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Composite Behaviour of Unbraced Multi-Storey Reinforced Concrete Infilled Frames Based on Modified One-Strut Model

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Abstract
A comparative assessment on analytical outputs of the composite behavior of multi-storey reinforced concrete infilled frames using the macro models of the one-strut configuration and the finite element micro model is presented. The effect of openings in the infill was given particular attention in multi-storey building frames. The analysis demonstrated the simplicity of modified one-strut model, compared to the more complex multi strut and FE models while at the same time yielding highly accurate results. The introduction of the shear stress reduction factor clearly enhanced the efficiency of the one-strut model to reproduce the shear strength, lateral stiffness and seismic demand of infilled frames with openings.
Key words: Shear reduction factor, infilled frame, diagonal strut model, FE model.

I. INTRODUCTION

The composite behavior of infilled frames is rather complex. This is due to the uncertainty in the interaction between the infill and frame as well as failure mechanisms of infill whether elastic or plastic. In spite of these, numerous experimental and numerical modeling have been undertaken by researchers in order to develop reasonable conceptual framework of the behavior of infilled frames. The result of the various test are documented in details in [1-6]. Attempts at approximate analysis and finite element modeling are reported in [7-12]. As a result of these researches, the mechanism of the resistance of infilled frames has been formulated. An infilled frame comprises a relatively flexible frame braced by the in-plane rigidity of the brittle masonry wall. On its part, the frame provides all round confinement of the brittle masonry after cracking, resulting in a far greater load bearing capacity and stiffness compared to an unframed wall. However, a major deviation from this confinement of the infill is found to occur only on a limited length of contact length between the beam and column adjacent to the compression corner. It is obvious that the above mechanism will get even more complicated in multistory frames with openings in the infill walls.

Lateral displacement and inter-storey drift are the predominant modes of response in multistory building frames. Thus, lateral stiffness is critical in the mechanism of resistance of multi-storey frames. The difficulties in assessing the effect of infill masonry wall with openings on the lateral stiffness of unbraced frames have been recognized in previous studies [13-16]. To obtain a better and deeper understanding of the complex composite behavior of infilled frames, several macro models, ranging from one-strut to multiple strut configurations, have been developed in addition to the finite element model [17-23]. However, the applicability of these models to a wider scope of problems has been rather limited by their complexity and computational resource requirements.

Consequently, the need for more simplified models that could account for the effect of openings and other features of the infill on the performance of the multistory building frame remains topical among researchers.

In response to this need, the authors developed a modified one-strut macro model in which the effect of openings was accounted for through the introduction of a shear strength reduction factor proposed by the authors. The model was validated for a single-storey single-bay infilled frame with central opening of varying opening ratios [24]. This paper is an attempt to extend the modified one-strut model to a multi-storey frame with complex opening configurations. The effects of openings on the floor displacements, inter storey drift, axial force, shear force and bending moments in exterior columns and edge beams were computed based on the modified one-strut model. The results were validated with the outputs of FE model of the multistory frame under consideration.

II. THEORETICAL FRAMEWORK FOR THE ONE-STRUT MACRO MODEL

Studies by Hendry [25] have shown that the geometric properties of the diagonal struts are functions of the length of contact between the wall and the column α_h and between the wall and beam α_L, respectively. The mechanism of deformation of a typical infilled frame is shown in Figure 1.

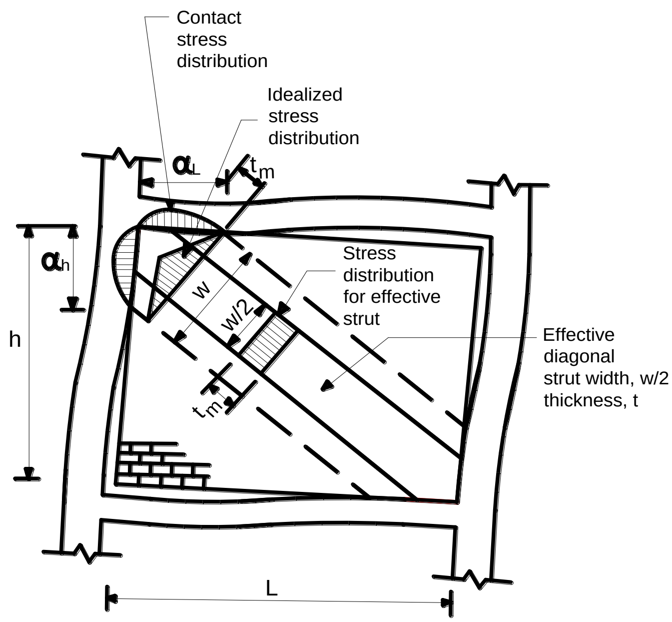


Figure 1: Diagonal Strut Model

Thus, assuming a beam on elastic foundation as proposed by Hetenyi [26] and later Amrhein *et al* [27] the contact lengths α_h and α_L can be expressed as follows:

$$\alpha_h = \frac{\pi}{2}\sqrt[4]{\frac{4E_f I_c h}{E_m t Sin 2\theta}} \quad (1)$$

$$\alpha_L = \pi\sqrt[4]{\frac{4E_f I_b L}{E_m t Sin 2\theta}} \quad (2)$$

where, E_m, E_f = elastic moduli of the masonry wall and frame material respectively.

t, h, L = thickness, height and length of the infill wall, respectively.

