Lateral Stiffness of Masonry Infilled Reinforced Concrete (RC) Frames with Central Opening

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Window and door openings are inevitable parts of infill walls for functional reasons. Currently, publications like FEMA-273 and ATC-40 contain provisions for the calculation of stiffness of solid infilled frames mainly by modeling infill as a "diagonal strut." However, such provisions are not provided for infilled frames with openings. The present study proposes a reduction factor for effective width of diagonal strut over that of the solid reinforced concrete (RC) infilled frame to calculate its initial lateral stiffness when a central window opening is present. The study is based on initial lateral stiffness which is taken at 10% of the lateral strength of the infilled frames. [DOI: 10.1193/1.2942376]

INTRODUCTION

Performance of buildings in the recent earthquakes (e.g., 1985 Mexico City earthquake, 2001 Bhuj earthquake) clearly illustrates that the presence of infill walls has significant structural implications. Therefore, the structural contribution of infill walls cannot simply be neglected particularly in regions of moderate and high seismicity where, the frame–infill interaction may cause substantial increase in both stiffness and strength of the frame in spite of the presence of openings. Generally, presence of these openings decreases stiffness and strength of infilled frames. A review of analysis and design provisions related to masonry infilled RC frames in seismic design codes of different countries shows that only a few codes have considered the effect of infill in analysis and design of masonry infilled RC frames (Kaushik et al. 2006). On the other hand, the stiffness and strength of the infilled frames with opening are not taken care of by most of the codes. Hence, the behavior of infilled frames with openings needs to be studied extensively in order to develop a rational approach or guidelines for design.

In the present study, a finite element (FE) analysis has been carried out on single-bay single-story, single-bay two-story, and single-bay three-story infilled frames to examine the effect of central openings of different sizes on the initial lateral stiffness of infilled frames. Lateral load-deflection curve of an infilled frame can be divided into three parts. In the initial part, there may be a lack of fit between frame and infill. The second part is approximately linear and reflects the interaction between frame and infill. In the present study, this stiffness has been considered assuming that this is achieved well before a load level of 10% of the lateral strength of infilled frame. In the third part of lateral load-deflection relationship, a stiffness reduction may take place due to progressive degrada-

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tion of the infill material with increasing stress. A substantial variation of stiffness has been observed in this part due to variation of material properties and failure mechanism. Because the aim of the present paper is to study the effect of opening on stiffness (rather than the value of stiffness as such), the stiffness degrading stage of the load-deflection curve is not considered. Therefore, the initial lateral stiffness is defined as the stiffness at lateral load level corresponding to 10% of the lateral strength of infilled frame. The FE model has been verified using experimental results of seven different specimens published in the literature. Based on the parametric study, a reduction factor is proposed to determine the width of strut for a central opening present in an infilled frame.

The stiffness of infilled frames is influenced by the size and location of the openings. Experiments on four story steel frames with RC infills illustrated that a central opening of size 20%–30% of the panel area may reduce the stiffness by about 70%–80% in absence of shear connector (Liauw 1979). Based on experimental and analytical research, it was found that an opening at either end of the loaded diagonal reduces the stiffness of infilled frame by about 85%–90% in comparison with infilled frame without opening (Mallick and Garg 1971). Usually, a RC band/stiffener around the opening increases the stiffness of the infilled frame. Effects of different types of RC bands/stiffeners on the stiffness of infilled frame were studied by Polyakov (1956), Dawe and Seah (1989), Jagadish et al. (1992), and Raj (2000).

Analytical models that have been developed to estimate lateral stiffness and strength of the infilled frames with openings include the equivalent frame model, the single diagonal strut model, and the multi-diagonal strut model. The equivalent frame model is based on the concept of equivalent frame, where members have the properties of the composite sections of the actual structure (Liauw 1972, Kodur et al. 1998). The equivalent diagonal strut model is the most simplified yet reasonably accurate macro-model. This is usually done by modeling the infill panel as a single diagonal strut connected to the two compressive diagonal corners. The key to this approach lies in determination of effective width of equivalent diagonal strut. In the last few decades, several attempts have been made to compute the effective width of diagonal strut for infilled frames without opening (Holmes 1961, Smith and Carter 1969, Mainstone 1971, Liauw and Kwan 1984, Paulay and Priestley 1992). The effective width of diagonal strut for infilled frame without opening may be reduced by a reduction factor to simulate the presence of openings of various aspect ratios in the infilled frame (Durrani and Luo 1994, Al-Chaar 2002). Multi-strut models were proposed to represent the local effects due to presence of an opening (Thiruvengadam 1985, Buonopane and White 1999, Al-Chaar 2002).

The published researches on infilled frames point to a need for suitable quantitative design provisions to account for effect of openings. The expression for strut-width proposed by Durrani and Luo (1994) can be used to obtain the lateral stiffness of infilled frames due to presence of central opening. It was developed numerically on the basis of Finite Element (FE) analyses only and was not verified with experimental results. The expression developed by Durrani and Luo are somewhat too complex for use in design office because these account for beam stiffness, column stiffness, and both infill and panel aspect ratios. On the other hand, strut-width proposed by Al-Chaar (2002) is simpler than that proposed by Durrani and Luo (1994). It is based on both experimental and
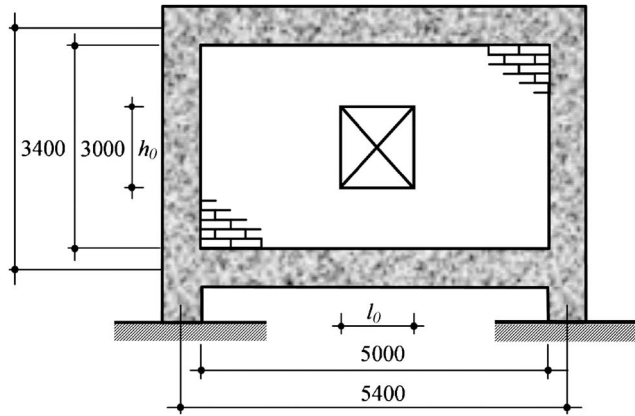
Figure 1. Dimensions (mm) of single-bay, single-story infilled frame with symmetric central opening (infill thickness: 225 mm; beam size: 250 mm $\times$ 400 mm; column size: 400 mm $\times$ 400 mm).

numerical research. Pushover analysis of infilled frame with openings using Al-Chaar's width of strut predicts in-plane strength but underestimates the initial lateral stiffness. However, modification factors have been proposed by Al-Chaar to obtain a reasonable value of initial stiffness directly from the pushover curve. In the present paper a simple expression has been developed to obtain directly the initial lateral stiffness of infilled frames with a central opening. It is based on numerical study that has been calibrated and verified with published experimental results.

METHODOLOGY

A parametric study is performed to obtain lateral stiffness of infilled frames with varying sizes of central openings. In the study, two types of analysis methods are used: the FE method and the Single Equivalent Diagonal Strut (SEDS) method. The FE model is first calibrated using published results of experimental specimens available in the literature. This calibrated model is used in the parametric study to determine the lateral stiffness of infilled frames with openings. The width of equivalent diagonal strut for the SEDS method is estimated so as to obtain the same lateral stiffness as estimated from the FE method. That is, equivalent width of diagonal strut is determined that will give correct value of lateral stiffness. Finally, a strut-width reduction factor is proposed to multiply the "strut-width for fully infilled panel" proposed by some researchers earlier (e.g., Paulay and Priestley 1992, Liauw and Kwan 1984 and Holmes 1961).

