BUILDING RESEARCH JOURNAL

VOLUME 60, 2012 NUMBER 1 – 2

COMPOSITE BEHAVIOR OF MASONRY PARTIALLY INFILLED REINFORCED CONCRETE FRAMES

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Partially infilled reinforced concrete frames are susceptible to short-column effect. Past earthquakes have often damaged a large number of structures, which included masonry partially infilled concrete frames. This study is conducted to quantify the shear force developed within the columns having masonry partial infills using equivalent diagonal strut model. Similarly, the study is done for stiffness behaviors and fundamental period of vibration for partially infilled frames. The partially infilled frames were found most vulnerable to damage when the masonry infills were about 40 % filled.

Keywords: Flexural model, masonry partially infilled frames, short column effect

1. Introduction

The reinforced concrete frames are flexible structures, which become highly stiff when brick masonry walls are inserted within them. However, it is still in practice to analyze structures without modeling the masonry infill within the frames. Frames may be fully or partially infilled. It is well known that the stiffness of bare frame is lesser than that of a fully infilled frame. The stiffness of frame and infill collectively contribute to enhancing the strength of the whole structure. The infills on one hand are regarded as elements which improve the lateral resistance of frame structures, but on the other hand, when placed partially within the frame, are considered to cause a short column effect which damages the columns during lateral loading. The studies so far also suggest that the damage is due to the shear force exerted by the walls which terminate at certain height within the frame. If the shear force exerted by the partially filled walls were known, it will be convenient to design column elements for shear force values at any location within the column.

The damages can be mitigated once the analysis of partially infilled frames is possible. The difficulty of replicating the behavior of partial infills in analytical model has been the major reason for neglecting the infills presence in the model. Moreover, the uncertainties of workmanship, material properties and masonry-concrete interface interaction have added complexities in understanding the exact behavior of partially infilled framed structures. Diagonal strut models are very popular among the various other models in the studies of infilled frames. In this study too, Flexural model

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proposed by Pradhan (2012) for partially infilled reinforced concrete frames has been considered. Analytical models are used to understand the responses offered by partially infilled frames during lateral loading.

2. Past Studies

Many researchers have suggested that the masonry infills contribute to resisting lateral force significantly through diagonal strut action. They have established the relations for equivalent strut width, among which the expressions suggested by Polyakov (1960), Smith (1962) and Paulay and Priestley (1992) are popular. Though there are numerous study reports on full infilled frames, the works on partially infilled frames are scarce. Moreover, the available documents are experimental ones. The work by Guevera and Garcia (2005) explains that the partially infilled masonry wall induces a short column effect and leads to a severe failure of the columns at the point where the wall terminates. They also emphasize that the completely filled masonry wall increases the stiffness of the structure. The study deals with both experimental and analytical approaches for fully infilled as well as partially infilled frames. The works done by Al-Chaar (2002) indicate that partially infilled frames are to be analyzed with a modified equivalent strut width. The modification is done to the Smith expression for the strut width (Smith and Carter, 1969). Accordingly, the strut width is calculated by considering the reduced infill height instead of using fully infilled height. Later the expression suggested by Mainstone (1971) was used to obtain the strut width, which is further modified using two reduction factors. The exact expression for partially infilled frames however is yet a topic of interest for structural engineers. Pradhan et al. (2010) have stated that the columns get damaged due to excessive shear from short column effect in partially infilled frames. The smaller the opening the lesser is the shear in column. If the wall height is reduced to less than 50 % of the clear frame height, the resistance against lateral displacement increases significantly, thus allowing more shear in the windward column. Pradhan (2012) has proposed a flexural model for equivalent strut width calculation, which uses single strut as an equivalent element representing partial masonry infill within concrete frame.