I_c, I_b = moments of inertia of the column and the beam of the frame respectively.

$\theta = \tan^{-1}\left(\frac{h}{L}\right)$

As evidenced from Figure 1, the stress distribution is rather complex. However, this can reasonably be approximated by a triangular stress distribution along the width *w* of the strut and the average compressive stress is one-half of the maximum stress f_m. With this assumption, the force in the strut equals $\frac{1}{2}f_m wt$, while the effective strut width *w* can be expressed as

$$w = \sqrt{\alpha_l^2 + \alpha_h^2} \quad (3)$$

Openings in infills result in reduction of the shear strength of the infill. A numerical FE experimentation was conducted by the authors on several infilled frames to determine the functional dependence of the shear strength of infill with opening ratio. On the basis of regressional analysis of experimental and FEM data for several infills with central openings, an analytical expression, relating the strength reduction factor λ_m of the compression strut and the infill opening ratio β, was obtained and used to modify the equivalent strut area to take account of the openings. The following expression was developed for the modified infill stiffness parameter as a function of the opening ratio β

$$\lambda_m = e^{0.06\beta} \quad (4)$$

With this in view, the modified area of the diagonal strut that takes account of the effect of opening can be expressed as

$$A_m = \lambda_m A \quad (5)$$

where, A_m is the modified area

III. IMPLEMENTATION OF THE ONE-STRUT MODEL FOR MULTI-STOREY REINFORCED CONCRETE FRAME STRUCTURE

For the present study, a hypothetical 10-storey building frame, with the structural plan and cross sectional views, shown in Figure 2, was considered. The building is symmetrical in plan with respect to the two orthogonal axes. The building has plan dimensions of 15m x 15m, overall height of 33.5 m and frame spacing of 5m.

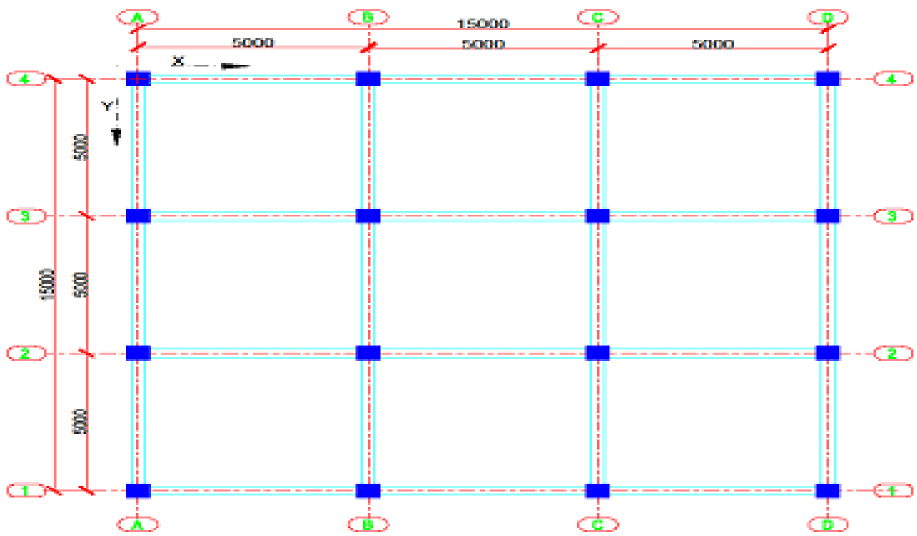
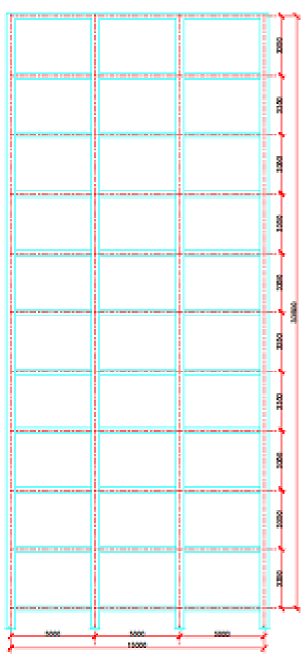
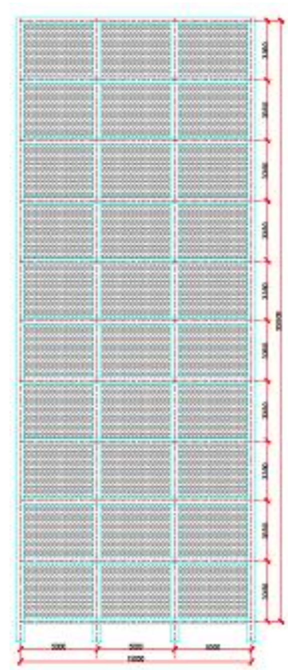


