Effect of Infill as a Structural Component on the Column Design of Multi-Storied Building

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Abstract

The structural effect of brick infill is generally not considered in the design of columns as well as other structural components of RC frame structures. The brick walls have significant in-plane stiffness contributing to the stiffness of the frame against lateral load. The lateral deflection is reduced significantly in the infilled frame compared to the deflection of the frame without infill. This leads to different steel requirements for frame structures considering infill. In order to understand the behavior of frames and steel requirements of column having brick masonry infill and without infill a finite element investigation is performed by modeling a 10-storied three-dimensional building frame. Common three-dimensional frame elements were used to model the beam and columns and shell elements were used to model the slab. The in-plane stiffness of brick wall contributing the stiffness of the frame element against lateral load is calculated by an equivalent strut method and is incorporated in the finite element model using special link element having only axial stiffness. A detailed investigation is performed using various loads and load combinations of the building considering infill and without infill to find out steel requirements and to see the effect of infill in the sway characteristics of the building. Typical corner column, exterior column and interior column are considered keeping same dimensions of beams and columns for the analysis of the building considering infill and without infill. It is observed that frames with infill produce much smaller deflections as compared to frames without infill. It is also observed that there is no significant difference in steel requirements of interior column but there is moderate difference in steel requirements in exterior column and significant difference in steel requirements in corner column. This indicate considering stiffness of the infill may not result in an economy in the design of multi-storied buildings if the number of interior columns is significantly greater compared to the number of exterior and corner columns.

Keywords: Infill; Stiffness; Diagonal strut; Steel requirement; Sway; Masonry compressive strength

Introduction

Reinforced concrete frame structure is quite common in civil engineering field due to the ease of construction and design. Frames are often constructed with infill as partition wall. Lateral deflection of frame is considered as one of the principal design criteria for structural design of frame structures. It has significant effect in column design due to change in design moment for horizontal sway.

Generally the lateral deflection of a frame under lateral load is calculated by taking the stiffness of columns and beams into consideration. But the stiffness of infill is almost never considered in these calculations. The stiffness of the frame increases in the presence of infill, which reduces the lateral deflection. Thus the deflections and internal forces for frames with infill are less than for frames with infill. This leads to reduced forces and reinforcing steel requirements in columns for high-rise building considering infill.

The present code of practice does not include provision of taking into consideration the effect of infill. It can be expected that if the effect of infill is taken into account, the design of resulting structural elements may be significantly different.

Brick made from burning clay is a unique construction material available in this subcontinent. It is used widely in our country as one of the principal construction material due to unavailability of stones. Brick is used for partition walls in virtually all framed structures in our country, which also acts as infill to the frame. Lack of knowledge of the mechanical properties of brick masonry prohibit us from considering infill as a structural element, although it is apparent that brick infill has significant in-plane stiffness contributing to the stiffness of the frame elements against lateral load.

It is therefore necessary to understand the characteristics of brick masonry infill RC frame in order to better understand the structural behavior of the frame itself. With this objective in mind, the present investigation is performed to understand the effect of brick masonry infill in the design of column of high-rise building.

The infilled frame consists of a steel or reinforced concrete column-and-girder frame with infill of brick works or concrete block work. In addition to functioning as partitions, exterior walls and walls around stair, elevator, and service shafts, the infill may also serve structurally to brace the frame against horizontal loading. The frame is designed for gravity loading only and in the absence of an accepted design method, the infill is presumed to contribute sufficiently to the lateral strength of the structure to withstand the horizontal loading. The simplicity of construction and expertise in building this type of structure have made the infilled frame one of the most economical structural forms for tall buildings.

In countries with stringently applied codes of practice, the absence of a well recognized method of design for infilled frames has restricted their use for bracing. When designing an infilled frame structure, it has been more usual in such countries to arrange for the frame to carry the total vertical and horizontal loading. The infills have been included on the assumptions that, with precautions taken to avoid load being transferred to them, they do not participate as part of the primary structure. It is evident from the frequently observed diagonal cracking of such infill walls that the approach is not always valid. The walls do sometimes attract significant bracing loads and, in so doing, modify the structure's mode of behavior and the forces in the frame (axial force, bending moment, shear force etc). In such cases it would have been better to design the walls for the lateral loads, and the frame to allow for its modified mode of behavior.