3. Analytical works

The equivalent strut width proposed by various researchers as shown in Table 1 are displayed in Figure 1 (Pradhan, 2012) for a particular case as per the data of Table 2. The equation proposed by Pradhan (Pradhan, 2012) for the equivalent strut width of partially infilled frames has been used to obtain various responses like shear force on column, stiffness of composite structure and fundamental period of vibration of the frame during the application of lateral loading on analytical models with data as per Table 2. The parameters L_m, h_m and t are the length, height and thickness of masonry infill respectively. Similarly, E_c and E_m are the Elastic Modulus of concrete and masonry wall respectively. The parameters D and H are the length of diagonal strut and column height respectively as per Mainstone (1971). The parameter θ is the angle made by diagonal strut with the horizontal. The parameters I_c and I_b are the second moment of areas of columns and beams respectively. The height of column according to Pradhan (2012) is h_c.

Table1. Strut width formulae (Pradhan, 2012)

Researchers	Strut width (w)	Remarks
Holmes (1961)	0.333 d_m	d_m is the length of diagonal
Mainstone (1971)	$0.175\ D\ (\lambda_1\ H)^{-0.4}$	$\lambda_1\ H = H\ [E_m t\mathrm{Sin}2\theta/4\ E_c I_c h_m]^{1/4}$
Liauw and Kwan (1984)	$0.95\ h_m\ \mathrm{Cos}\ \theta/\surd(\lambda h_m)$	$\lambda = E_m t\ \mathrm{Sin}\ 2\ \theta/\ 4\ E_c I_c h_m]^{1/4}$
Paulay and Priestley (1992)	0.25 d_m	d_m is the length of diagonal
Hendry (1998)	$0.5\ [\alpha_h + \alpha_L]^{1/2}$	$\alpha_h = \pi/2\ [E_c I_c\ h_m/2\ E_m t\sin2\theta]^{1/4}$ and $\alpha_L = \pi\ [\ E_c I_b L/\ 2\ E_m t\sin2\theta]^{1/4}$
Pradhan (2012)	$\frac{\pi}{2}2.29\left[\frac{E_c I_c h_m}{E_m t h_c}\right]^{\frac{1}{3}} \frac{L_m}{\sqrt{L_m^2+(h_m-k_x)^2}}$	$k_x = \frac{\pi}{2}2.29\left[\frac{E_c I_c h_m}{E_m t h_c}\right]^{\frac{1}{3}}$

The equivalent strut width calculated for data in Table 2 for various aspect ratios of frame height to frame span has been studied and tabulated in Tables 3, 4 and 5. A particular case of equivalent strut width values are shown in Figure 1 for aspect ratio (frame height: frame span) of 0.6:1.
The Figure 1 indicates that the equivalent strut width values suggested by various researchers are comparable between all the researchers except for the Mainstone's (1971) value for an aspect ratio of 0.6:1. The equivalent strut width, given by the various researchers in Table 1 satisfies for the fully infilled frames. In addition, Pradhan's Flexural Model (Pradhan, 2012) can be applicable for partially infilled frame also and thus it has been used in this study to find out various responses like shears, stiffnesses and vibration periods of the structure.

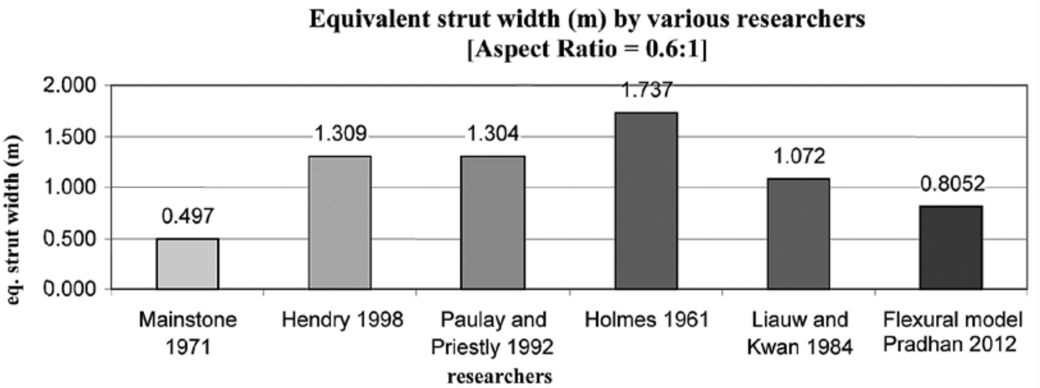

Figure 1. Comparison between strut width values by various researchers (fully infilled frames)

