Mondal and Jain (2008)

Based on finite element studies and experimental data of reinforced concrete infilled frames, Mondal and Jain [23] proposed a linear relationship for stiffness reduction factor as follows:

$$R_F = 1 - 2.6(A_o/A_p) \tag{7}$$

It suggests that the contribution of infill to the stiffness of the system can be neglected when opening area is greater than approximately 38% of the infill area.

2.5. Tasnimi and Mohebkhah (2011)

Based on a series of experiments on the in-plane seismic behaviour of steel frames with clay brick masonry infills having openings, Tasnimi and Mohebkhah [24] proposed the following expression as the reduction factor in strength only where an upper limit of A_o/A_p ratio is set to be 0.4.

$$R_F = 1 + 1.49(A_o/A_p)^2 - 2.238(A_o/A_p) \tag{8}$$

2.6. Asteris et al. (2012)

Asteris et al. [25] proposed the following expression for reduction factor in stiffness only. The author placed an upper limit of A_o/A_p of 0.5, above which the infill was considered negligible.

$$R_F = 1 - 2(A_o/A_p)^{0.54} + (A_o/A_p)^{1.14} \tag{9}$$

2.7. Mohammadi and Nikfar (2013)

Through a statistical analysis using experimental data, Mohammadi and Nikfar [26] concluded that the material of confining frames (steel or concrete) affected the reduction in strength but not the stiffness due to openings. Reduction on the infill strength with RC bounding frames was less than that with steel bounding frames. Hence Mohammadi and Nikfar [26] proposed two separate sets of reduction factor expressions for strength and stiffness of infill with openings as follows:

For stiffness:

$$R_F = 1 + 1.1163(A_o/A_p)^2 - 1.6534(A_o/A_p) \tag{10}$$

For strength:

$$R_F = 1 - 2.12(A_o/A_p) \quad \text{for steel frames} \tag{11}$$

$$R_F = 1 - 1.05(A_o/A_p) \quad \text{for RC frames} \tag{12}$$

3. Finite element model

3.1. General

In this study, the infill was modelled using a simplified micro-modelling where the infill was represented by homogeneous and isotropic continuum elements placed in running bond. A convergence study on mesh size showed that 2 × 2 plane-stress elements for each unit provided sufficient accuracy in comparison with a higher number of elements. Therefore this mesh size was used for the finite element study. The sketch of such an infilled frame is shown in Fig. 1. The opening, if required, was introduced in the infill by simply removing the plane stress elements and joint elements on infill panel which were covered by the opening. The opening dimensions were designed to be multiple of the mesh size of plane stress elements so no complication in meshing may be caused by introducing openings.

3.2. Element description

The steel frame members were modelled using 3D beam elements having six degrees of freedom per node. Four-node plane-stress element, PLANE42 was used to model the masonry infill continuum. The interface between the infill and the frame was modelled using 2-D point-to-point contact elements, CONTAC12. The CONTAC12 represents two surfaces which may maintain or break physical contact and may slide relative to each other. The connection between masonry blocks was modelled