Certain reservations arise in the use of infilled frames for bracing a structure. For example, it is possible that as part of a renovation project, partition walls are removed with the

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result that the structure becomes inadequately braced. Precautions against this, either by including a generously excessive number of bracing walls, or by somehow permanently identifying the vital bracing walls, should be considered as part of the design.

According to the latest development, the P-Δ effect in a fully restrained multistory frame is a major design factor. The more flexible the frames, the greater are the secondary bending moments. Therefore the influence of infilling walls is much more significant today than in the past, they provide lateral stiffness and minimize the P-Δ effect.

The main objective of this paper is to find out the effect of infill in the design of column in reinforced concrete frames under different combinations and types of loading including lateral load (earthquake load). The objective is focused on the sway values of different representative columns of high-rise building including infill and without infill, replacing the brick wall by an "Equivalent Diagonal Strut" proposed by Saneinejad and Hobbs (1995). The difference in steel requirements to sustain design load with infill and without infill is the final objective of the paper.

Characteristics of Infilled Frames

The behavior of masonry infilled frames [Fig. 1(a), (b)] has been extensively studied in the last four decades (e.g., works by Smith & Coull 1991, Mosalam et al. 1997, Madan et al. 1997, Papia 1998, Asteris 2003 among others) in attempts to develop a rational approach for design of such frames. The use of a masonry infill to brace a frame combines some of the desirable structural characteristics of each, while overcoming some of their deficiencies. The high in-plane rigidity of the masonry wall significantly stiffens the otherwise relatively flexible frame, while the ductile frame contains the brittle masonry, after cracking, up to loads and displacements much larger than it could achieve without the frame. The result is, therefore a relatively stiff and tough bracing system. The wall braces the frame partly by its in-plane shear resistance and partly by its behavior as a diagonal bracing strut in the frame. When the frame is subjected to horizontal loading, it deforms with the columns and beams bent in double-curvature.

The "perpendicular" tensile stresses are caused by the divergence of the compressive stress trajectories on opposite sides of the leading diagonal as they approach the middle region of the infill. The diagonal cracking is initiated at and spreads from the middle of the infill, where the tensile stresses are a maximum, tending to stop near the compression corners**,** where the tension is suppressed.

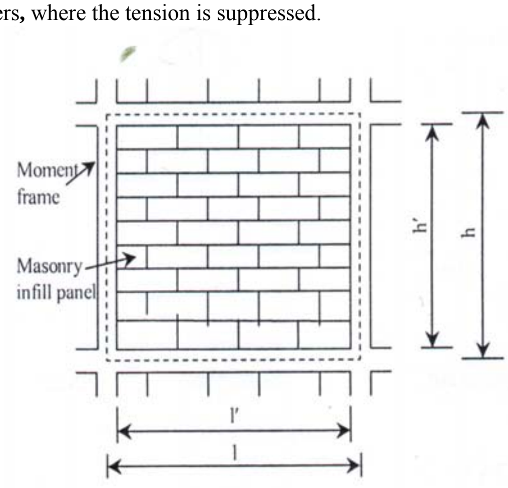


Fig. 1(a) Masonry infill panel in frame structures

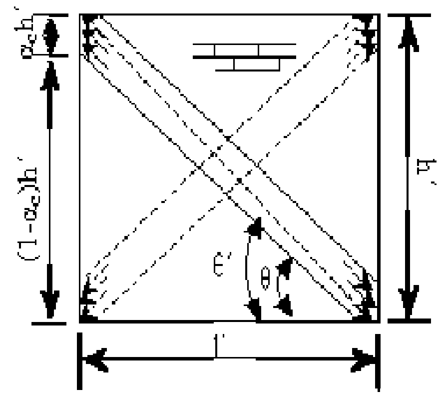


Fig. 1(b) 'Equivalent Diagonal Strut' model for infill panel

The nature of the forces in the frame can be understood by referring to a analogous braced frame. The windward column or the column facing earthquake load first, is in tension and the leeward column or the other side of the building facing earthquake load last, is in compression. Since the infill bears on the frame not as a concentrated force exactly at the corners, but over short lengths of the beam and column adjacent to each compression corner, the frame members are subjected also to transverse shear and a small amount of bending. Consequently, the frame members or their connections are liable to fail by axial force or shear, and especially by tension at the base of the windward column.