A one storey by one bay frame has been considered for the study which is subjected to monotonic lateral load of 100 kN at the roof level for all the cases. The displacements of the frames at roof level for the fully infilled, partially infilled and bare frame cases were analyzed by using the analytical program SAP2000. Thus, the stiffness values for all these cases were obtained by using the concept of $P = k_b \delta$, where P is the applied lateral force, k_b is the lateral stiffness of the structure and δ is the roof displacement. The stiffness value for bare frame has been compared with the expression used by Bergami (2007),

$$k_b = \frac{12E_c I_c}{h^3}\left[\frac{6I_b h + I_c L}{3I_b h + 2I_c L}\right] \tag{1}$$

The analyses were also done to observe the behavior due to infills for fundamental period of vibration. Similarly, the shear force due to the partial infill was determined by using the equivalent diagonal strut.

Table 2. Data

Parameters	**Data**	**Unit**
Grade of concrete	20	MPa
Young's Modulus of concrete E_c	22360.67	MPa
Young's Modulus of masonry E_m	13800	MPa
Depth of column C_D	450	mm
Width of column C_b	300	mm
Moment of inertia of column I_c	2278125000	mm^4
Depth of Beam B_D	450	mm
Width of beam B_b	300	mm
Moment of inertia of beam I_b	2278125000	mm^4
Thickness of infill t	230	mm
Height of infill h_m	2550	mm
Length of masonry L_m	4550	mm
Height (s) of frame c/c (three cases)	3000/3000/3000	mm
Span (s) of frame c/c (three cases)	5000/3000/2000	mm

4. Behaviors of infilled frames

Composite behavior of masonry infilled frames with various aspect ratios (frame height: frame span) like 0.6:1, 1:1 and 1.5:1 have been studied for periods, stiffnesses and shear forces in windward columns for some arbitrary lateral loading of 100 kN. Bare frame, fully infilled frames and partially infilled frames are studied for a particular case as chosen in Table 2. Adopting the equivalent strut width, the portal frames with varying wall heights are analyzed for various responses like frame displacements, shear forces in columns, stiffness calculations, and fundamental period of vibration. The results of the analyses are tabulated in Tables 3, 4 and 5.

Case I (Aspect ratio = 0.6:1)
Column height = 3000 mm c/c, beam span = 5000 mm c/c

Table 3. Shear force, stiffness and period for A.R. 0.6:1

Wall height (mm)	Equivalent strut width (mm)	Shear on column due to Strut (kN)	Stiffness of frame with strut (N/mm)	Time Period (s)
2550.00	805.222	103.49	131019.10	0.0296
2295.00	789.444	111.36	108463.78	0.0336
2040.00	769.291	120.18	86395.46	0.0393
1785.00	744.195	129.53	67687.83	0.0462
1530.00	713.455	138.11	52897.67	0.0542
1275.00	676.108	142.69	41644.40	0.0630
1020.00	630.681	136.47	33430.93	0.0721
765.00	574.587	109.81	27957.58	0.0806
510.00	502.391	61.87	24988.35	0.0866
255.00	398.559	16.39	23724.19	0.0896
0.00	0.000	0.00	26117.44	0.0912

Case II (Aspect ratio = 1:1)
Column height = 3000 mm c/c, frame span = 3000 mm c/c

Table 4. Shear force, Stiffness and period at A.R. 1:1

Wall height (mm)	Equivalent strut width (mm)	Shear on column due to Strut (kN)	Stiffness of frame with strut (N/mm)	Time Period (s)
2550.00	715.925	98.95	114752.48	0.026751
2295.00	719.080	106.70	106660.47	0.028287
2040.00	716.883	115.84	93135.72	0.031313
1785.00	707.976	126.31	77833.71	0.035767
1530.00	690.901	137.55	63383.79	0.041415
1275.00	664.099	147.54	51014.98	0.048047
1020.00	625.792	150.56	41108.57	0.055422
765.00	573.499	134.18	33840.37	0.062925
510.00	502.389	85.74	29472.78	0.06909
255.00	398.126	25.06	27694.46	0.072534
0.00	0.000	0.00	29535.48	0.074297

