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Lateral strength of partial masonry infill wall in concrete frame under static load

Prachand Man Pradhan [1], Prajwal L. Pradhan [2] and Ramesh K. Maskey [1]

[1] *Department of Civil & Geomatics Engineering*
Kathmandu University, Dhulikhel, Nepal
[2] *Department of Civil Engineering,*
Institute of Engineering, Tribhuvan University, Nepal

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Abstract

The analyses of infilled frame structures are generally done ignoring the presence of brick masonry in the analytical models. The real behavior of such buildings thus will vary during the earthquake events. Researches show that an infilled frame structure actually performs better against earthquake forces, however, when a structure is only partially infilled, the phenomena is again different. The lateral resisting capacity of infilled wall actually restricts the windward column only up to the wall height but above the wall height the free column deforms easily. In this paper, the strength of partial infilled wall has been analyzed and compared with experimental results as obtained by two other researchers and it is concluded that if the wall height is reduced to less than 50% of the clear frame height, the strength increases significantly, thus allowing more shear in the windward column which in turn, plays adverse role in damaging the column. The equivalent width of partial infill is also recommended.

Keywords: Partial infilled frame, lateral strength, strut width

1. Introduction

It is a general practice in Nepal and other developing countries to provide brick masonry infill walls within the columns and beam frames of Reinforced concrete frame structures. Such composite structures formed by the combination of a moment resisting plane frame and infill walls are also termed as "infilled frames". Infill walls are usually provided for functional as well as for architectural reasons and they are normally considered as non-structural elements. Their strength and stiffness contributions are generally ignored in the structural analysis works despite significant advances in computer technology and availability of modern computational resources. The reason may be due to the complication involved in the analysis and also the uncertainty about the non-integral action between infill and the frame.

When subjected to gravity loads only, the infill walls only add their self weight and thus they increase the base shear of the structure. However, an infill wall tends to interact with the frame when subjected to lateral loads such as wind and earthquake forces. The performance of structures can be greatly improved by the increase in strength arising from the non-structural components. On the contrary, this increase in strength also accompanies an increase in initial stiffness of the structure, which may consequently attract additional seismically induced lateral inertia forces (Slu et al. 2005). An infill wall also exhibits energy dissipation characteristics under earthquake loading as the frame members compress the infills at some locations. The infill walls when compressed carry a part of the load by providing strut action to the frame. As such, the infill walls contribute as a surplus benefit during the times of earthquake occurrences. It has also been observed from past earthquakes that the infills contribute in the enhancement of overall lateral stiffness of the structure, as strong infills have often prevented collapse of relatively flexible and weak reinforced concrete frames. Brick masonry, in cement mortar, exhibits highly non-homogeneous behavior due to relatively weak shear strength of mortar and sometimes due to weak compressive strength of bricks. The behavior of reinforced concrete frames with brick masonry infills depend upon the composite action of the frame and the infill. The structural response is quite complex as it involves an interaction of infill behavior, reinforced concrete frames behavior and length of contact between infill and frame.

Some structures are also provided with infill walls only up to partial heights of the frame known as partial infilled frames. These are the walls of partial height built to fit a window over the remaining height (see fig.1a and b). The adjacent columns behave as short columns due to presence of these walls. In many cases, other columns in the same storey are of regular height, as there are no walls adjoining them.

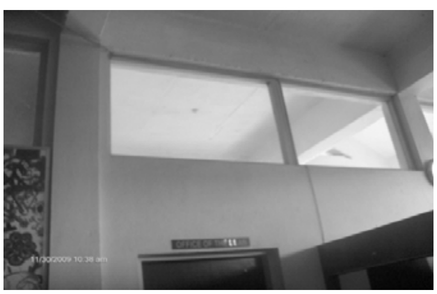

Fig.1a and b. Partial Infill structure

When the floor slab moves horizontally during an earthquake, the upper ends of these columns undergo the same displacement. However, the stiff walls restrict the horizontal movement of the lower portion of a short column, and get deformed by the full amount over the short height adjacent to the window opening (Fig. 2b). The regular columns get deformed over the full height. Since the effective height over which a short column can freely bend is small, it offers more resistance to horizontal motion and thereby attracts a larger force as compared to the regular column. As a result, the short column sustains more damage.