Saneinejad and Hobbs (1995) developed a method based on the equivalent diagonal strut approach for the analysis and design of steel and concrete frames with concrete or masonry infill walls subjected to in-plane forces. The proposed analytical development assumes that the contribution of the masonry infill panel to the response of the infilled frame can be modeled by replacing the panel by a system of two diagonal masonry compression struts. The stress-strain relationship for masonry in compression used to determine the strength envelope of the equivalent strut can be idealized by a polynomial function. Since tensile strength of masonry is negligible, the individual masonry struts are considered to be ineffective in tension. However, the combination of both diagonal struts provides a lateral load resisting mechanism for the opposite lateral directions of loading.

The lateral force-deformation relationship for the structural masonry infill panel is assumed to be a smooth curve bounded by a bilinear strength envelope with an initial elastic stiffness until the yield force V_y thereon a post-yield degraded stiffness until the maximum force V_m is reached. The corresponding lateral displacement values are u_y and u_m respectively [Fig. 2(a), (b)]. The analytical formulations for the strength envelope parameters were developed on the basis of the available equivalent strut model for infilled frames. Considering the infilled masonry frame, the proposed maximum lateral force V_m and corresponding displacement $\boldsymbol{u_m}$ in the infill masonry panel are

$$V_m^{+}(V_m^{-}) \le A_d f'_m \cos\theta \le \frac{vtl'}{(1-0.45\tan\theta)\cos\theta} \le \frac{0\cdot 83\, tl'}{\cos\theta} \tag{1}$$

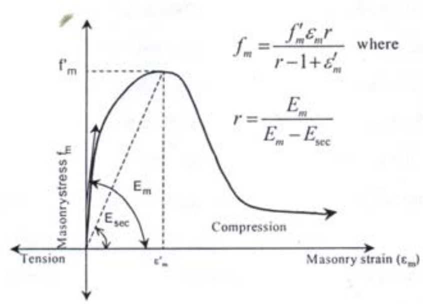
$$u_m^{+}(u_m^{-}) = \frac{\varepsilon'_m L_d}{\cos\theta} \tag{2}$$

Here, t = thickness of the infill panel, l'= lateral dimension of the infill panel, f'_m = masonry compressive strength, ε'_m = masonry compressive strain, θ = inclination of the diagonal strut, v = basic shear strength of masonry, A_d = area of equivalent diagonal strut, L_d = length of equivalent diagonal strut. These quantities can be estimated by using the formulations of the "equivalent strut model" proposed by Saneinejad and Hobbs (1995). The initial stiffness K_0 of the infill masonry panel may be estimated using the following formula (Madan et al. 1997),

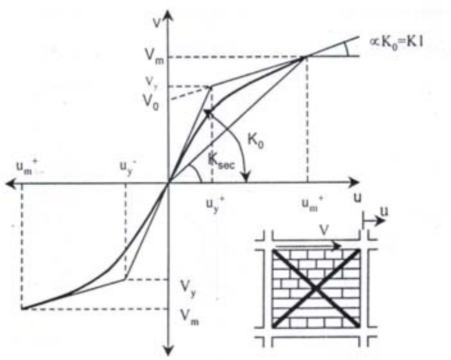
$$K_o = \frac{2V_m}{u_m} \tag{3}$$

Computational Modeling

The computational investigation presented in this paper is based on three-dimensional modeling and analysis of a typical RC building frame. Common two-noded frame elements having six degrees of freedom per node has been used for beams and columns. Four noded elastic shell element is used to represent the slab which has six degrees of freedom at each node. The infills are modeled as diagonal struts using two-noded truss elements having only two translational degrees of freedom at node.