Case III (Aspect ratio = 1.5:1)
Column height 3000 mm c/c, frame span 2000 mm c/c

Table 5. Shear force, stiffness and period at A.R. 1.5:1

Wall height (mm)	Equivalent strut width (mm)	Shear on column due to Strut (kN)	Stiffness of frame with strut (N/mm)	Time Period (s)
2550.00	580.458	90.34	74240.75	0.029609
2295.00	602.642	98.32	78146.89	0.029314
2040.00	622.214	107.79	77218.59	0.030253
1785.00	636.736	118.93	71747.41	0.032677
1530.00	642.924	131.65	63351.23	0.036519
1275.00	636.792	144.89	53938.59	0.041549
1020.00	614.103	154.58	44966.04	0.047535
765.00	570.818	148.90	37434.19	0.054094
510.00	502.386	106.80	32279.62	0.060122
255.00	397.054	34.80	30035.26	0.063893
0.00	0.000	0.00	31382.60	0.065806

4.1 Shear in column

When 100 kN monotonic load is applied laterally to the portal frame the shear forces are evaluated through SAP2000 linear analysis. The results are tabulated in Tables 3, 4 and 5. Figure 2 shows that initially when the frame is bare the shear force within the column will be zero due to the absence of strut (disregarding the concrete frame). However, if the wall is inserted in the frame, then the strut action causes shear force in the columns. For case I (aspect ratio of 0.6:1), the column experiences 103.49 kN shear at the beam level when the wall height is kept full, i.e., 2250 mm, due to strut action, but as the wall height is reduced, the column experiences higher shear forces. Say for 2040 mm wall height (20 % opening), the shear force on the column is 120.18 kN. When the wall height reduces to 1020 mm (60 % opening), the shear on the column is 136.47 kN. After reducing the wall height to about 40 % opening, it shows that the shear force on the column reduces abruptly, indicating that the strut has no effect in shear force in the column when the wall height is less than 40 % of the full height. Thus, it is observed that the shear force in windward column is about 1.5 times more than the lateral force applied at the roof level and it is suggested to design the columns for higher value of shear force of about 1.5 times the lateral load at the critical height of 50 % (when the wall is only 50 % of full height). Similarly, from cases II and III, the critical height of 60 % opening requires about 1.5 times increased shear for a design purpose.

4.2 Stiffness behaviors

The strut width obtained by Flexural model was utilized to obtain various responses by bare frame as well as fully infilled frames. Initially, for the bare frame, the stiffness values were calculated by using the Eq. (1) as per Table 2 and are tabulated in Table 6.

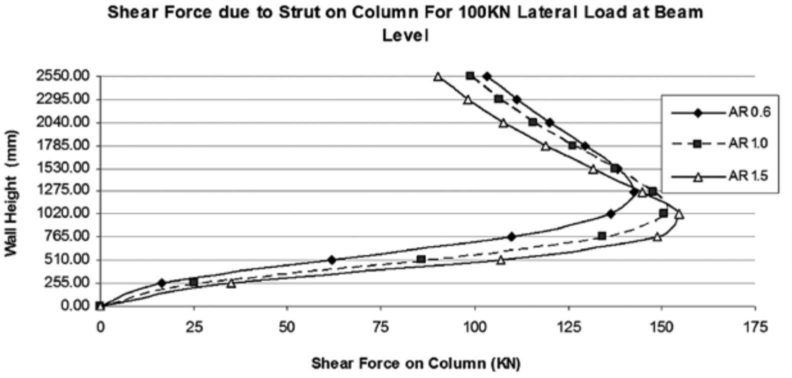

Figure 2. Shear force on column due to strut for 100 kN lateral load

Table 6. Lateral stiffness verification for bare and fully infilled frame

A.R. Frame height: frame span	Bare frame K_b (Bergami Eq.1) (N/mm)	Bare frame K_b SAP2000 (N/mm)	Difference (%)	Fully infilled K SAP2000 (N/mm)	Stiffness (K) enhancement SAP2000
0.6:1	27405.6	26117.44	4.7 %	131019.1	131019.1/26117.44 = 5.02 times
1:1	31696.25	29535.5	6.8 %	114752.48	3.89 times
1.5:1	34831.04	31382.6	9.9 %	74240.75	2.37 times