In the parametric study, two parameters, i.e., number of stories and size of openings are considered. For this purpose, three sets of RC infilled frames, namely single-bay single-story, single-bay two-story, and single-bay three-story are analyzed and their lateral stiffness is determined by linear elastic analysis. The single-bay single-story infilled frame considered is shown in Figure 1. All the stories of two-story and three-story in-
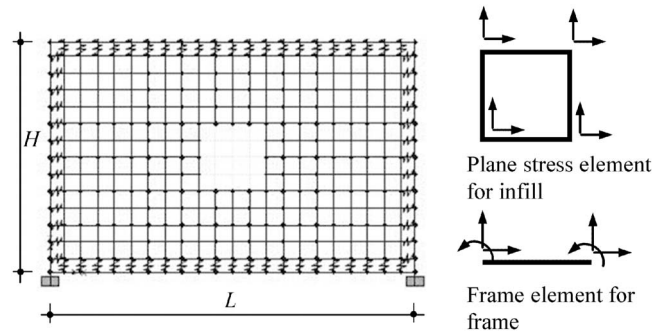
Figure 2. FE modeling of single-bay, single-story infilled frame with opening.

filled frames are identical to the single-bay single-story infilled frame. Central openings of widths 500 mm, 1000 mm, 1500 mm, 2000 mm, 2500 mm and 3000 mm are taken one at a time for each of these three sets of infilled frames. For each of these widths of opening, the considered heights of openings are 500 mm, 1000 mm, 1500 mm, 2000 mm and 3000 mm. Furthermore, one bare frame and one fully infilled frame of each of these three sets of infilled frames are analyzed. Thus a total of 96 models are analyzed in the parametric study. All the analyses are performed using the software SAP 2000 Version 8 (CSI 2000a, 2000b).

Masonry of compressive prism strength 5 MPa and concrete having a characteristic compressive strength (f_{ck}) of 25 MPa are used. The characteristic compressive strength of concrete is specified by compressive strength of 150 mm size cube at 28 days (expressed in MPa) which is almost 1.25 times the 28 day compressive strength of concrete cylinder specified in ACI 318-05 (2005). Poisson's ratios of masonry and concrete are taken as 0.18 and 0.20, respectively. All the models are analyzed by applying lateral load in combination with gravity load. Lateral loads are taken as 10% of the lateral strength of the frames (Choubey and Sinha 1994) and are applied at the floor level as in the experimental models. Lateral strength of frames is estimated by the pushover analysis by using the modified diagonal strut model (Al-Chaar 2002).

FINITE ELEMENT (FE) ANALYSIS

In the FE method, standard two-noded frame elements with two translational degrees of freedom and one rotational degree of freedom at each node are used to model the frame elements. The infills are idealized by four-noded plane stress rectangular or square area elements with two translational degrees of freedom at each node (Figure 2). Interface of the infill and frame are modelled using linear springs incapable of taking any tension. Similar elements were also used earlier by some investigators, e.g., Thiruvengadam (1985).

Table 1. Comparison of finite element analysis and experimental values for initial lateral stiffness[a]

Model No.	Authors	Type of Specimen	FEA	Experimental	Error (%)
				Stiffness (kN/mm)	
1	Choubey and Sinha (1994)	1-Story 1-Bay Bare Frame	3.8	3.9	−2.4
2	Pillai (1995)	5-Story 1-Bay Bare Frame	3.9	4.4	−20.7
3	Choubey and Sinha (1994)	1-Story 1-Bay Infilled Frame without Opening	37.9	25.4	49.3
4	Al-Chaar et al. (2002)	1-Story 1-Bay Infilled Frame without Opening	66.9	71.8	−6.8
5	Pillai (1995)	5-Story 1-Bay Infilled Frame without Opening	12.5	29.3	−57.6
6	Choubey and Sinha (1994)	1-Story 1-Bay Infilled Frame with Opening	14.6	16.0	−8.8
7	Raj (2000)	1-Story 1-Bay Infilled Frame with Opening	25.6	25.5	0.4

[a] Semirigid end-offset, cracked flexural rigidity of components, $E_m = 550 f_m$, and frame-infill separation are considered.

CALIBRATION OF THE FE MODEL

Experimental results available in the published literature for two RC bare frames, three RC infilled frames without any opening, and two RC infilled frames with central window openings are used to calibrate the FE model (Table 1). The influence of the following four factors namely, (*a*) flexural rigidity of components (*b*) modulus of elasticity of masonry, (*c*) rigidity of beam-column junction, and (*d*) the separation between frame and infill are examined in the FE analysis. Results of initial lateral stiffness by FE model are compared with experimental initial lateral stiffness and based on these comparisons a FE model is chosen for the subsequent parametric study. Cracking in infill and frame is not considered since the stiffness has been considered at a load level corresponding to 10% of the lateral strength of infilled frame. Since the present study focuses on the effect of opening on initial lateral stiffness of infilled frame, failure mode and material properties are not important parameters. Therefore, these parameters are not considered in the present study.

Flexural Rigidity of Components

In flexure dominated components (e.g., beams, columns, etc.), effective cross section of the member is reduced significantly due to the appearance of flexure cracks. Therefore, in the present study, two types of flexural rigidity of components are taken, namely flexural rigidity of components considering uncracked section and cracked section. Uncracked flexural rigidity of components is taken as $E_c I_g$, where I_g is the gross cross section of the components and E_c is the modulus of elasticity of concrete as per IS 456: 2000:
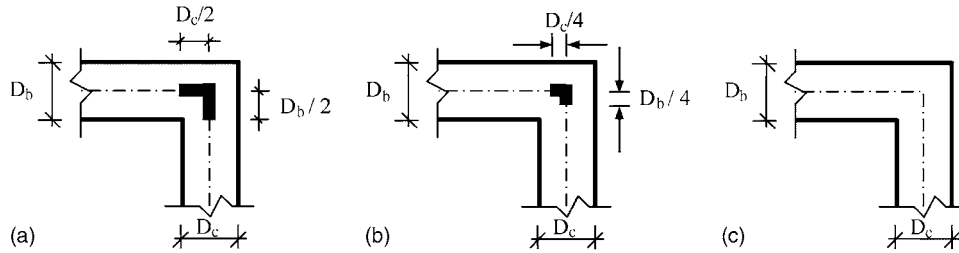
Figure 3. Modelling of beam-column joint-end-offsets: (a) rigid end-offset, (b) semirigid end-offset, and (c) flexible end-offset.

$$E_c = 5000\sqrt{f_{ck}}, \tag{1}$$

where f_{ck} is the characteristic compressive strength (MPa) of concrete cube at 28 days. Cracked flexural rigidity of components is taken as $0.5E_cI_g$ in beam and in tension column and $0.7E_cI_g$ in compression column, where E_c is the modulus of elasticity (Equation 1) (ATC-40 1996, and FEMA-273 1997). For the specimens 2 and 5, the modulus of elasticity of concrete has been reported based on compressive tests on concrete cubes; these are used in separate cases.

Modulus of Elasticity of Masonry

Drysdale et al. (1993) have recommended that modulus of elasticity of masonry may be taken as:

$$E_m = kf_m, \tag{2}$$

where f_m is the compressive strength of masonry prism in MPa and k lies between 500 to 600. In the present study, this expression is used with k taken as 550 to model the initial stiffness of the infilled frames with openings.