(a)



(b)

Fig. 2 Constitutive model for infill panel and strength envelope for masonry infill panel

The reference model is a 10-story beam column structure having 4 aisles by 5 bays. According to the objective of the paper a plan of a representative high-rise building providing all modern facilities is required to have a realistic result of the effect of infill in the column design. The effect of infill is basically prominent in high-rise building design because of lateral load resisting capabilities of the infills. The effect of wind or earthquake load is not severe in low-rise building up to six or seven stories. Due to the normal tendency of vertical expansion within the limit of our economical capability high rise building of ten to twelve stories is now common in Dhaka city as well as in some major cities in Bangladesh. The rate of commercialization due to globalization, the frequency of high-rise office building is high now in Bangladesh. For that reason a 10-storied office building is considered for the analysis. The span length is normally high in office buildings compared to the span length of residential high-rise buildings which increases the severity of lateral load in the column. This is another reason to select 10-storey office building for the present study.

Though shear wall is used in high-rise buildings it is an expensive type of structural component. The investigation of steel requirement in the columns for high-rise frame building considering infill may justify the design of high-rise building having beam-column layout only. This presumption leads to the selection a plan having beam and column only, The simplicity in design having beam column layout also leads to compare column design considering infill and without infill.

The infill is the masonry wall in between beam and column without having any opening like windows and doors. In the presented plan there are 9 infills out of 49 panels spanning in both directions. The number is 4 in the longer panel direction (from front to back) and 5 in the shorter direction (from left to right). The quantity of infill in the outer wall is dominant in the plan fulfilling office space requirement. It is six in number in the outer wall and three in number in the inner wall. All the outer walls have 0.25m thickness in contrast to the 0.15m thickness of the inner wall. Wall thickness of 0.25m shows more resistance to sustain lateral load.

The properties of the reference RC model are given in Table 1. The plan as well as the locations of infills is shown in Figs. 3 and 4, while Fig. 5 represents a 3-dimensional diagram of the building, as modeled in ANSYS.

Loads and Load Calculation

Dead loads, live loads and earthquake loads are considered in the analysis. The dead loads include column load, beam load, slab load, wall load, stair load, lift load and overhead tank load. The wall load, stair load, lift load and overhead tank load are calculated from actual plan. The wall load is provided as a surface load on the plan area.

Table 1 Properties of the reference RC frame

Parameters	Reference Values
Modulus of elasticity of concrete	2.49×10^7 kN/m^2
Density of concrete	23.54 kN/m^3
Number of story	10
Height of each story	3.5 m
Thickness of slab	0.15 m
Size of column	0.6 m × 0.6 m
Size of beam (width × depth)	0.3 m × 0.6 m
Number of panels	49
Size of each span	5.5 m, 7.5 m
Amount of infilled panels	9 (18.5 % of total panels)
Thickness of infill	0.15 m, 0.25 m