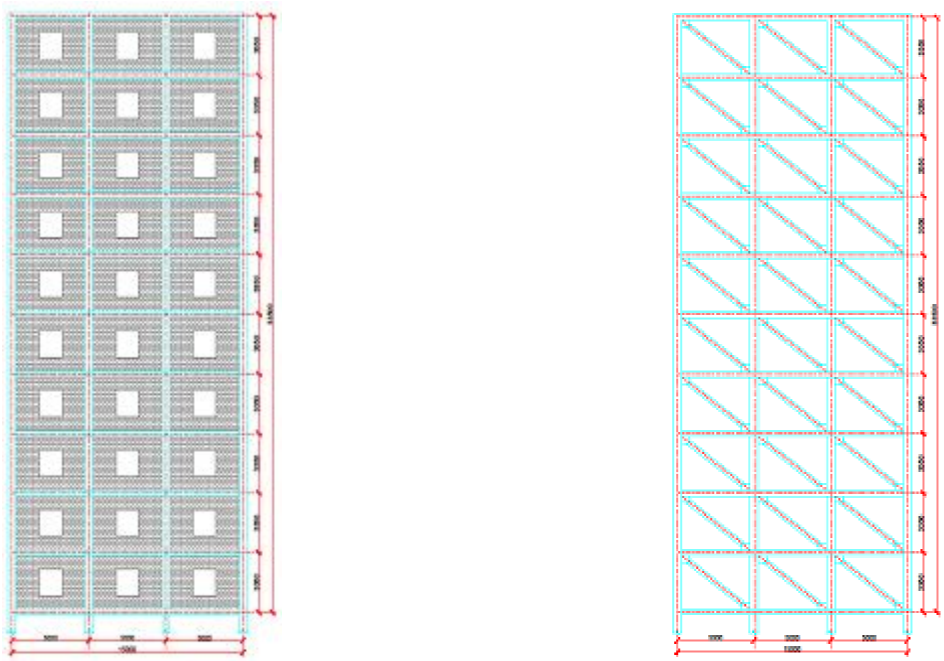
Figure 2a: Typical Plan of the Multi-Storey Structures under Study



(b) Cross Sectional View of bare frame model



(c) Rigid frame model



(d) Infill Frame Model with Central openings **(e) Modified One-strut model with Central openings**

Figure 2b: Structural Models of the Infilled Multi-Storey Structure

3.1 Computational Process

In order to utilize the one-strut macro model, the infill panel was replaced with an equivalent diagonal strut with modified area given by equation 5. In view of the numerous elements involved in a multistory building frame, the STAAD.Pro software was employed for the analysis as a skeletal triangulated frame structure.

3.1.1 Input Data

For a typical one-strut macro model, the following data were input into the programme in addition to geometric nodal coordinates.

General Model Information

Type of structure = Multi-storey frame structure
Seismic Zone to EC 8 = III
Response reduction = 5
Importance factor = 1
Number of storeys = 10
Height of building = 33.5 m
Ground storey height = 3.35 m
Floor to floor height = 3.35 m

Section Properties

Wall thickness = 230 mm
Depth of slab = 150 mm
Size of all columns = 500 x 500 mm
Size of all beams = 300 x 600 mm
Area of beam A_b = 180,000 mm^2
Area of column A_c = 250,000 mm^2
Moment of inertia of beam I_b = 5.4 x10^9 mm^4
Moment of inertial of column I_c = 5.21 x 10^9 mm^4
Length of diagonal strut = 5.27 m
Computed strut width w = 1.150 mm
Size diagonal strut = λ_m (230) x 1.15

Material Properties

Elastic modulus E_m = 4.4 x 10^6 KN/m^2
Elastic modulus E_f = 2.9 x 10^7 KN/m^2
Poisson's ratio of masonry = 0.22
Poisson's ratio of concrete = 0.20
Unit weight of reinforced concrete = 24 KN/m^3
Unit weight of brick masonry = 20 KN/m^3
Weight of floor finish = 1 KN/m^2

Primary Loading

Live load on floor = 3 KN/m^2
Live load on roof = 1.5 KN/m

3.1.2 Determination of Base Shear

To determine the base shear force F_b, for each horizontal direction in which the building is analyzed, reference was made to Eurocode 8: Design of

Structures for Earthquake Resistance [28]. The base shear force is represented by the expression:

$$F_b = S_d\left(T\right)m \tag{6}$$

Where

S_d is the ordinate of the design spectrum at period which also represents the spectrum acceleration coefficient.

T is the fundamental period of vibration of the building for lateral motion in the direction considered.

m is the total mass of the building, above the foundation or above the top of a rigid basement.

When the fundamental mode shape is approximated by horizontal displacements increasing linearly along the height, the horizontal forces F_i is given by:

$$F_i = F_b \cdot \frac{Z_i.m_i}{\sum Z_j.m_j} \tag{7}$$

where

z_i, z_j are the heights of the masses m_i , m_j above the level of application of the seismic action which could be foundation or top of a rigid basement.

From the foregoing, the STAAD. Pro analysis may be summarized into the following steps:

(a) Generation of the geometric model of the structure.
(b) Computation of α_h and α_L and replacement of infill with equivalent pin-jointed diagonal strut.
(c) Computation of the fundamental time period (T) based on the EC 8 model and the corresponding spectrum acceleration coefficient S_d.
(d) Computation of the base shear and distribution of same as horizontal forces at storey levels.
(e) Solution of the structure equilibrium matrix and determination of displacements and member stress resultants.

3.2 Validation with Finite Element Model

The main purpose of this analysis was to study the overall behavior of the structure and investigate the effect of infill walls on lateral load response of a typical multistory building frame based on the equivalent one-strut macro model and to compare the results with outputs from an FE model. The FE micro model was executed using SAP 2000 version 8, a sophisticated software package for finite element modeling with capacity to model infill openings. Minor details that do not significantly affect the analysis were deliberately left out from the models for ease of analysis. Furthermore, to make the comparative analysis more comprehensive, various models without openings and partial infilled panels with centrally located openings were investigated.