Rigidity of Beam-Column Junction

In RC structures, the assumption of centerline dimensions is often inaccurate. Finite size of the joint can be modelled through the use of rigid-end-offsets option. In fact, rigid-end-offsets allow modeling the ends of a member such that these are not considered to be part of the flexible portion. In the present study, three types of rigidity of the beam-column joints namely, rigid, semirigid, and flexible are used to investigate the effect of finite size of the joint (Figure 3). In case of rigid beam-column joint, the end-offset is up to half column depth along beam from center line of column and half beam depth along column from center line of beam. In case of semirigid beam-column joint, rigid end-offset is upto quarter column depth along beam from center line of column and quarter beam depth along column from center line of beam while, in case of flexible beam-column joint, length of rigid end-offset is taken as zero.

Frame and Infill Interface

In the present study, two types of frame-infill interface are considered. In the first type, separation between frame and infill is not allowed while in the second type, separation between frame and infill at the non-loaded diagonal is allowed. To account for this, linear springs are used as interface elements. Stiffness of the spring is the axial stiffness of mortar, i.e., $A_{mor}E_{mor}/t_m$ where, A_{mor} is the effective area of mortar, t_m is the thickness of mortar, and E_{mor} is the modulus of elasticity of mortar. In absence of specific data on modulus of elasticity of the mortar, it is taken same as modulus of elasticity of masonry (i.e., $E_m=550f_m$). As the mortar is weak in tension, its tensile strength is neglected in the FE analysis. For a given lateral load, the forces in these link elements are evaluated and those carrying tension are removed. The process is repeated till all the links remaining are in compression and the contact lengths are established. Due to unavailability of reliable data on stiffness of mortar it was assumed that the axial stiffness of mortar and brick is comparable. Hence, after identifying the length of contact, the link elements are done away with and the infill is extended to the centerline of the frame at the contact portion and the frames are analyzed to obtain the lateral stiffness. This slightly increases the overall stiffness of infilled frames.

Results

Results of the bare frames, i.e., specimen 1 and 2 show that the uncracked flexural rigidity of components results in up to 120% error (average 70%). Models with flexible beam-column joints show up to 50% error with an average of 26%. On the other hand, the models involving the combination of cracked flexural rigidity of components and rigid and semirigid beam-column joints result in maximum 20% error with an average error of 10%.

Analysis of infilled frames, i.e., specimen 3, 4 and 5 shows that the modulus of elasticity of masonry based on Drysdale et al.'s (1993) empirical formula (Equation 2) yields reasonable estimate of the initial lateral stiffness. Complete contact between the frame and the infill resulted in large error in initial lateral stiffness, as large as 300%. Therefore, the separation between frame and infill at the non-loaded diagonal proved to be a significant factor. Use of these two parameters along with the cracked flexural rigidity of components and semirigid beam-column joint, as discussed above, give the best correlation with experimental values of lateral stiffness; difference being up to 57% (with an average of 38%). Therefore, this combination is considered for analysis of infilled frames with openings.

Use of the above mentioned parameters on infilled frames with openings resulted in less than 10% error in initial stiffness as compared to the experimental initial lateral stiffness. Therefore, results of the models considering cracked flexural rigidity of components, semirigid beam-column joint, and separation between frame and infill at the non-loaded diagonal are summarized in Table 1. Detailed results of all the other models are available elsewhere (Mondal 2003).

Figure 4 shows bar diagram of difference between FE model and experimental value of initial lateral stiffness for specimen 3, 4, 5, 6 and 7. Specimen 1 and 2 are not in-
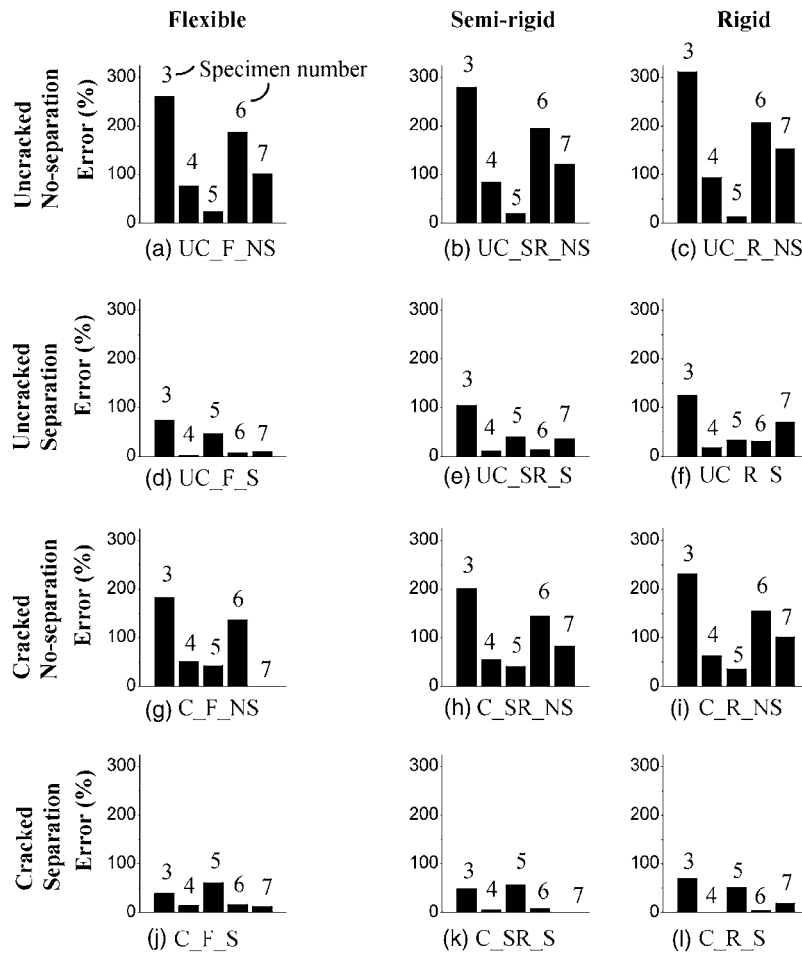
Figure 4. Comparison of different FE models. (UC: uncracked flexural rigidity of components; C: cracked flexural rigidity of components; F: flexible end-offset; SR: semirigid end-offset; R: rigid end-offset; NS: no separation at the frame-infill interface; S: separation at the frame-infill interface).

cluded in the comparison since these are bare frames, where comparison of separation of frame and infill at non-loaded diagonal is meaningless. Comparisons of Figures 4a–4c with Figures 4d–4f, and Figures 4g–4i with Figures 4j–4l show that separation of frame-infill interface at the non-loaded diagonal should be considered. Similarly, comparisons of Figures 4a–4c with Figures 4g–4i, and Figures 4d–4f with Figures 4j–4l indicate that cracked flexural rigidity of components should be taken in the analysis. This figure also indicates that semirigid beam-column junction minimizes difference between FE model and experimental value of initial lateral stiffness. On the whole, Figure 4k gives the best
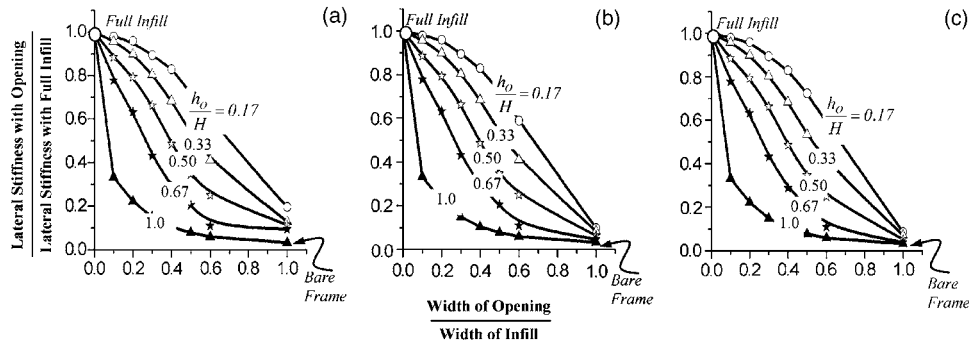
Figure 5. Effect of opening size on lateral stiffness of infilled frame determined by FE analysis: (a) single-story, (b) two-story, and (c) three-story.

match between FE model and experimental results; this model considers cracked flexural rigidity of components, semirigid beam-column junction and separation of frame-infill interface at non-loaded diagonal.