Since the lateral stiffnesses by SAP2000 analysis and by using Eq. (1) for various aspect ratios (frame height: frame span) are approximately similar, it is considered that the computer model prepared is correct. Thus, computer analyses were done for various aspect ratios with the computed strut width for fully infilled as well as partially infilled frame to find displacements at roof level. The displacements were observed both at roof level as well as at the wall level for partially infilled frames to calculate the lateral stiffness of structures.

Figure 3 indicates that the stiffness of the frame with full infill is very high for aspect ratio 0.6:1 which gradually gets reduced as the wall height is reduced. When the aspect ratio is 1:1, the lateral stiffness reduces gradually till the wall height is reduced to 765 mm (70 % opening), like in the case of 0.6:1. When the aspect ratio is 1.5:1, which means the bay width is smaller than the height of the frame, the lateral stiffness is increased significantly by the infill till the opening is 80 % of full infill. Then the lateral stiffness gets reduced. Thus, it can be concluded that the infill increases stiffness of the frame but if the infill height is only about 30 % of the full height, the stiffness increment is insignificant. The abnormal behavior of stiffness reduction beyond 80 % wall inclusion (20 % opening) for the case of 1.5:1 aspect ratio, suggests that such structures are much slender having high deflection at roof level. Furthermore, the stiffness degrades due to partial infills for slender structures.

The results show that the infills are beneficial in increasing the lateral stiffness, but as the infill heights are reduced in case of partial infill, the lateral stiffness gradually reduces and in turn the shear in the column will increase causing adverse effect to the structure during lateral loadings.

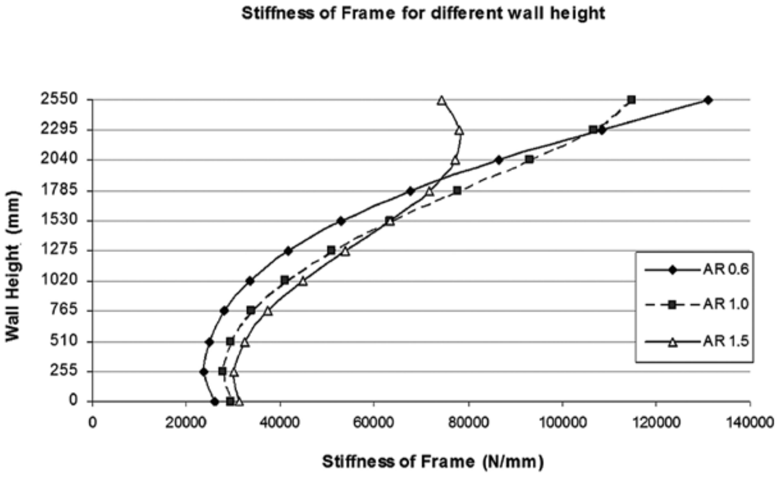

Figure 3. Stiffness of frame for partial infills

4.3 Fundamental Period of frames

Dynamic analyses were performed by using SAP2000 to evaluate the period of vibration of the models with, without and for partially infilled frames. The period of vibration reduces significantly due to infill. In the case of aspect ratio 0.6:1, the period of the structure reduced by 3.08 times when bare frame was infilled fully, indicating a significant increase in stiffness of the structure. Similarly, for other aspect ratios too, the period of vibration reduced significantly. The empirical formulae for period as suggested by IS1893 (Part 1): 2002 (IS1893, 2002), are $T = 0.075\, h^{0.75}$ for RCC bare frame and $T = \frac{0.09h}{\sqrt{d}}$ (s) for fully infilled frame, where *h* is the height of the frame (in m), and *d* is the dimension of frame (in m) along the direction of the earthquake loading. The empirical formulae were also used to find the periods for equivalent static load case and the periods reduce in this case too for fully infilled frames.