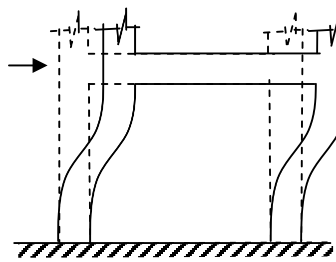

Fig. 2(a) Lateral deformation in bare frame

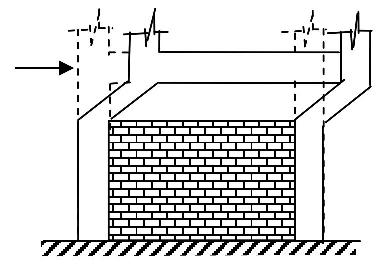

Fig. 2(b) Lateral deformation in partial infilled frame

Short column effect is the effect caused to the full storey slender column whose clear height is reduced by its part height contact with relatively stiff non-structural elements, such as a masonry infill, which constrains its lateral deflection over the height of contact. The partial infill keep some portion of the column captive and only the free portion of the column can deform laterally. Fig. 3 illustrates some examples of captive column and its damaging effect due to earthquake.

(a) (b) (c)

Fig. 3. Captive column Effects; 3(a) Wall cracking and damaged column at Tacna school, (June 23, 2001 Peruvian Earthquake (source:peer.berkeley.edu/.../site_effects.html) 3(b) Greece Earthquake (source: http://www.civl.port.ac.uk/athens/photos.htm) and 3(c) Captive column failure (source: J.P. Moehle)

2. Past Works on Infill Frames

1.1 Infills with and without openings

Thomas (1952) and Ockleston (1955) made the earliest contributions for the understanding of the interaction between wall and frame (Sabnis, 1979). Thomas conducted tests essentially to demonstrate experimentally the additional strength that infill walls add to the steel frames. Okleston (1955) investigated the effectiveness of infill walls in the behavior of three-story frames during the demolition of a hospital building in South Africa, (Sabnis, 1979). Later in 1956, Polyakov started his research on "Masonry in Framed Buildings". During the 1950s initial efforts were made for analytical modeling of infilled frames and at the beginning the infill panels were replaced by vertical cantilevers having equivalent shear and flexural properties. It was assumed that when an infilled frame is subjected to lateral loads, the transfer of load takes place through a truss action in the infill and this led to the development of diagonal strut model. The strut action takes place when infill along the unloaded diagonal gets separated from the beams and columns due to flexural deformation of adjoining frame members and a strut action is formed along the compressed infill diagonal (Polyakov, 1956). Benjamin and Williams (1957, 1958) tested brick infilled frames also with openings (Sabnis, 1979). They concluded that the stiffness and strength of infilled frames was independent of frame stiffness, provided that the frame was strong enough to produce the infill failure. Sachanski (1960) reported tests on infilled model and prototype frames and developed a method of analysis, based on the theory of elasticity (Sabnis, 1979). Polyakov (1960) suggested the possibility of considering the effect of infill in each panel as equivalent to diagonal bracing and this suggestion was later taken by Holmes (1961), who suggested that infill panel can be replaced by equivalent pin-jointed diagonal strut of width one third of the diagonal length of wall. Subsequently, many investigators developed the strut width value related to the length of contact between wall and the columns and between the wall and the beams. As per Agarwal and Shrikhande (2006), the proposed range of contact length is between one-fourth and one-tenth of the length of panel. There have been a lot of research works related to infilled framed structures with micro and macro modeling. Most of the researchers have adopted single and some have adopted multiple struts in their studies. Smith (1962) has so far been found the pioneer in the use of single strut to represent the masonry infill. Later, Pauley and Priestly (1992), Mainstone (1971), Klingner and Berter (1978), Liauw and Kwan (1984), Crisafulli (1997), Tomazevic (1999) etc. have put their efforts in researches towards the infilled framed structures.