PARAMETRIC STUDY USING CALIBRATED FE MODEL

The initial lateral stiffness of single-bay single-story, single-bay two-story, and single-bay three-story RC infilled frames with varying sizes of central openings are determined using calibrated FE model. Cracked flexural rigidity of components, semirigid beam column junction and frame-infill separation are considered in the analysis. The RC beams and columns are discretized as frame elements and the infill as 250 mm × 250 mm plane stress elements (Figure 2). A lateral load is applied at the roof level in combination with gravity load.

Initial lateral stiffness determined by FE analysis of frames is shown in Figure 5. Width and height of opening is normalized with respect to width and height of infill, respectively, and the lateral stiffness of infilled frames is normalized with respect to that of the fully infilled frames. The following observations are made from the analysis:

(a)   Presence of opening significantly reduces the initial lateral stiffness of infilled frames. As expected, the lateral stiffness decreases with increase of area of opening. When central opening occupies about 15% of the infill area, initial lateral stiffness is reduced by about 40%.

(b)   A sharp decrease in initial lateral stiffness is observed for the openings extended to full height or full width of the infill. This is because extension of opening to the full height or full width of infill divides infill panel into two sub-panels and the single diagonal strut cannot develop.

(c)   In case of two similar rectangular frames with equal areas of openings, the frame having larger width of opening exhibits more initial lateral stiffness. This is because the possibility of formation of single diagonal strut is more in case of larger width of opening as the panels considered in the analysis are rectan-
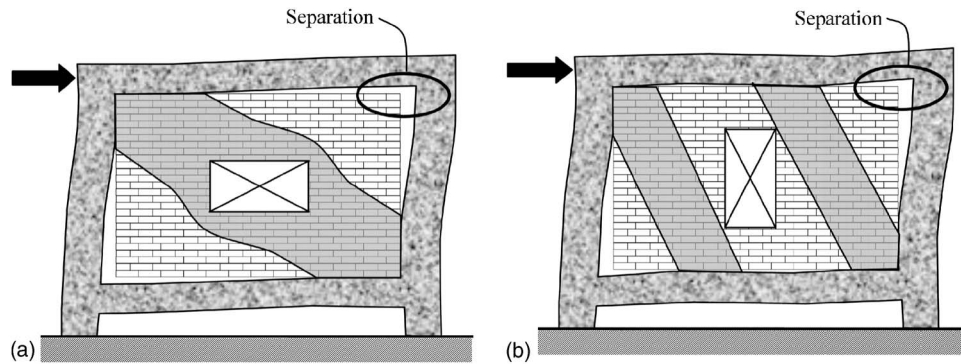
Figure 6. Formation of diagonal strut: (a) single diagonal strut, (b) multi-strut.

Table 2. Effect of dimensions of opening on initial lateral stiffness of infilled frame

| Width Smaller than Height		Width Larger than Height		
Opening Size (mm×mm)	Lateral Stiffness (KN/mm)	Opening Size (mm×mm)	Lateral Stiffness (KN/mm)	Difference (%)
		Single Story		
500×1000	125	1000×500	120	−4.2
500×1500	114	1500×500	117	2.5
500×2000	98	2000×500	105	5.8
1000×1500	97	1500×1000	101	3.3
1000×2000	75	2000×1000	85	8.3
1500×2000	54	2000×1500	62	6.7
		Two Story		
500×1000	68	1000×500	70	1.7
500×1500	62	1500×500	64	1.7
500×2000	51	2000×500	58	5.8
1000×1500	54	1500×1000	55	0.8
1000×2000	41	2000×1000	47	5.0
1500×2000	29	2000×1500	32	2.5
		Three story		
500×1000	44	1000×500	44	0.0
500×1500	40	1500×500	41	0.8
500×2000	35	2000×500	38	2.5
1000×1500	36	1500×1000	37	0.8
1000×2000	29	2000×1000	31	1.7
1500×2000	20	2000×1500	22	1.7
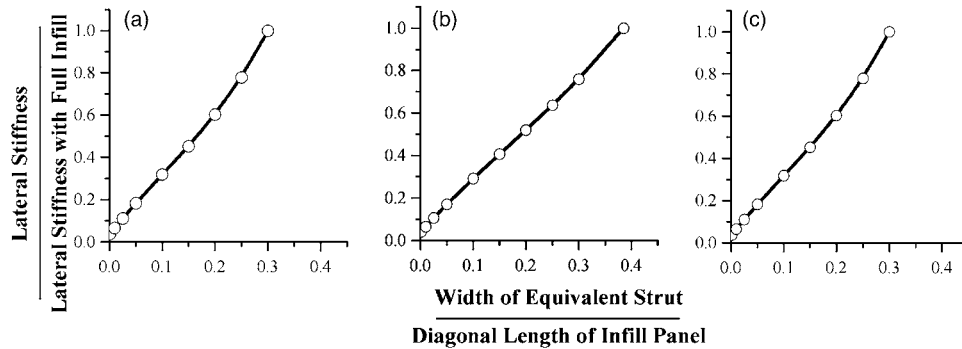
Figure 7. Effect of width of equivalent diagonal strut determined by single equivalent diagonal strut analysis on lateral stiffness: (a) single-story, (b) two-story, and (c) three-story.

gular (5000 mm × 3000 mm) (Figure 6). As the height of opening increases the panel is divided into two sub-panels which increase the possibility of formation of multi-strut as shown in Figure 6.

(d) For the same area of opening if the dimensions of opening vary, the difference in initial stiffness is less than 10% (Table 2). Hence, except in extreme cases, area of opening (and not the height-to-width ratio of opening) governs the lateral stiffness of infilled frame. Therefore, the reduction factor proposed in this article does not depend upon the height to width ratio of the opening.

SINGLE EQUIVALENT DIAGONAL STRUT (SEDS) ANALYSIS

Initial lateral stiffness of the three identical infilled frames (namely single-story, two-story and three-story) is also obtained by SEDS analysis. In this analysis, infills are modelled as single equivalent diagonal struts and the widths of diagonal struts are taken as $0.001d$, $0.01d$, $0.025d$, $0.05d$, $0.1d$, $0.15d$, $0.2d$, $0.25d$, $0.3d$, $0.4d$ and $0.5d$, where d in the diagonal length of infill. The strut is connected to the diagonal nodes at the beam-column joint so that it can take only axial force. The thickness of the struts is kept same as that of the infill. The beams and columns are modelled as frame elements. Semirigid end-offsets are considered to account for the finite size of beam-column junctions. Cracked flexural rigidity of components and modulus of elasticity of masonry $E_m = 550 f_m$ are considered for the analysis.