Table 7. Period of vibration of structure for various aspect ratios

Aspect ratio (Height: Span)	Period (s). Dynamic Analysis			Period (s). Empirical Formula		
	Bare Frame	Infilled Frame	Reduction in period	Bare Frame	Infilled Frame	Difference
0.6:1	0.0912	0.0296	3.08 times	0.171	0.12	1.425 times less
1:1	0.0743	0.0267	2.78 times	0.171	0.16	1.07 times less
1.5:1	0.0658	0.0296	2.22 times	0.171	0.19	1.12 times more

The dynamic analyses indicate that the bare frame is flexible compared to infilled frame. In the dynamic analysis, for aspect ratio, 0.6:1 (height of frame: span of frame), the period of fully infilled frame is 0.0296 s, which is about 3 times less than that of bare frame, which is 0.0912 s. Similarly, from the codal empirical formulae, the fully infilled frame is observed to have period of about 1.425 times less than that for the bare frames (0.12 s of infilled frame compared to 0.171s of bare frame). The similar responses were obtained for various other aspect ratios (Table 7). However, the empirical formula for fundamental period (IS1893, 2002) indicates that the period of structure gets increased when infills are inserted within frames for the aspect ratio of 1.5:1. The partially infilled frame when analyzed by SAP2000 was found to have periods of structure as given in Tables 3, 4 and 5 for various aspect ratios and they are graphically represented in Figure 4.

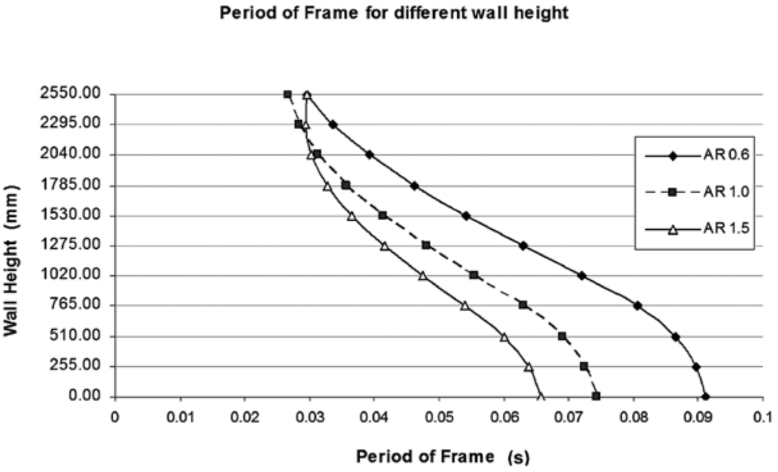

Figure 4: Periods of partially infilled frames

5. Conclusions and Recommendations

The partially infilled frames are obviously stiffer than the bare frames, however, the stiffness increment due to partial height up to 40 % of full frame height is insignificant but after the wall height crosses 40 %, the frame becomes highly stiff, particularly due to the increased shear in the column at the terminated wall level.

The study indicates that the partially infilled frames are most vulnerable to earthquake loads, especially when the wall height is provided only up to 40 % of the floor height. The excessive increment of shear force in the windward column suggests that additional stirrups need to be provided as per the shear force increment due to the strut action where the wall terminates. This concept will be useful to structures having short column effect. The shear force value wherever the partial wall height terminates is easily determined by using the Flexural model formula for the strut width. Thus, the earthquake risk due to short column effect may be minimized.

The period of structure gets reduced as the height of infill increases, but the decrement in period is considerable in the case when the span is more than the frame height. Thus, a partially infilled frame with frame height to frame span ratio less than 1 would be comparatively better in performance for earthquake loading than for other cases. Partially infilled frames are not beneficial to structures. However, Flexural model can be used to identify the shear force in the short-column and accordingly shear stirrups may be designed. The structures may thus be analyzed included with equivalent struts for partial infills for the safe design.

It is also to be noticed that the study was done for the static loading condition and also within the elastic limits of forces, thus, it is recommended for further work to study inelastic responses. The study may be extended for post yield responses.

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