2.2 Partially Infilled Frames

Very few literatures are available regarding partial masonry infilled framed structures so far. Paulay and Priestley (1992), state that the partial infill wall stiffens the frame, reduces the natural period and increases seismic forces. They say that if the frame is designed for ductile response to design level earthquake, without considering the effect of the infill, plastic hinges might be expected at the top and bottom of columns or preferably in beams at the column faces. These hinges could develop at a fraction of the full design level earthquake. If there are three columns (two bays) the influence of infill will be to inhibit beam hinges and stiffen the center and the column at the windward side, causing plastic hinges to form at the top of the column and top of the infill. The column shears would increase significantly. The actual column moment is also seen to be increased in the partial infilled frame compared to the assumed column moment in fig. 4.

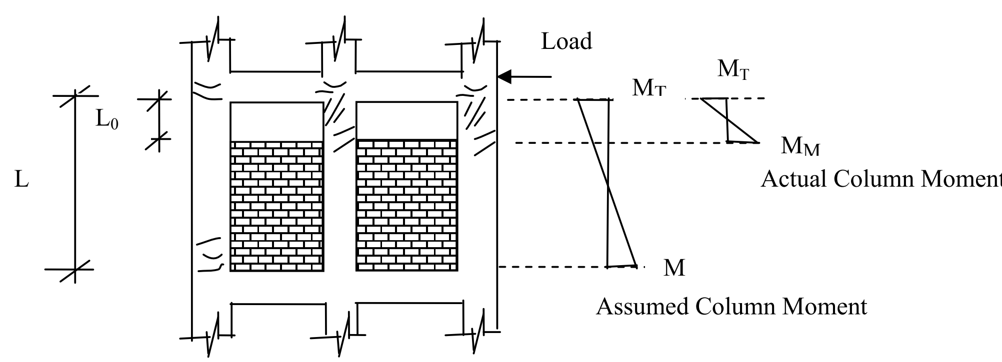

Fig. 4. Partial infilled frame

Ghassan (2002) also has mentioned that in a partial infilled frame, the shortened column length shall be equal to the unbraced opening length for the windward column, while the length for the Leeward column remains as it is. The strut width calculating expression is also provided.

Huang et al (2006) have tested six reinforced concrete frames with or without masonry infill (including partial infilled) under horizontal cyclic loads. They have compared their work with Chen's (2003) research for verification.

Taher and Afefy (2008) have done investigation on infill (including partial infill) in the seismic resistance of reinforced concrete structures. The studies for various percentage openings are performed. The most simplified equivalent frame system is considered to handle multistory multi-bay infilled frames. The system consists of homogeneous continuum for the reinforced concrete members braced with unilateral diagonal struts for each bay, which activate only in compression. The effect of number of storeys, number of bays, infill proportioning and infill locations are investigated. Geometric and material nonlinearity of both infill panel and reinforced concrete frame are considered in the nonlinear finite element analysis. The results reflect the significance of infill in increasing the strength, stiffness, and frequency of the entire system depending on the position and amount of infilling. Lower infilling is noted to provide more stiffness for the system as compared with upper locations.

Pradhan (2009) studied on the influence of infilled wall on reinforced concrete frames and states that when infilled frames are laterally loaded the first crack in the infilled frames appears at about 1/3rd of the ultimate load when there is no opening and about 1/2 of the ultimate load when there are large openings. He further states that the length of contact is about 1/3rd of the column height at the top of column and about 1/6th of the length of beam on either side of it. From his modified strut models he concludes that beyond 40% of opening in infill wall, the stiffness is about 1/4th of the fully infilled frame. Cracks appear at the corners of openings and they need to be strengthened initially.