The effect of strut-width on lateral stiffness of the infilled frames is shown in Figure 7. It is seen that the lateral stiffness of infilled frames increases almost linearly with increase in strut-width.

STRUT-WIDTH REDUCTION FACTOR

The effect of opening on the lateral stiffness of the infilled frame can be represented by a diagonal strut of reduced width. This reduction in strut-width can be represented by a factor (ρ_w), which is defined as ratio of reduced strut-width to strut-width corresponding to fully infilled frame, i.e.,

$$\text{Strut} - \text{width reduction factor } (\rho_w)$$

$$= \frac{\text{Strut} - \text{width of Infilled Frame with Opening } (w_{do})}{\text{Strut} - \text{width of Fully Infilled Frame } (w_{ds})} \tag{3}$$

For an infilled frame with a given size of opening, strut width required to obtain the lateral stiffness can be evaluated from Figure 8. From this figure, strut-widths are obtained for single-story, two-story, and three-story infilled frames with openings, considered in the present study. For example, in Figure 8, width of equivalent diagonal strut is about $0.15d$ for $\frac{l_0}{L}=0.6$ and $\frac{h_0}{H}=0.33$, regardless of the number of stories.

Area of opening, A_{op}, is normalized with respect to area of infill panel, A_{infill}, and the ratio is termed as opening area ratio, α_{co}, i.e.,

$$\text{Opening-Area-Ratio } (\alpha_{co}) = \frac{\text{Area of Opening } (A_{op})}{\text{Area of Infill } (A_{\text{infill}})} \tag{4}$$

Strut width reduction factors for various opening-area-ratios for all the frames are obtained and are shown in Figure 9. A sharp decrease of initial stiffness has been observed when the opening is extended up to full height or full width of the panel. Except such extreme cases, it is observed that the area of opening is important for initial lateral stiffness of infilled frame. Therefore, the cases in which the openings are extended up to the full height or full width of the panel ($\frac{h_0}{H}=1$ or $\frac{l_0}{L}=1$) are excluded in regression analysis as they do not reflect the strut action adequately. Regression analyses of these data are performed and, linear, second-order polynomial, and third-order polynomial trend lines are shown in Figure 9. Also shown in this figure are the equations of the trend lines and the coefficient of correlation (R-value).

The linear-fit follows the data reasonably well with R value of about 0.97. The polynomials of higher order fit the data slightly better than linear-fit with R value about 0.98. However, considering the simplicity the following linear-fit equations adequately represent the data:

$$\rho_w = 1 - 2.47\alpha_{co} \text{ (one story)} \tag{5}$$

$$\rho_w = 0.96 - 2.56\alpha_{co} \text{ (two story)} \tag{6}$$

$$\rho_w = 1.05 - 2.56\alpha_{co} \text{ (three story)} \tag{7}$$

These equations show that the strut-width reduction factor is not sensitive to the number of stories. Hence, data of all the three stories are plotted in a single figure and
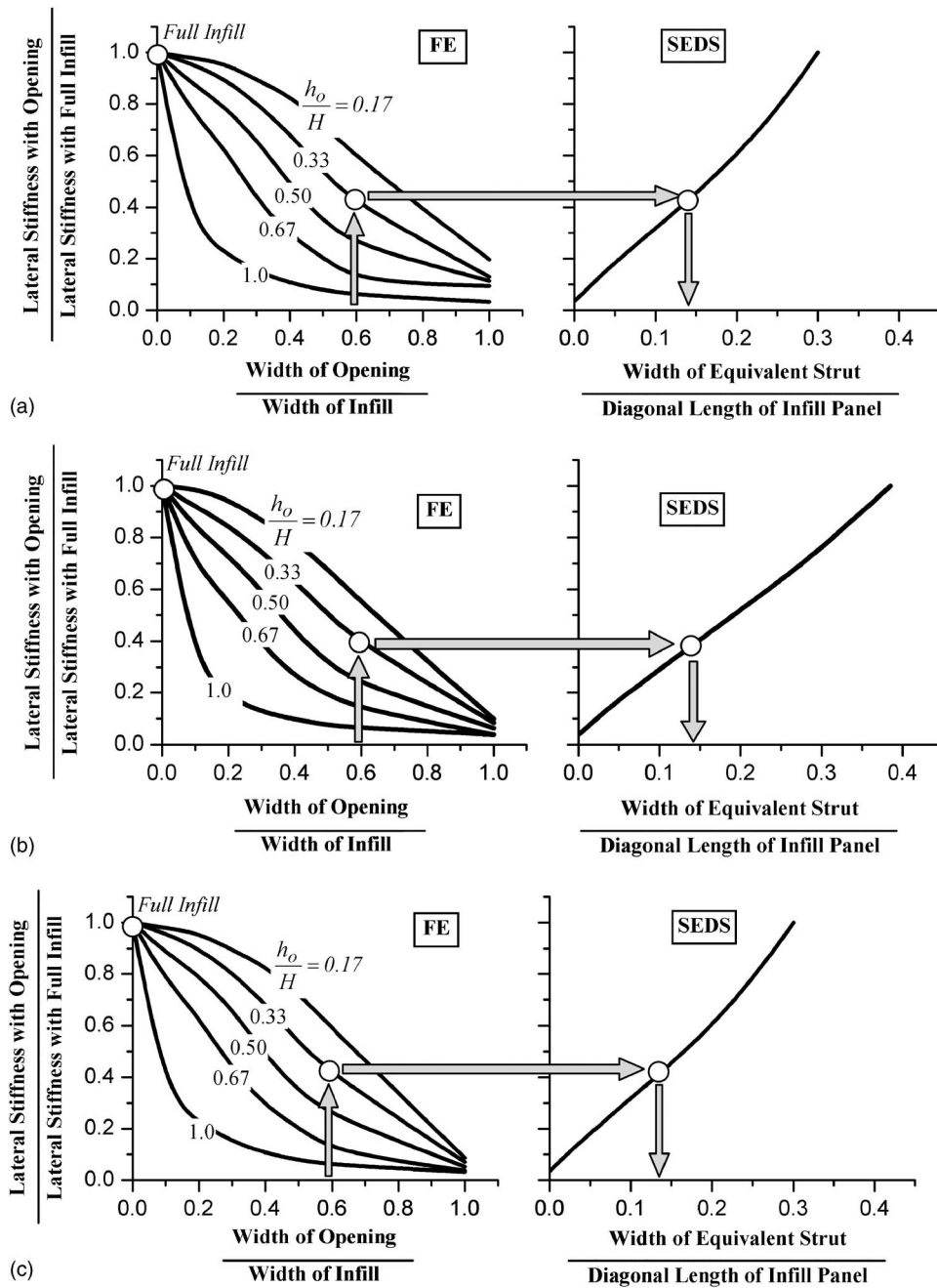
Figure 8. Effect of opening size on equivalent diagonal strut: (a) single-story, (b) two-story, and (c) three-story.
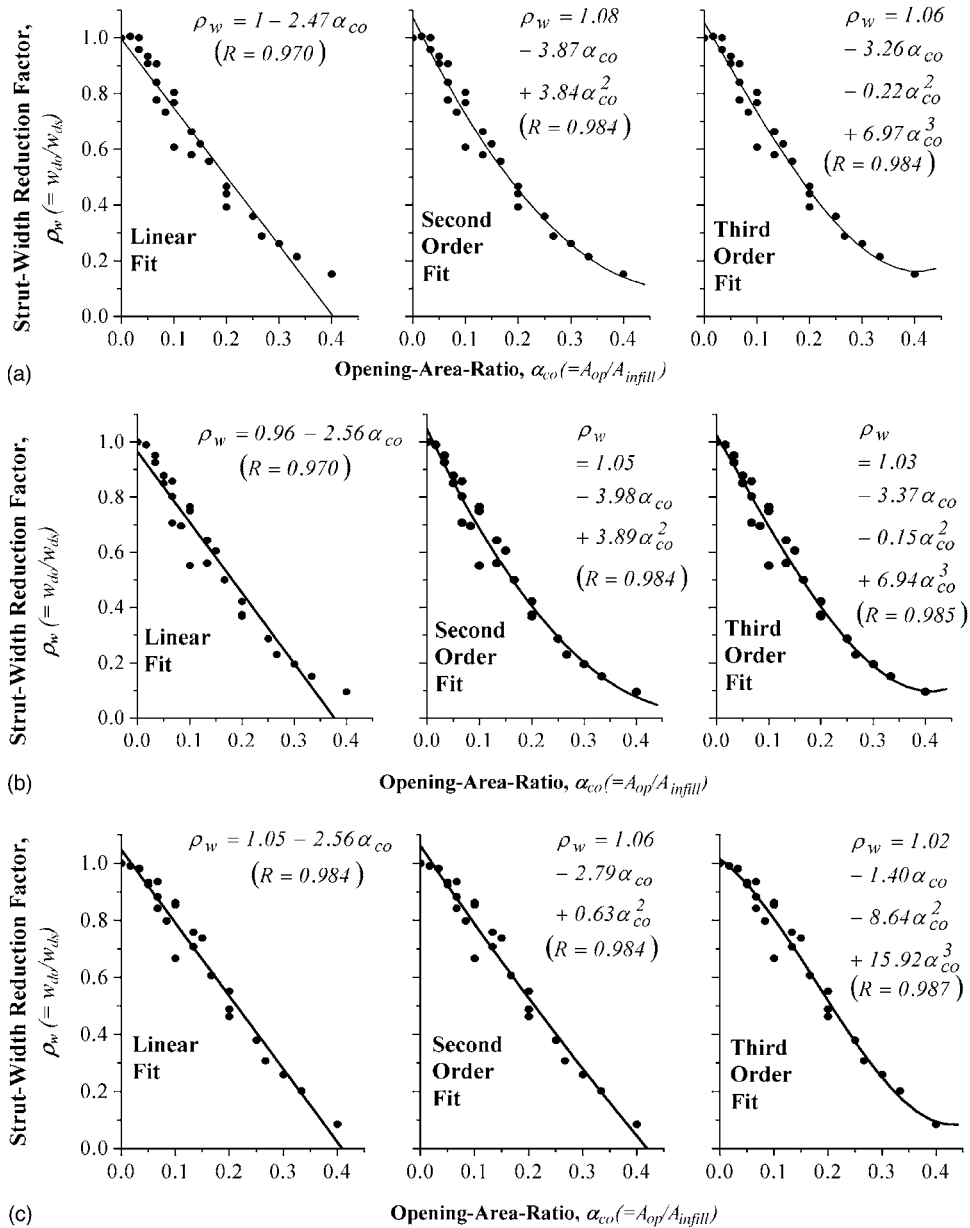
Figure 9. Effect of opening-area-ratio on strut-width reduction factor: best fit curves of analytical results (a) single-story, (b) two-story, and (c) three-story.