Thus the analysis was broken into two parts.

(i) Analysis of frame with all infills taken as solid (β=0)
(ii) Analysis of frame is analyzed with infills containing centrally located openings with opening ratios (β) of 10, 20, 30, 40 and 50 percent.

IV. RESULTS AND DISCUSSION

The results of the study include computed values of lateral displacements and inter-storey drift and member forces in columns and beams. These results were generally computed as a function of the opening ratio of the infill panel. The outputs of these computations are presented in tables and graphs and discussed in the relevant subheads that follow.

4.1 Lateral Displacement and Inter-Storey Drift

The computed values of lateral displacements and inter-story drift for a case of solid infilled frame (β=0) and infilled frame with opening (β= 30% and 50%) are presented in Tables 1 and 2. The basic idea here was to show how the introduction of the infill panel in the analysis affects the response of the frame and compare the output of the proposed modified one-strut model with results from the FE model.

A quick study of the Tables shows that the floor displacement and inter-story drift are adequately predicted by the one-strut model as evidenced by the close agreement of computed values with those obtained from FEM.

Table 1 Average Floor Displacement (mm)

Floor Level	β= 0		β= 0.3		β= 0.5		Bare Frame Model
	One–Strut Model	FE Model	One–Strut Model	FE Model	One–Strut Model	FE Model	
	Floor displacements (mm)						
0	0	0	0	0	0	0	0
1	0.86	0.90	1.26	1.32	2.24	2.39	5.37
2	1.86	1.93	2.79	2.95	5.02	5.37	13.41
3	2.93	3.06	4.28	4.49	7.63	8.16	19.13
4	4.03	4.23	5.92	6.21	10.56	11.19	29.87
5	5.14	5.54	8.03	8.51	14.47	15.33	37.69
6	6.23	6.47	9.20	9.66	16.23	17.12	44.92
7	7.25	7.69	10.91	11.45	19.80	20.88	51.28
8	8.35	9.70	13.87	14.97	26.19	29.33	55.76
9	9.61	11.90	16.90	20.92	36.01	42.03	60.04
10	10.74	13.86	19.86	24.43	42.72	49.55	63.20

From Table 1, it can be observed that the one-strut model analysis predicted better results as the values were closer to FE model executed with the sophisticated SAP 2000 computer software package with an average deviation of 2.2%. However, a larger deviation was observed between the results of the one-strut model and the FE model as the storey height increased beyond the 8th storey level where the one-strut model tended to give rather exaggerated results.

The analysis of the inter-storey drift in Table 2 reveals a trend to the variation of the lateral displacement with height. Higher values of inter-story drift were observed in the bare frame model with a gradual reduction in value beyond the 7th floor. The inter-storey drift coefficient θ was calculated using the following expression from EC 8

$$\theta = \frac{P_{tot}\ d_r}{V_{tot}\ \ h}$$

P_{tot} is the total gravity load at and above the storey considered in the seismic design situation; d_r is the design inter-storey drift, V_{tot} is the total seismic storey shear and h the inter-storey height. The values calculated for the modified strut model when solidity ratio is 0% is presented in the ninth column of Table 2.

Table 2: Computed Average Inter-Story Drift (mm)

Floor Level	β= 0		β= 0.3		β= 0.5		Bare Frame Model	Drift Coefficient *θ for* β=0
	One–Strut Model	FE Model	One–Strut Model	FE Model β= 0.3	One–Strut Model	FE Model β= 0.5		
	Inter-storey drift (mm)							
0	0	0	0	0	0	0	0	0.011
1	0.86	0.90	1.26	1.32	2.24	2.39	5.37	0.012
2	1.00	1.03	1.53	1.63	2.78	2.98	8.04	0.013
3	1.07	1.10	1.49	1.54	2.61	2.79	5.72	0.015
4	1.10	1.17	1.63	1.72	2.93	3.03	10.74	0.018
5	1.11	1.31	2.11	2.30	3.91	4.14	7.82	0.020
6	1.09	0.93	1.17	1.15	1.76	1.79	7.23	0.022
7	1.02	1.22	1.71	1.79	3.57	3.76	6.36	0.025
8	1.10	2.01	2.96	3.52	6.39	8.45	4.48	0.027
9	1.26	2.20	3.03	5.95	9.82	12.7	4.28	0.029
10	1.13	1.96	2.96	3.51	6.71	7.52	3.16	0.031

According to Eurocode 8, the second–order P-Δ effects need not be taken into account when the inter-storey drift coefficients are larger than 0.1. The greatest value of inter-storey drift coefficient of 0.031 occurred at the 10th storey level and constitutes about ten times the threshold value of EC 8.

From the above, it can be seen that the inclusion of infill in the analysis gives better response as an average reduction of 70% was recorded in the computed lateral displacements at floor levels. This, coupled with the very low inter-storey drift coefficient is indicative of the significant contribution of the infill to the lateral stiffness and shear resistance of multistory building frame. The bare frame maximum deflection of 63.2 mm at the topmost floor level constitutes a deflection-to-span ratio of 1/530 which is in conformance with 1/500 stipulated in most building codes.