Subramanian and Jayaguru (2009) have conducted study on behavior of partial infilled reinforced concrete frames with masonry infills. Experimental investigations were done on partially infilled 1/3 scale model reinforced concrete frames with and without masonry units under lateral loading. The partially infilled masonry wall induced captive column effect and leads to a severe failure of the column, on the other hand, the masonry inserts over the partial infill stiffness of structure by forming a compression strut thereby avoiding critical captive column damage. The results demonstrate the failure with respect to strength, stiffness, ductility and hysteretic characteristics.

3. Analytical Model

As it is found that the partial infilled masonry wall is vulnerable to earthquake forces, an effort is put up to incorporate the partial action in the analysis of frame structure by the use of diagonal strut which has already been accepted for full infilled wall or walls with openings so far. However, there is no logic in providing a single diagonal strut connecting the windward top node of frame and leeward bottom node of frame, as done for the cases of fully infilled walls, because partial infilled walls do not extend to the top beam level. In reinforced concrete structures, considering rigid diaphragm action it is assumed that the brick masonry wall slides horizontally when it is subjected to lateral force. As such, there will be a possibility of compression resistance by the wall within the strut as shown in the figure below. We shall consider rigid diaphragm for the case of present study.

According to Huang et al (2006), there are three stages of lateral strength of infill based on the amount of deformation on a partial infilled frame structure. The cases are just before the wall slides, just during sliding and after siding. They also have compared their experimental result with an expression provided by Chen according to Huang et al (2006). The expression for lateral strength of infill as per Chen is,

$$V_n = (0.7\tau_f + 0.113\, f_{mbt})\, l_{inf} \,.\, t \tag{1}$$

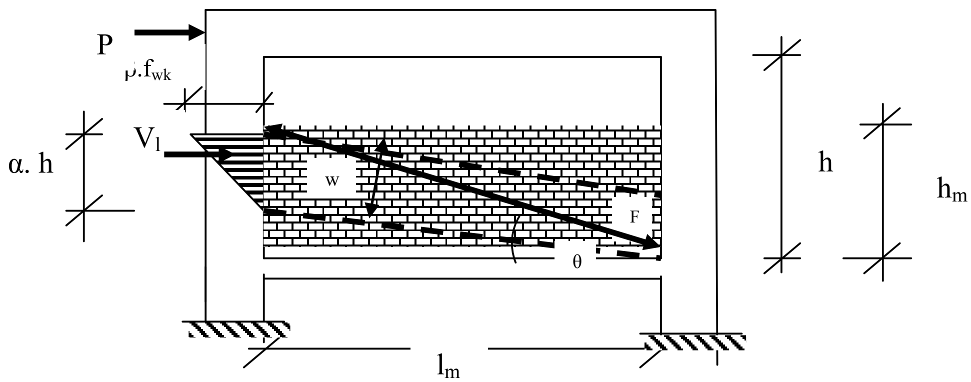

Fig. 5. Analytical model of partial infilled wall with frame

where, $\tau_f = 0.0258\, f_{mc}^{0.885}$ is the friction stress along the bed joints, $f_{mbt} = 0.232\, f_{mc}^{0.338}$ is the tensile strength of the brick-mortar interface, f_{mc} = compressive strength of mortar (4.3MPa), l_{inf} is the diagonal length of masonry infill and t is the thickness of the wall. Using these expressions, they have obtained the lateral strength of the partial infill 59.72 kN for a particular case in which the height of infill was 0.85m (half of the clear height of 1.7m) and length of the infill as 2.5m enclosed with in a frame of 300 mm width by 500 mm depth sized columns and beams.