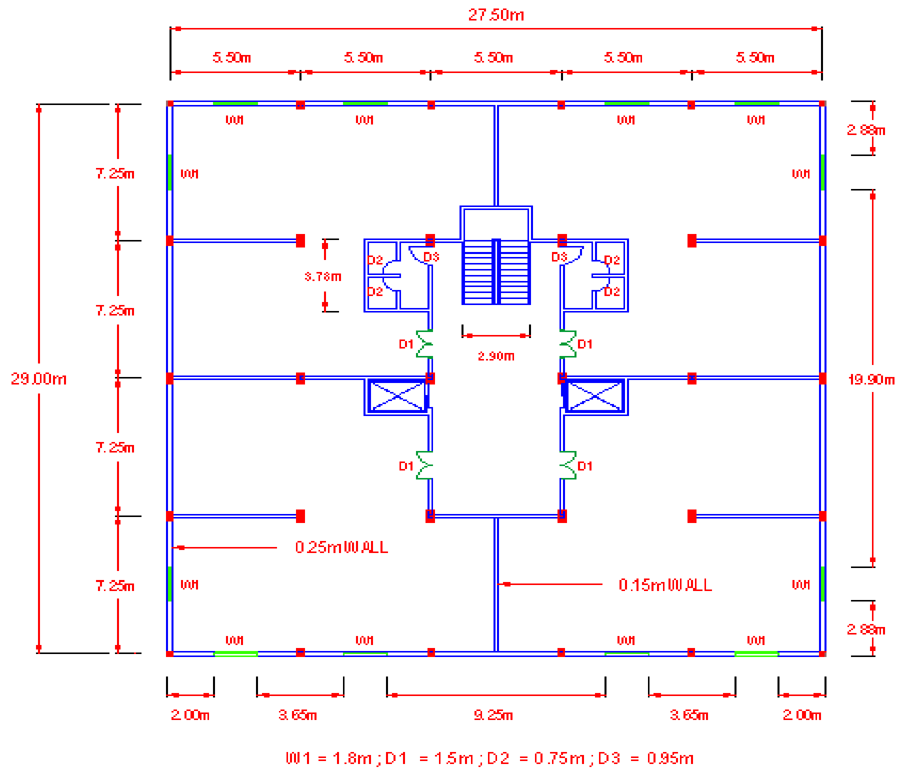


Fig. 3 Typical floor plan

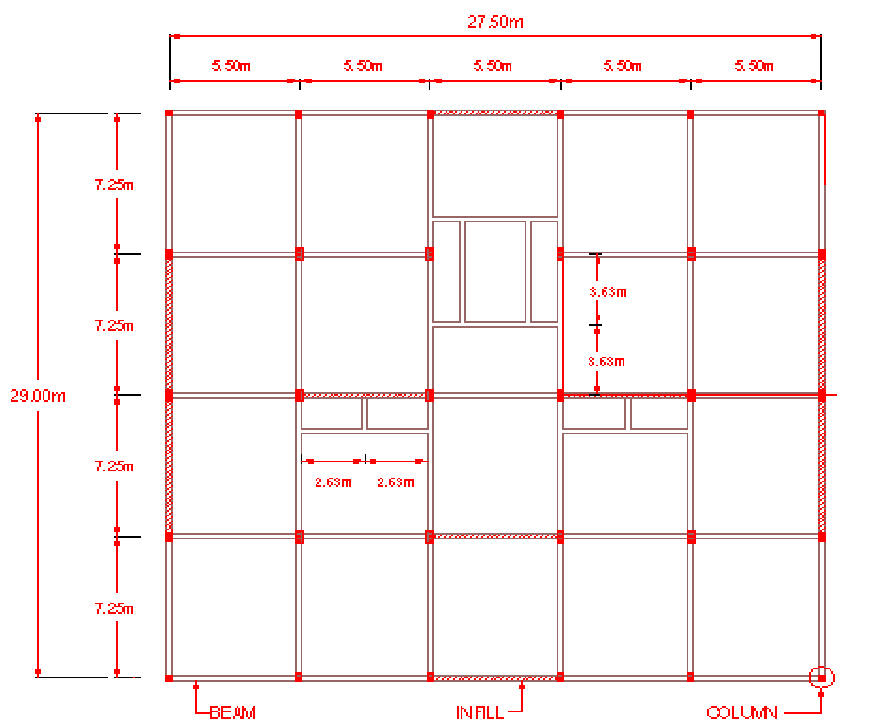


Fig. 4 Beam-column layout (with infill)