4.2 Member Forces

The computed values for axial force, shear force and bending moments for end and corner columns, as well as the beams for a case of a rigid frame with solid infill are presented in Tables 3 - 5.

Table 3: Computed Values of Axial Force, Shear Force and Bending Moment in Exterior Column for Rigid Infilled Frame (β= 0)

Stress Resultant	Model Type	Floor Level									
		1	2	3	4	5	6	7	8	9	10
Axial Force	Bare Frame	483.89	409.74	350.17	285.02	217.11	156.93	103.33	58.54	25.201	6.24
	OSM	559.73	449.25	431.66	362.69	292.71	223.49	157.19	97.07	47.22	13.05
	FEM	570.69	481.83	436.08	364.60	292.72	222.12	155.06	94.73	45.23	11.95
Shear Force	Bare Frame	70.92	56.43	55.26	52.92	49.95	45.72	39.96	32.04	22.41	6.48
	OSM	12.15	4.68	5.67	5.31	5.13	4.68	4.14	3.33	2.43	0.18
	FEM	13.95	5.45	6.48	6.08	5.85	5.36	4.73	3.78	2.7	0.09
Bending Moment	Bare Frame	167.4	99.36	93.15	87.57	81.27	72.63	61.02	45.81	27.18	2.79
	OSM	27.54	7.92	10.26	9.27	8.64	7.65	6.39	4.77	2.7	0.63
	FEM	31.50	9.14	11.66	10.58	9.81	8.69	14.49	5.36	2.97	0.23

4.2.1 Column axial forces

From simple analysis of the analogous diagonal compression strut model of frame under lateral load, it is evident that the windward column will be in tension while the leeward columns are under compression. The results, when compared to the bare frame model, show that the one-strut model produced higher axial forces in columns but lower shear forces in both beams and columns. These values reveal an increase of about 14 percent in axial forces for the external columns. The implication of this is that the predominantly moment resisting structural action of the bare frame is transformed into a truss action by the consideration of infill panel, acting as a diagonal strut.

4.2.2 Shear forces and bending moments

The infill models predicted higher axial forces in columns but lower shear forces and bending moments in both beams and columns. As evidenced from Tables 3 and 4, the results compare favorably with those from the FE model.

Table 4: Shear force and Bending Moments in Edge Beam for Rigid Infilled Frame (β= 0)

Beam No.	Shear Force			Bending Moment		
	Bare Frame Model	One-Strut Model	FE Model	Bare Frame Model	One-Strut Model	FE Model
24	64.13	8.02	9.24	151.17	18.80	21.65
26	57.25	7.55	8.67	143.61	18.86	21.68
28	57.86	7.74	8.88	144.65	19.34	22.20
30	57.25	7.61	8.73	142.63	19.12	21.92
32	64.13	7.50	8.74	169.51	20.03	23.33

The close agreement of the results testifies to the ability of the modified area of the one-strut model to adequately model the shear response of the structure.

The shear force in the column can be estimated as the horizontal component of the diagonal compression strut while the vertical component yields the shear force in the beam at the loaded corner. The beam shears presented in Table 4 also reflect that the drastic reduction in the beam shears similar to the bending moment.

Based on the mechanism of deformation described earlier in the introduction, the bending moment in the columns is basically caused by the perpendicular thrust of the infill acting as elastic foundation. As shown in Table 4, the bending moment reduced drastically by about 6 times when compared to similar quantities in the bare frame. This justifies the position of the most building codes in prescribing an nominal moment of Nh/20 for design of columns in infilled frames. It was also observed that the stress resultants generally reduced with increase in floor level.

4.3 Effect of Opening Ratio on the Response of Infilled Frames

In the previous section, the variation of deflection, inter-storey drift and member forces was discussed to confirm the ability of the model to accurately predict these characteristics for multistory building frame. The variation of these quantities as a function of opening ratio is now considered for discussion.

4.3.1 Seismic demand

The effect of infill openings on the lateral displacement and inter-story drift of a building structure are important parameters to assess the seismic demand of a building structure. Accordingly, building codes specify an upper limit to both lateral displacement and inter-story drift because the effect of infill is usually ignored. Figures 3 and 4 clearly demonstrate a dramatic reduction in the lateral displacement and inter-storey drift due to the effective participation of infill. However, lateral displacements and inter-storey drift increased gradually with increase in the size of openings in the infill panel. Thus, the presence of infill panel resulted in a general reduction of the seismic demand and better response of the look at Figure 3 confirms the established fact that when the bare frame is subjected to horizontal loading, its beams and columns deform into a double curvature configuration. However, as the infill solidity increases, the in-plane rigidity of the masonry significantly reduces the shear mode of deformation, bringing the deflection profile to purely flexural configuration.