The same model is considered in the study and an expression for lateral strength of wall is formulated assuming that there is only sliding action of the partial height wall and the wall is considered as a diagonal strut as shown in fig.5. It is considered that the lateral force (P) acting on the node will be resisted by the height αh, i.e., some fraction of the clear height of the frame will be resisting the lateral force acting on the structure just when the structure start yielding such that the masonry wall gets compressed. If f_{mb} = 0.3 MPa, is the bond strength of mortar and f_{wk} = 5 MPa is the compressive strength of masonry wall (Pradhan, 2009). The expression to determine the compressive force on the strut for the analytical model shown in fig.5 takes the form of equation (2) proposed by the authors.

$$F = \alpha . h . t \sqrt{\frac{1}{4}\beta^2 f_{wk}^2 + f_{mb}^2}\,, \tag{2}$$

where, $\beta = (2.\, f_{mb}.l_m) / (h_m \,.\, f_{wk})$, t is the thickness of wall and α is a coefficient for contact length with respect to the clear frame height.

The lateral strength of the infill wall can be obtained by $V_l = F. \cos\theta$. (3)
where, θ is the angle made by the strut with horizontal.

The strut width (w) can also be determined using the following expression:

$$w = \alpha \cdot \frac{h}{h_m} \cdot \frac{f_{mb}}{f_{wk}} \cdot \sqrt{l_m^2 + h_m^2} \tag{4}$$

The lateral strength of infill wall is found to increase with the increase in thickness of wall. The strut width expression (eqn.4) indicates that if the wall height is reduced the equivalent strut width will be increased which in turn increases the lateral strength of the infill. The increase in wall thickness also increases the strut width. Upon increasing the lateral strength, the free portion of the column gets heavily sheared which leads to excessive deflection at the roof level. This in turn will lead to heavy damage of the column members. This phenomena rightfully justifies the past earthquake effects on the partially infilled structures.

4. Results and Discussion

Upon applying the authors' data in the compressive force equation (2), the magnitude will be 69.71 kN where $\alpha = 0.2$ and thus the lateral resistance of strut denoted by F Cosθ will be 66 kN. This value is similar to the experimental result obtained by Huang et al (2006) using Chen's expression for yielded case (59.72 kN). The coefficient α used as 0.2 will give αh as 0.34m which means 40% of the wall height is the contact length just when the wall fails. The result obtained by equation (3) is again compared to the experimental results of Subramanian and Jayaguru (2009) in which the first failure of the windward column begins at the load of 8 kN (20% of 40kN, the base shear at first storey level) and this exactly tallies. The coefficient α assumed as 0.2 gives αh as 0.24m (i.e, nearly 27% of the wall height). Equation (3) holds good both for Chen's and Subramanian's works, while, Chen's formula holds good for Subramanian's model in terms of lateral strength of the partial infill wall. Thus, the similarity in results indicates that the formulation is justified. The comparisons of parameters used and results are shown in the following tables.

Table 1
Comparison with Chen's formula (dimensions in mm, stress in N/mm^2)

Friction stress along bed joint (τ_f)	Tensile strength of brick-mortar (f_{mbt})	Compr. Strength of mortar (f_{mc})	Bond strength (f_{mb})	Compr. Strength of brick (f_{mc})	Masonry height (h_m)	Masonry length (l_m)	Wall thickness (t)	Clear height (h)	Model of
0.094	0.38	4.3	-	-	850	2500	220	1700	Chen
-	-	-	0.3	5.0	850	2500	220	1700	Authors

Table 2
Comparative result Chart

% difference	Lateral strength of wall (kN)	Force on strut (N)	Contact length $\alpha . h$ (mm)	coefficient (α)	Researcher
9.55	59.72	-	-	-	Chen
	66.0 at θ = 18.78°	69710.5	340	0.2	Authors

Table 3
Comparison with Subramanian's experimental data (dimensions in mm, stress in N/mm^2)

Friction stress along bed joint (τ_f)	Tensile strength of brick-mortar (f_{mbt})	Compr. Strength of mortar (f_{mc})	Bond strength (f_{mb})	Compr. Strength of brick (f_{mc})	Masonry height (h_m)	Masonry length (l_m)	Wall thickness (t)	Clear height (h)	Models
-	-	-	-	3.38	900	1000	100	1200	Subramanian& Jayaguru Experimental
-	-	-	0.3	5.0	900	1000	100	1200	Authors