regression analysis is performed on the combined data. A linear-fit curve ($\rho_w = 0.99 - 2.58\alpha_{co}$, with $R = 0.965$) follows the trend of data reasonably well (Figure 10). Based on the above equations and linear fit curve, the reduction factor for the infilled frame with opening can be simplified as:
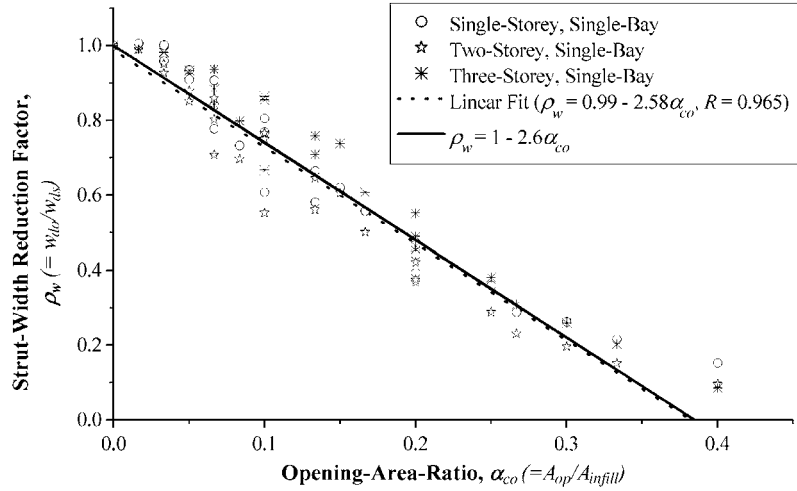
Figure 10. Linear trend line of all the merged data and comparison with the proposed equation of strut-width reduction factor.

$$\rho_w = 1 - 2.6\alpha_{co} \tag{8}$$

regardless of the number of stories. The above expression for the reduction factor (i.e., $\rho_w = 1 - 2.6\alpha_{co}$) is also plotted in Figure 10. The comparison between this curve and the linear fit curve shows that the proposed equation (Equation 8) is a good estimation of initial lateral stiffness of the infilled frame with a central opening.

Thus one may conclude that the stiffness contribution of infill may be neglected when opening area is greater that 40% of the area of infill. Similarly, presence of opening may be ignored if it is less than 5% of area of infill panel.

WIDTH OF STRUT

The reduction factor proposed above is with respect to analytical strut-width for fully infilled frame. In practice, one may use strut-width of solid infilled frames based on a number of equations available in the literature, each giving a different value of lateral stiffness. There has been a concern by some researchers (Meharbi et al. (1994), Al-Chaar (2002), and Al-Chaar et al. (2003a, 2003b)) that the single equivalent diagonal strut does not predict satisfactorily the lateral stiffness of infilled frame. It is therefore important to compare the width of diagonal strut of solid infilled frames obtained from several empirical relationships available in the literature with that obtained by the finite element analysis. The following relations have been considered:

$$w_{ds} = 0.58\left(\frac{l}{h}\right)^{-0.445}(\lambda H)^{0.335d}\left(\frac{l}{h}\right)^{0.064} \text{(Smith and Carter 1969)} \tag{9}$$

Table 3. Comparison of width of equivalent diagonal strut for infilled frame without opening