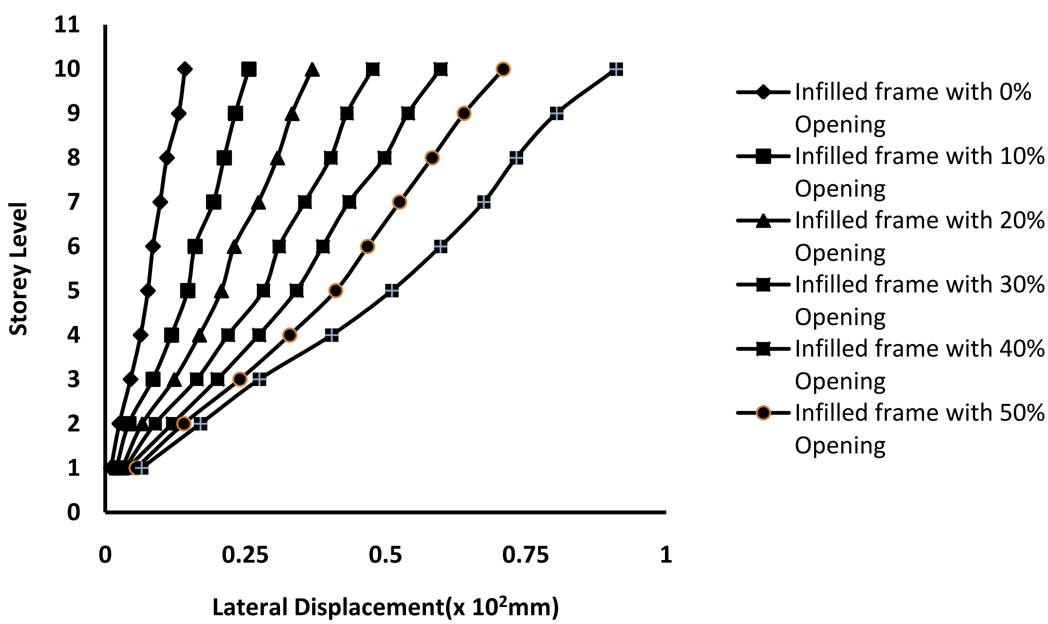


Figure 3: Plot of Average Floor Level Lateral Displacements for various Values of Opening Ratios

Based on the predicted values of the inter-storey drift in Figure 4, a similar improvement in structural response of the infilled model in comparison to the bare frame can be deduced. On the other hand, the storey displacement and drift increased significantly with increase in size of the infill opening. The inter-storey drift coefficient of the infilled frame showed a steady increase with storey height up to maximum values occurring approximately at mid height. Thereafter, a sharp decrease was observed. However, a reduction of about 50 percent of the bare frame drift coefficient was found to occur at opening ratio of 25 percent. The infill panel reduces the seismic demand of the structure, which probably explains why buildings designed in conventional way behave practically elastically, even during strong earthquake.

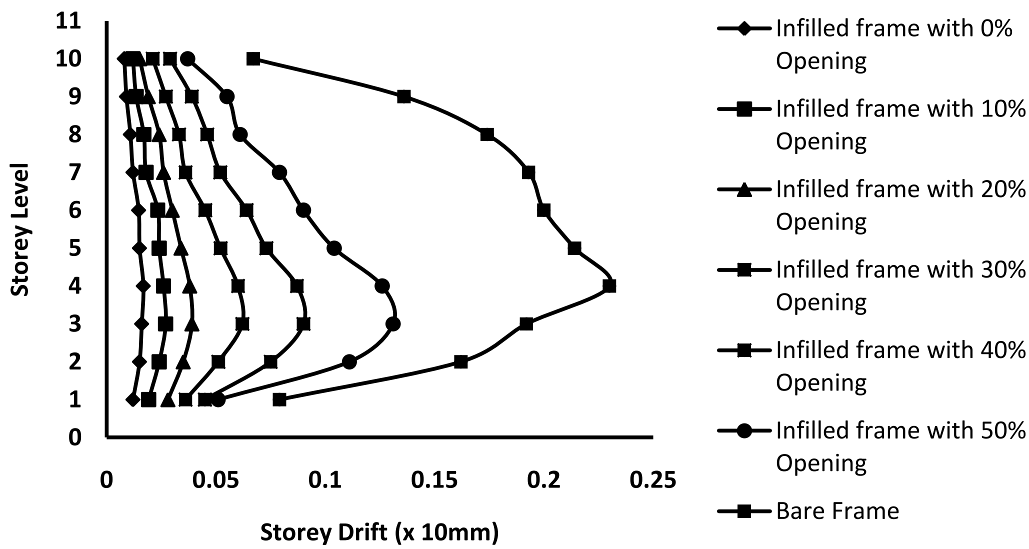


Figure 4: Plot of Storey Drift for varying Values of Opening Ratio

The axial forces in columns are compared for bare frame model and the single strut model for all the opening cases. The axial forces for a corner column for different floor levels are shown in Table 5. The axial forces reduced with increase in opening ratio by about 1 percent while there was a moderate reduction of about 8 percent with increase in storey height. Generally, axial force values, computed from this single-strut model were greater than those obtained from the bare frame model. The increase in axial force was largest for the lower floor and goes on decreasing with increase in floor level.

Table 5: Axial Force in Corner Columns (in kN)

Height	Full wall	10% opening	20% opening	30% opening	40% opening	50% opening
0	1042	1031	1023	1115	1108	905
3.35	961	945	937	925	919	900
6.70	880	877	869	856	848	830
10.05	793	783	773	762	757	750
13.40	761	750	741	736	730	722
16.75	670	668	657	640	633	625
20.10	601	589	577	565	549	537
23.45	505	475	473	469	462	454
26.80	349	340	338	335	332	310
30.15	194	179	165	151	141	130

Table 6 contains the values of computed lateral load capacity at each floor level of the 10-storey building frame considered in the study**.** As evidenced from these values, shear forces and bending moment in both beams and columns were generally found to decrease with increasing opening ratios. Generally, with increase in opening ratio, the stiffness of the infill reduces. The reduced stiffening effect results in greater bending of the frame and shear displacements of the frame. Further opining ratios beyond 50% brings the frame into a bare frame configuration with increased shear flexure behavior.