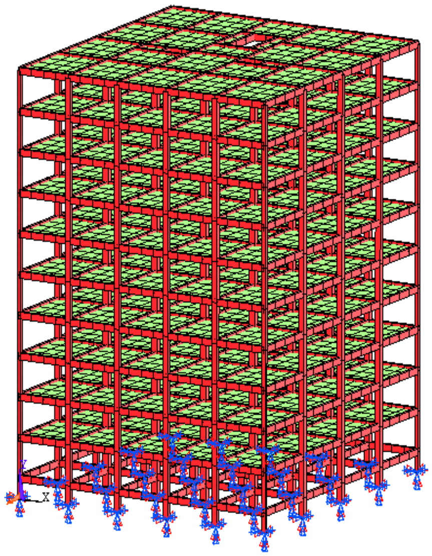


Fig. 5 Three-dimensional modeling of 10-storied building

The stair load is distributed to the adjacent two beams as a uniformly distributed load per length. The lift load is divided in the four columns that are supporting it. The overhead tank load is distributed to the surrounding beam as a uniformly distributed load. Live load is taken as a standard value of 3 kN/m^2 from BNBC in the floor area. The live load in the stair is taken as 4.78 kN/m^2 on the horizontal projected area.

The dynamic load in the design is earthquake load. The earthquake load is taken according to the procedure described in BNBC (1993) considering the building is located in Dhaka. The earthquake load is generated from both the directions of the building to find out the most severe combinations of loads. The loads are incorporated in the script separately and are combined to get the axial force and moments in the column to find out the steel requirements in the column.

Steel Reinforcement

In this work the design of columns are based on conventional methods of RC design (e.g., Winter & Nilson 1987). The reinforcement required for infilled corner column significantly varies from reinforcement needed for corner column without infill (Table 2). The difference is as high as 3% of steel (percentage based on cross-sectional area of column) in some floors. However it shows little change in steel requirement for exterior column (Table 3) and almost no change for the interior column (Table 4). The floor-wise percentage requirements are shown below.

Table 2 Design steel for corner column

	Percentage of Steel	
Column Floors	**With Infill**	**Without Infill**
Column below Ground Level	1.71	1.71
Ground Floor Column	1.71	3.22
Floor 1 Column	1.71	4.30
Floor 2 Column	1.00	3.22
Floor 3 Column	1.00	2.15
Floor 6 Column	1.00	1.00

Table 3 Design steel for exterior column

	Percentage of Steel	
Column Floors	**With Infill**	**Without Infill**
Column below Ground Level	2.34	2.60
Ground Floor Column	2.34	2.60
Floor 1 Column	1.82	3.12
Floor 2 Column	1.04	2.08
Floor 3 Column	1.04	1.04
Floor 6 Column	1.04	1.04

Table 4 Design steel for interior column

	Percentage of Steel	
Column Floors	**With Infill**	**Without Infill**
Column below Ground Level	4.51	4.51
Ground Floor Column	4.33	4.33
Floor 1 Column	3.24	3.24
Floor 2 Column	2.16	2.34
Floor 3 Column	1.26	1.26
Floor 6 Column	1.08	1.08

Sway

The sways are calculated for different columns in the top most point of the building. It is found that the sway without infill for the proposed plan is almost twice of the sway with infilled walls in either direction. In order to design high-rise building specially the column the lateral deflection has to be within acceptable limits (e.g., 1/480th of the building height according to BNBC 1993). The sway characteristics of building are different for frames considering infill rather than frames without infill. The sway values for different types of columns according to their location in the building are shown in Table 5.

Conclusion

The findings from the design of columns of a 10-storied office building with and without the effect of infill are summarized below:

1. The steel requirements in corner columns considering infill are significantly less compared to the steel requirements of corner columns without considering infill.
2. The exterior columns considering infill also require less steel in some floors compared to the requirement of exterior column without infill. However, the difference is not as significant as for the corner columns. The difference for the interior columns is even less significant.
3. The deflections are found to be much smaller (i.e., of the order of one-half) in frames with infill compared to frames without infill having same dimensions of different columns and beams.

Table 5 Sway characteristics of different columns

Earthquake Load	Sway for Corner Column (mm)	Sway for Exterior Column (mm)	Sway for Interior Column (mm)	Maximum Value of Sway (mm)
From Left to Right without Infill	54.3	54.2	54.8	56.6
From Left to Right with Infill	32.3	32.2	33.0	35.7
From Front to Back without Infill	73.2	73.2	73.1	73.2
From Front to Back with Infill	37.5	37.6	37.5	37.6

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