		Width of Strut of Solid Infill								
	FEM	Smith and Carter, 1969		Mainstone, 1971		Paulay and Priestley, 1992		Liauw and Kwan, 1984		Holmes, 1961	
Fully Infilled Frames	mm	mm	Error (%)	mm	Error (%)	mm	Error (%)	mm	Error (%)	mm	Error (%)
1-Story	1577	4059	−157.4	635	59.7	1458	7.6	1352	14.3	1944	−23.2
2-Story	1785		−127.4		64.4		18.3		24.3		−8.9
3-Story	2245		−80.8		71.7		35.1		39.8		13.4

$$w_{ds} = 0.175(\lambda H)^{-0.4}d \text{ (Mainstone 1971)} \tag{10}$$

$$w_{ds} = \frac{d}{4} \text{ (Paulay and Priestley1992)} \tag{11}$$

$$w_{ds} = \frac{(0.95h \cos \theta)}{\sqrt{\lambda H}} \text{ (Liauw and Kwan 1984)} \tag{12}$$

$$w_{ds} = \frac{d}{3} \text{ (Holmes 1961)} \tag{13}$$

In Table 3 the widths of struts for single-story, two-story, and three-story solid infill, calculated by the Equations 9–13, are compared with the widths of struts determined by FE method. The difference in width of strut from FE analysis and that using Equation 9 (Smith and Carter 1969) is up to 150%. Strut width proposed by Mainstone (1971) substantially underestimates the lateral stiffness of infilled frames (the strut width proposed by Mainstone is 60% to 70% smaller than that found from FE analysis) which supports the conclusion of Meharbi et al. (1994, 2003). Therefore, the proposed reduction factor cannot be applied to widths of struts proposed by Smith and Carter (1969), and Mainstone (1971). However, results from Equations 11–13 (Paulay and Priestley 1992, Liauw and Kwan 1984, and Holmes 1961) compare well with the strut widths from FE analysis. Hence, only these three proposals are considered for further discussion.

New strut-width reduction factor values are calculated wherein the strut-width of solid infill (w_{ds}) is based on Equations 11, 12 or 13. Two linear-fits are considered, one is the best fit and the other a constrained fit with the ρ_w-intercept forced to be unity (Figure 11). Poor correlations are obtained for strut-width reduction factor values from Equations 11 (Paulay and Priestley 1992) and 12 (Liauw and Kwan 1984). On the other hand, the width of strut using Equation 13 (Holmes 1961) provides the best results for the proposed strut-width reduction factor for infilled frames with openings. The two equations for unconstrained fit ($\rho_w = 0.96 - 2.44\alpha_{co}, R = 0.928$) and constrained fit ($\rho_w = 1 - 2.62\alpha_{co}, R = 0.924$) match very well (Figure 11). Furthermore, the constrained fit curve is very close to the proposed strut-width reduction factor (i.e., $\rho_w = 1 - 2.6\alpha_{co}$).
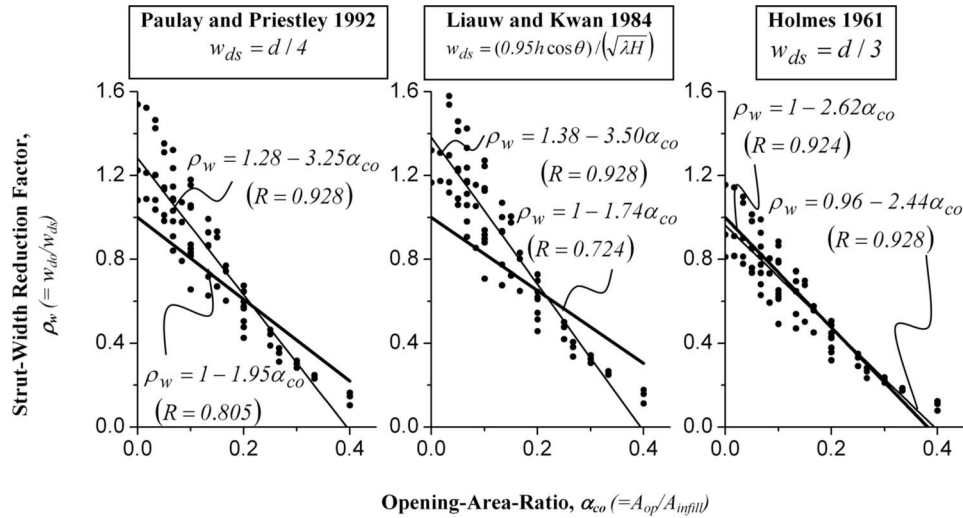
Figure 11. Strut-width reduction factor based on available strut-width for solid infill.

Therefore, the strut-width for solid infill as per Equation 13 (Holmes 1961) can be taken as the basis to apply the proposed strut-width reduction factor due to presence of opening.

VERIFICATION OF THE PROPOSED REDUCTION FACTOR

In the parametric study, all the parameters except the number of stories and the size of openings are kept constant for different models. Based on this, a reduction factor for infilled frames with openings is proposed. To demonstrate the applicability of the proposed reduction factor, some of the parameters of the single-bay single-story model are changed one at a time while all others are kept constant. In addition, results of experimental specimens available in the literature are considered to verify the proposed strut-width reduction factor. Moreover, the proposed strut-width reduction factor is compared with that proposed by Durrani and Luo (1994), and by Al-Chaar (2002).

The effects of the sizes of beam and column, compressive strength of concrete, thickness and area of infill panel on strut-width reduction factor are shown in Table 4. It is seen that a 37.5% reduction in size of beam results in 8% error in the strut-width reduction factor. Similarly, 70% reduction in size of column leads to 8% error in reduction factor. A 7% error in reduction factor was observed due to a 20% increase in the compressive strength of concrete. Table 4 also displays that reduction factor is weakly dependent on thickness and area of infill panel. All these strut-width reduction factors are also plotted in Figure 12 along with the proposed strut-width reduction factor as per Equation 8, which shows that there is not much variation in the reduction factor in relation to the changes made in the parameters.

The proposed reduction factor is further verified with three experimental specimens

Table 4. Effect of change of parameters on strut-width reduction factor

Parameters	In Parametric Study	In Verification	Error in Reduction Factor (%) for Different Opening Size (mm^2)		
			1000×1000	1500×1500	2500×1500
Size of Beam (mm^2)	250×400	250×250	7.7	8.3	0.0
Size of Column (mm^2)	400×400	250×250	8.1	3.2	1.2
f_{ck} (MPa)	25	30	7.0	4.7	6.9
Thickness of Infill (mm)	225	112.5	12.0	1.7	0.0
Area of Infill Panel (mm^2)	3000×5000	4000×5000	4.8	9.0	2.0

published in literature. These include single-bay single-story specimens with a window opening of Raj (2000), Choubey and Sinha (1994), and Combescure and Pegon (2000). The first two specimens were also used earlier for calibration of the finite element model (Table 1). Single equivalent diagonal strut analysis of these three specimens are performed in SAP 2000 where the infills are modelled as diagonal strut, and the width of struts is varied to find the strut-width which gives stiffness same as the experimental initial stiffness value of these specimens. The corresponding strut-width reduction factor for the three specimens are also plotted in Figure 12 which shows a good match with proposed strut width reduction factor.
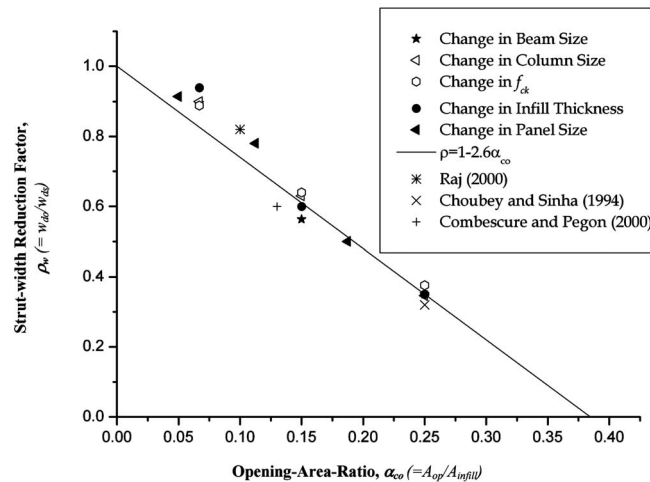
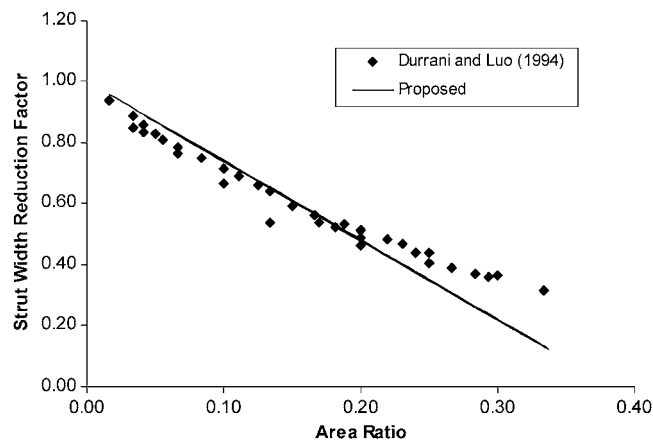**Figure 12.** Verification of the proposed strut-width reduction factor.