In summary, it was found that the fundamental period, inter-storey drift coefficients and lateral displacement in the infilled frame structure all increased with increasing opening ratio, while the shear forces and moments were generally found to decrease. Generally the study of the analytical models for infilled frames with opening predicted softer structure as seen in the reduction of design forces as displayed in Table 6.

Table 6: Computed Values of Axial Force, Shear Force and Bending Moment in Exterior Column

Stress Resultant	**Model Type**	**Floor Level**									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Lateral Force capacity	**0%**	10.06	40.23	90.53	160.93	251.46	362.10	492.86	643.46	814.18	523.28
	10%	6.91	27.63	62.16	110.50	172.66	248.63	338.42	442.01	559.42	523.28
	20%	5.57	22.28	50.13	89.12	139.24	200.51	272.92	356.46	451.15	315.00
	30%	4.67	18.68	42,03	74.71	116.74	168.11	228.81	298.86	378.24	276.22
	40%	4.15	16.59	37.33	66.36	193.69	149.32	203.24	265.45	335.96	257.06
	50%	3.72	14.86	33.43	59.44	92.87	133.74	182.03	237.75	300.91	241.77
Storey Shear	**0%**	3389.09	3379.03	3338.80	3248.27	3087.34	2835.88	2473.78	1980.92	1337.46	523.28
	10%	2342.63	2335.72	2308.09	2245.94	2135.43	1962.77	1714.14	1375.73	933.72	374.30
	20%	1902.38	1896.81	1874.53	1824.40	1735.29	1596.04	1395.53	1122.61	766.15	315.00
	30%	1607.07	1602.40	1583.73	1541.70	1466.98	1350.24	1182.13	953.32	654.46	276.22
	40%	1300.51	1296.80	1281.94	1248.50	1189.06	1096.19	962.46	780.43	542.68	241.77
	50%	1195.31	1191.90	1178.24	1147.51	1092.88	1007.52	884.61	717.30	498.78	222.21
Storey Moment	**0%**	74385.96	63066.2	51881.22	40999.5	30656.92	21156.71	12869.55	6233.46	1752.98	0
	10%	51542.54	43717.88	35985.76	28461.87	21308.17	14732.89	8990.51	4381.83	1253.88	0
	20%	41963.31	35609.00	29329.32	23217.58	17404.37	12057,63	7382.59	3621.84	1055.24	0
	30%	35547.45	30179.41	24873.94	19709.26	14794.88	10271.57	6311.42	311.80	925.34	0
	40%	31926.96	27119.73	22368.08	17741.49	13337.21	9280.30	5723.59	247.73	861.13	0
	50%	28943.39	24599.12	20304.64	16122.16	12138.79	8466.54	5224.32	2627.89	809.92	0

V. CONCLUSION

This paper presented a comparative analysis of two different analytical methods for the study of shear response of multi-storey infilled frames. From the results of the analysis, the significant effects of the infill in the design of RC frames have been confirmed when compared to those from the common analysis of a bare frame where the infill is assumed as non-structural and ignored in the analysis. The basic input made in this paper was to formulate an appropriate one strut macro model by modifying the stiffness parameter of the equivalent strut to account for openings.

From the above, it can be seen that

1. The inclusion of infill in the analysis gives a better response with average reduction of 70% in lateral displacements at floor levels.
2. The maximum value of inter-storey drift coefficient of 0.031, representing about 10 folds the EC 8 threshold, is indicative of the significant

contribution of the infill to the lateral stiffness and shear resistance of multistory building frame.

3. The one-strut model analysis predicted better results with 2.2% agreement with as the values from FE model executed with the sophisticated SAP 2000 computer software but gave exaggerated results as the storey height increased beyond the 8th level.
4. The infill models predicted higher axial forces in columns but lower shear forces and bending moments in both beams and columns. The axial force in the external column increased by about 14%, while the bending moment reduced drastically by about 6 times when compared to similar quantities in the bare frame.
5. The bending moments in the infilled frame are relatively small compared to those of the bare frame. This justifies the position of the most building codes in prescribing a nominal moment of Nh/20 for design of columns in infilled frames.
6. The presence of infill panel resulted in a general reduction of the seismic demand and better response of the building structure both in terms of lateral displacement as well as inter-story drift. Closer observation of the results confirms the established fact that when the bare frame is subjected to horizontal loading, its beams and columns deform into a double curvature configuration. However, as the infill solidity increases, the in-plane rigidity of the masonry significantly reduces the shear mode of deformation, bringing the deflection profile to purely flexural configuration.
7. The inter-storey drift coefficient of the infilled frame showed a steady increase with storey height up to maximum values occurring approximately at mid height. Followed by a sharp decrease was observed. However, a reduction of about 50 percent of the bare frame drift coefficient, lateral load capacity, storey shear and bending moment was found to occur at opening ratio of 25 percent

The results from the one strut model applied to the hypothetical multi-frame structure were found to compare favorably with those from the Finite Element Micro model. Hence, the modified one-strut macro model developed is recommended as a simplified analytical and design tool, capable of prediction the shear response of infilled frame structures with openings.