Table 4
Comparative result Chart

% difference	Lateral strength of wall (kN)	Force on strut (N)	Contact length $\alpha.h$ (mm)	coefficient (α)	Researcher
0	8.00 (20% of 40kN)	-	-	-	Subramanian & Jayaguru Experimental
	8.00 at θ = 41.98°	10762.9	240	0.2	Authors

Table 5
Comparison between Chen's formula and Subramanian's experimental parameters:

Friction stress along bed joint (τ_f)	Tensile strength of brick-mortar (f_{mbt})	Compr. Strength of mortar (f_{mc})	Bond strength (f_{mb})	Compr. Strength of brick (f_{mc})	Masonry height (h_m)	Masonry length (l_m)	Wall thickness (t)	Clear height (h)	Models
-	-	-	-	3.38	900	1000	100	1200	Subramanian & Jayaguru
.094	0.38	4.3	-	-	900	1000	100	1200	Chen

Table 6
Comparative result chart between Chen's result and Subramanian et al result

% difference	Lateral strength of wall (kN)	Force on strut (N)	Contact length $\alpha.h$ (mm)	Coeff. (α)	Researcher
0.87	8.00	-	-	-	Subramanian & Jayaguru Experimental
	8.07	-	340	-	Chen formula

The analytical formulation also gives us an idea that as the wall height is reduced, the infill becomes stiffer and as such it resists the column on the windward side up to the wall height level while the free portion of the column will get high shear force which eventually leads to failure of the structure. In full infilled structures, as the diagonal strut is provided node to node of frame, the effect is far more positive whereas when the strut is provided diagonally node to node of wall only, the effect is rather negative. Unlike the case in full infill the strut width gets increased if the height of wall is increased, it is just the reverse for partial infill.

4.1 Relationship between height of partial infill and lateral strength of wall

The expression for strut force (eqn. 2) was checked for various lengths of frame or wall (l_m) with respect to a constant height (h) of frame which included varied infill heights (h_m). For this, the clear height of the frame is kept 1700 mm and compared with various wall lengths of dimensions 1000, 1700, 2500, 3000 and 3500 mm (aspect ratio as 0.59:1, 1:1, 1.47:1, 1.76:1 and 2.06:1 respectively). Of course, the expression 3 was later used to find the lateral force as the equation 2 initially gives the inclined lateral load on strut only. The results show that as the wall length increases, the lateral strength of wall also increases if the infill height is lowered. This indicates that more resistance is offered by longer walls with shorter infill heights. Fig. 6 shows that as the masonry infill height is decreased the lateral strength increases gradually up to about half the height of the frame, however if the infill wall height is reduced below 50% of the clear height of frame, the lateral strength of the wall increases significantly. It is seen that the lateral strength is below 100 kN up to 850 mm wall height (half of the clear frame height), but as the wall height is reduced the curve shows sudden improvement in the lateral strength significantly for aspect ratio1.76:1 and 2.06:1. Thus, as the length of the bay increases the wall will have more resisting capacity against the lateral force up to the wall height. Ironically, this indicates that the windward column will be resisted by the shorter wall with greater force (i.e. great shear force on windward column) which in turn will cause the free portion of the captive column to deflect excessively leading to damages. This finding thus justifies the figures 3a, b and c, where the captive columns failure occur just at the locations where the infill walls are terminated.

For aspect ratio (length: height) of frame 0.59:1 and 1:1, the increase in lateral strength is found insignificant for infill wall up to 50% of clear height of frame, furthermore, the lateral strength is also found very less compared to other aspect ratio with greater wall length.