Figure 13. Comparison of proposed strut width reduction factor with that proposed by Durrani and Luo (1994).

The proposed strut width reduction factor is also compared with that proposed by Durrani and Luo (1994). For this comparison, infilled frames of aspect ratios 0.6 to 1.3 and central opening of aspect ratios 0.5 to 4.0 are considered. Figure 13 shows that the proposed reduction factor matches well with that proposed by Durrani and Luo (1994) up to area ratio 0.25 and beyond that Durrani and Luo (1994) give substantially higher value of reduction factor. The expression developed in the present study is far simpler than that proposed by Durrani and Luo (1994) and is very easy to implement in the design office.

The proposed reduction factor is also compared indirectly with that proposed by Al-Chaar (2002). The reduction factor proposed by Al-Chaar estimates the in-plane capacity (strength) of the infilled frame satisfactorily. However, it does not predict the initial lateral stiffness with sufficient accuracy. The initial lateral stiffness of infilled frame obtained from Al-Chaar's experiment is almost three times larger (for aspect ratio of panel between 0.67 and 1.5) than that estimated from the bilinear pushover curve of infilled frame obtained by using strut-width proposed by Al-Chaar (2002). Moreover, reduction factor for strength to account for openings proposed by Al-Chaar should be applied for eccentric single equivalent strut where strut element is connected to the columns rather than to the beam-column joints. Therefore, it is not possible to directly compare the strut width reduction factor. Instead, lateral stiffness reduction due to presence of openings obtained by using strut width proposed by Al-Chaar (2002) and that proposed in the present study are compared. For this purpose, specimen of Choubey and Sinha (1994) with varying opening size is considered. Figure 14 shows that Al-Chaar's reduction factor somewhat overestimates the stiffness reduction. This difference becomes quite significant beyond the area ratio of 0.25.
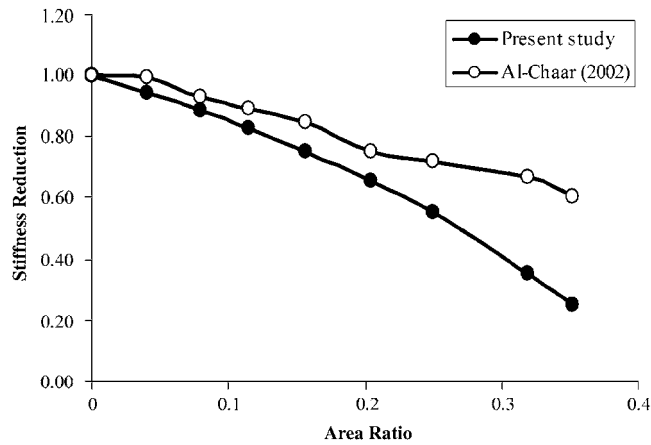
Figure 14. Comparison of stiffness reduction obtained by using proposed strut width reduction factor and that proposed by Al-Chaar (2002).

SUMMARY AND CONCLUSIONS

In many countries, multistory buildings are commonly built with reinforced concrete frame and masonry infill walls. Such buildings are usually designed assuming the infill walls to be nonstructural and ignoring their strength and stiffness. However, the recent earthquakes illustrate the significant structural contribution of the infill wall implying that infill wall should be taken into consideration in the design process. Some codes contain provisions for modeling solid infill walls using the diagonal strut method. Generally, infilled frames with openings have not been adequately covered in the codes.

In the present study, a reduction factor is proposed for effective width of diagonal strut over that of the solid infilled frame to calculate its initial stiffness when a central window opening is present. Seven specimens of infilled frame for which details of the specimens and experimental results are available in the published literature are considered. These include single-bay single-story to single-bay multi-story bare frames, infilled frames without openings, and infilled frames with central openings. These specimens are analyzed by Finite Element (FE) method using the software SAP 2000 Version 8 (CSI 2000a, 2000b). The present study is based on initial lateral stiffness corresponding to 10% of the lateral strength of the infilled frames. Based on the comparison between initial lateral stiffness using FE method and from experimental initial lateral stiffness it is found that best match with experimental results are obtained when (a) separation between the frame and the infill at the non-loaded diagonal is included, (b) end-offsets of beam-column joints in RC frames is assumed to be semirigid wherein quarter column-depth along beam from center line of column and quarter beam-depth along column from center line of beam are considered rigid, (c) the FE model is based on cracked flexural rigidity of beams and columns where the flexural rigidity of beam and column in tension is taken as $0.5E_cI_g$ and that of column in compression is taken as $0.7E_cI_g$

(ATC-40 1996), (d) modulus of elasticity of concrete (E_c) is assumed as $E_c = 5000\sqrt{f_{ck}}$, where f_{ck} is the characteristic compressive strength (MPa) of concrete cube at 28 days, and (e) modulus of elasticity of masonry is taken as $E_m = 550 f_m$ (Drysdale et al. 1993), where f_m is the compressive strength of masonry prism in MPa. Based on such a FE model, parametric study is performed for single-bay single-story, single-bay two-story and single-bay three-story infilled frames with different opening sizes.

It was proposed that in the single diagonal strut model of fully infilled frame, the width of the strut can be taken as one third of the diagonal length of the infill as proposed by Holmes (1961). The presence of central opening can be considered by reducing the effective width through a reduction factor, $\rho_w = 1 - 2.6\alpha_{co}$, where $\alpha_{co} =$ ratio of the area of opening to the area of the infill. The applicability of this proposed reduction factor is verified by varying some of the parameters that are kept constant during the parametric study and with three experimental specimens; these show good agreement.

It can also be concluded that the effect of opening on the initial lateral stiffness of infilled frames should be neglected if the area of opening is less than 5% of the area of the infill panel, and the strut-width reduction factor should be set to one, i.e., the frame is to be analyzed as a solid infilled frame. The effect of infill on the initial lateral stiffness of infilled frame may be ignored if the area of opening exceeds 40% of the area of the infill panel, and the strut-width reduction factor should be set to zero, i.e., the frame is to be analyzed as a bare frame. The proposed reduction factor is applicable for infilled frame with normal openings. Extreme cases where openings are extended to full height or full width of the infilled frame cannot be covered by the proposed reduction factor.

The present study is limited to infilled frames with central openings. Future work should be performed to obtain the effect of location of opening in the infilled frame. The effect of lintel bands or different types of stiffeners on the reduction factor should also be investigated.

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