REFERENCES

[1] Smith, B.S. (1966) Behaviour of square infilled frames. *J. Struct. Div*. ASCE, STI, 381- 403.

[2] Smith, B.S. and Carter, C. (1969). A method of analysis for infilled frames. *Proc. Instn. Civ. Engrs.*, 44, 31- 48.

[3] Page, A.W. (1981). Biaxial compressive strength of brick masonry. Proc. *Instn. Civ. Engrs.*, Part 2, 71, 893- 906.

[4] Mehrabi, A.B., Shing, P.B., Schuller, M. and Noland, J. (1996). Experimental evaluation of masonry infilled RC frames. *J. Struct. Eng*., 122 (3), 228-237.

[5] Buonopane, S.G. and White, R.N. (1999). Pseudodynamic testing of masonry infilled reinforced concrete frame. *J. Struct. Eng*., 125 (6), 578-589

[6] Santhi M.H., Knight, G.M.S. and Muthumani, K. (2005). Evaluation of the seismic performance of gravity load designed reinforced concrete frames. Journal of Performance of Constructed Facilities, 19 (4), 277-282

[7] Page, A.W., Kleeman, P.W. and Dhanasekar, M. (1985). An in-plane finite element model for brick masonry. *New Analysis Techniques for Structural Masonry*, *Proc. of a session held in conjunction with Structures Congress*, Chicago, Illinois, ASCE, 1-18.

[8] Liauw, T.C. and Kwan, K.H. (1984). Nonlinear behavior of non-integral infilled frames. *Comp. and Struct.*, 18, 551-560

[9] Dhanasekar, M. and Page, A.W. (1986). Influence of brick masonry infill properties on the behavior of infilled frames. . Proc. *Instn. Civ. Engrs.*, Part 2, 81, 593- 605.

[10] Saneinejad, A. and Hobbs, B. (1995). Inelastic design of infilled frames. *J. Struct. Eng*., 121 (4), 634-650.

[11] Asteris, P.G. (2003). Lateral stiffness of brick masonry infilled plane frames. *J. Struct. Eng*., 129 (8), 1071-1079.

[12] Moghaddam, H.A. (2004). Lateral load behavior of masonry infilled steel frames with repair and retrofit. *J. Struct. Eng*., 130 (1), 56-63.

[13] Mallick, D.V., and Garg, R.P. (1971). Effect of infill on the lateral stiffness of infilled frame. *Proceedings of Institute of Civil Engineers*, 49(6), 193-209.

[14] Liauw, T.C., and Lee, S.W. (1977). On the behavior and the analysis of multistory infilled

frames subjected to lateral loading. *Proc. Institute of Civil, Engineers,* 63 (2), 651-656.

[15] Zarnic, R. (1995). Modeling of response of masonry infilled frames. *10th European Conference on Earthquake Engineering,* 1, 1481-1486.

[16] Kadir, M.R.A. (1974). *The structural behaviour of masonry in fill panels in framed structures,* PhD thesis, University of Edinburgh.

[17] Polyakov, S.V. (1960). On the interaction between masonry filler walls and enclosing frame when loading in the plane of the wall, *Translation in earthquake engineering, Earth quake Engineering Research Institute,* San Francisco, 36-42.

[18] Holmes, M. (1961). Steel frames with brickwork and concrete infill. *Proc., Inst. Civ. Eng., Struct. Build.*, 19, 473–478.

[19] Thiruvengadam, V. (1985). On the natural frequencies of infilled frames. *Earthquake Engineering and Structural Dynamics,* 13 (3), 401-419.

[20] Chrysostomou, C.Z. (1991). *Effect of degrading infill walls on the nonlinear seismic response of two- dimensional steel frames.* PhD dissertation, Cornell University, Ithaca, N.Y.

[21] Hamburger, R.O. (1993). Methodology for seismic capacity evaluation of steel-frame buildings with infill unreinforced masonry. *Proceedings of National Earthquake Conference, Central U.S. Earthquake Consortium,* Memphis, Tennessee, Volume 2.

[22] El-Dakhakhni, W. W., Mohamed E., and Ahmad H. (2003). Three-strut model for concrete masonry-infilled steel frames. *Journal of Structural Engineering,* 129 (2), 177-185.

[23] Mehrabi, A.B., and Shing, P.B. (2002). Behaviour and analysis of masonry-infilled frames. *Prog.Struct.Engrg Matter*, 320-331.

[24] Nwofor, T. C., and Ephriam, M. E. (2014). “Validation of a FE micro model for RC frames.”International Journal of Innovative Research in Advanced Engineering, 1(9), 44 - 50.

[25] Hendry, A. (1981). *Structural Brickwork,* Macmillan, London.

[26] Hetenyi, M. (1946). *Beam on elastic foundations*. University of Michigan Studies, Scientific Series, Vol. XVI

[27] Amrhein, J.E., Anderson, J., and Robles, V. (1985). Mexico Earthquake –September 1985. *The Masonry Society Journal,* 4, (2), 12-17.A.

[28] Eurocode 8. (2004). *Design of Structures for Earthquake Resistance.* The European Standard EN