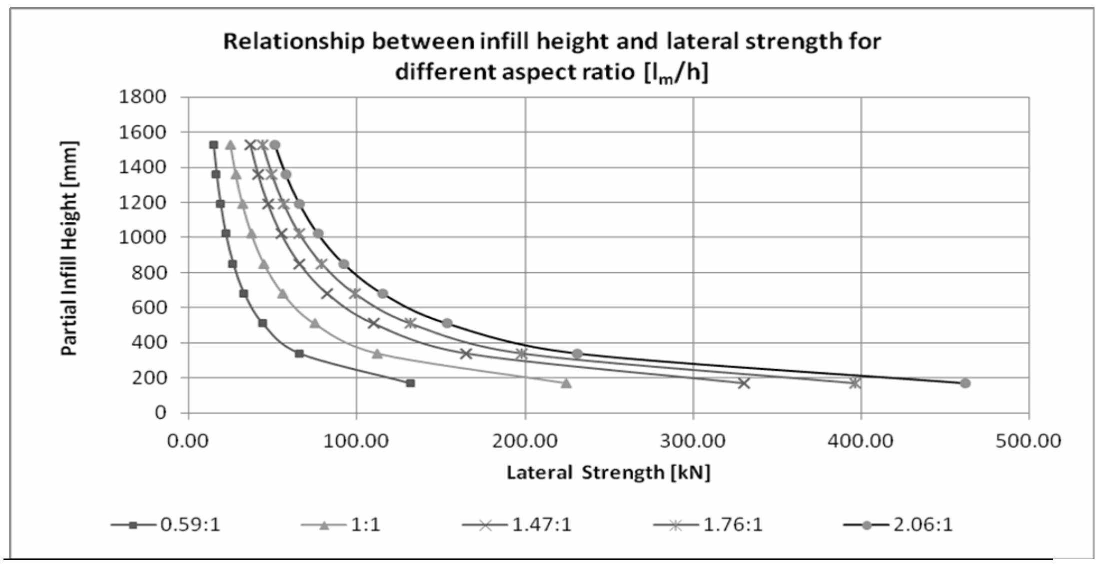

Fig.6: Relationship between infill height and lateral strength for different aspect ratio

4.2 Strut width value

The strut width value may be calculated using the equation number 4 and the expression indicates that the strut width value increases as the infill height is reduced. The increase in strut width for lower infill height further indicates that the shorter infill wall has more resistance to lateral force. Unlike the strut width value obtained by various researchers for full infill height, the partial infilled frames require different strut widths for different height of infill walls.

5. Conclusions and Recommendations

The expression 2 derived under the hypothesis that there would be only sliding action in the partially infill and no compression from the upper beam as well as from the lower beam due to rigid diaphragm action. The contact length just after the failure of wall has been estimated in this study so the loading is consider just before the brick wall reaches failure through sliding. Furthermore, the α value, which is the coefficient to calculate the contact length during the application of lateral force, is estimated as 0.2 comparing to the results observed from other researchers work. The result also tallies with works of Taher et al (2008) which mentions that lower infilling is noted to provide more stiffness of the system compared to walls in upper locations. There is a further work necessary to analyze the structure considering non linearity of wall up to ultimate loading.

The low partial walls have greater resisting capacity against earthquake forces. However, the irony due to high resistance up to wall level within the frame, the free portion of the column remains captive and thus there is high deflection at the roof level. This in turn will fail the captive column. It further indicates that it is rather beneficial to provide full wall than to provide partial infilled walls in buildings. Thus, if we are to provide partial infill wall it is necessary to analyze the structure considering the effect of infill wall up to the desired height with proper strut width. A better solution would be to provide small opening, in other words high partial infills rather to avoid great displacement of free column which may fail during earthquakes. It is also suggested to provide lesser bay width compared to the height of wall for partial infilled frames.

The strut width equivalent to the partial infill should be provided in the analytical model and accordingly the internal forces and deflections will be computed. Then, the reinforcement for bending and shear should be designed accordingly so as to obtain safe structures.

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