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RESPONSE OF R.C. FRAMES WITH PARTIAL INFILL SUBJECTED TO LATERAL IN-PLANE LOADING

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Abstract

Infill walls in reinforced concrete framed buildings are often constructed up to a limited height of columns to provide more lighting and ventilation especially in the corridor of public buildings like schools, hospitals, *etc*. These partial infill walls have an important role in lateral load-transfer mechanism in building frames. Performance of RC framed buildings in past earthquakes clearly illustrates that the columns of partial infilled frames fail due to short-column and captive-column effects. In the present study, finite element analysis of partial infilled frame with different height of infill are carried out in open source code OpenSees. In the analysis, nonlinear behaviour of frame elements is modelled while infills are assumed to be linear elastic. Separation and sliding at the frame-infill interfaces are also modelled. The lateral stiffness of partial infilled frame considering perfect contact at the interface is compared with the lateral stiffness of the same frame considering separation and sliding. It is concluded that the separation and sliding at frame-infill interfaces has an important role in reducing stiffness of infilled frame.

Keywords: Partial Infilled Frame; Separation and Sliding; Captive Column; Short Column

1. Introduction

In most design codes, infill walls in reinforced concrete (RC) framed buildings are considered as nonstructural elements. Such design consideration is acceptable for buildings subjected to vertical loading only. However, infill walls act as structural elements when buildings are subjected to lateral loading due to wind, earthquake, etc. These increase lateral stiffness and ultimate strength, and reduce natural period of buildings [1]. Sometimes infills walls are constructed up to a limited height of column to provide more lighting and ventilation especially in the corridor of public buildings like schools, hospitals, etc. These partial infills reduce the strength and stiffness of the frame as compared to fully infilled frame and cause short-column or captive column effects [2] as has been observed in the past earthquake (e.g., 2001 Peruvian earthquake [3], 2003 Bingol earthquake [4]). Failure due to short column and captive column effects is often caused by insertion of structural (beams, columns) and nonstructural (infill walls) elements, respectively, which are not taken into account during design of frame. Therefore, to avoid such failure either nonstructural elements should be separated from the structure or frame-infill interaction should be considered in the design of frame [5]. Guevara, and Garcia [5] suggested to avoid captive and short columns in buildings.

Only a few experimental and numerical studies of partial infilled frame have been performed in the past. Chiou *et al.* [6] have done experimental and numerical studies of a full-scale partial infilled frame subjected to in-plane monotonic loading. They observed the stress distribution of masonry infill walls and found that the partially infilled masonry wall induces a short column effect and leads to severe failure of the column. They suggested that stiffness of partial infilled frame can be increased with providing completely masonry infilled wall. Kumar *et al.* [7] performed an experimental study and obtained that the partial infilled frame has more lateral load capacity as compared to bare frame. They observed 20% more strength of partial infilled frame as compared to bare frame. Based on experimental observations, they proposed a mathematical model for calculating theoretical ultimate load for braced and partially infilled RC frames [7].

In partial infilled RC frame, height of infill wall varies depending upon functional requirements. Only a few studies [2, 6-8,] have been performed in the past on the effect of height of infill wall on the response of RC frame. In general, lateral strength and lateral stiffness of partial infilled frame depend on height of infill wall (2). Taher and Afefy [8] performed Finite Element analysis on infilled frame and found that the strength and stiffness of the entire frame increases with increase in height of infill. However, Pradhan *et al.* [2] observed that the stiffness of partial infilled frame remains same if the infill wall is provided up to 40% of the height of column; beyond that height, stiffness and strength of frame start to increase with increase in infill height.

Most of the past studies did not consider effects of separation and sliding at the frame-infill interface on the response of partially infilled frame. For better understanding of the performance of partial infilled RC frames, it is necessary to consider the frame-infill interface in the numerical analysis. Therefore, in the present study an attempt has been made to perform finite element analysis of partial infilled frame with different height of infill considering separation and sliding at the frame-infill interfaces. In the analysis, nonlinear behaviour of frame elements are modelled while infills are assumed to be linear elastic.

2. Finite element model

A two-dimensional (2D) finite element (FE) model of infilled frame was analyzed in open-source finite element code, OpenSees [9]. Fig.1 shows the FE model of infilled frame and various elements used in the FE model. Beam and columns were modelled using one dimensional (1D) beam-column elements which have two nodes with three degrees of freedom (3DOF), two translational and one rotational, at each node (Fig.1c). In masonry infill wall, brick and mortar were not modelled separately, rather they were considered as a single unit with property of masonry. Infill wall was discretized using 2D quadrilateral finite elements having four nodes with two translational degrees of freedom (DOF) at each node (Fig.1d). Mass of these elements was lumped at the element nodes. The masonry infill wall was considered to behave linearly and was analyzed under plane stress condition. Nonlinear behavior of beam and columns was modelled using nonlinear fiber sections which were discretized into fibers of cover concrete, core concrete, and reinforcing steel. The cover concrete was modelled using uniaxial Kent–Scott–Park constitutive model with unconfined properties of concrete [10, 11] and the core concrete was modelled by using confinement model proposed by Braga *et al.,* [12]. The main reinforcing steel was modelled using Giuffre–Menegotto–Pinto steel constitutive model [13-15]. Beam-column joints were modelled as rigid joint.

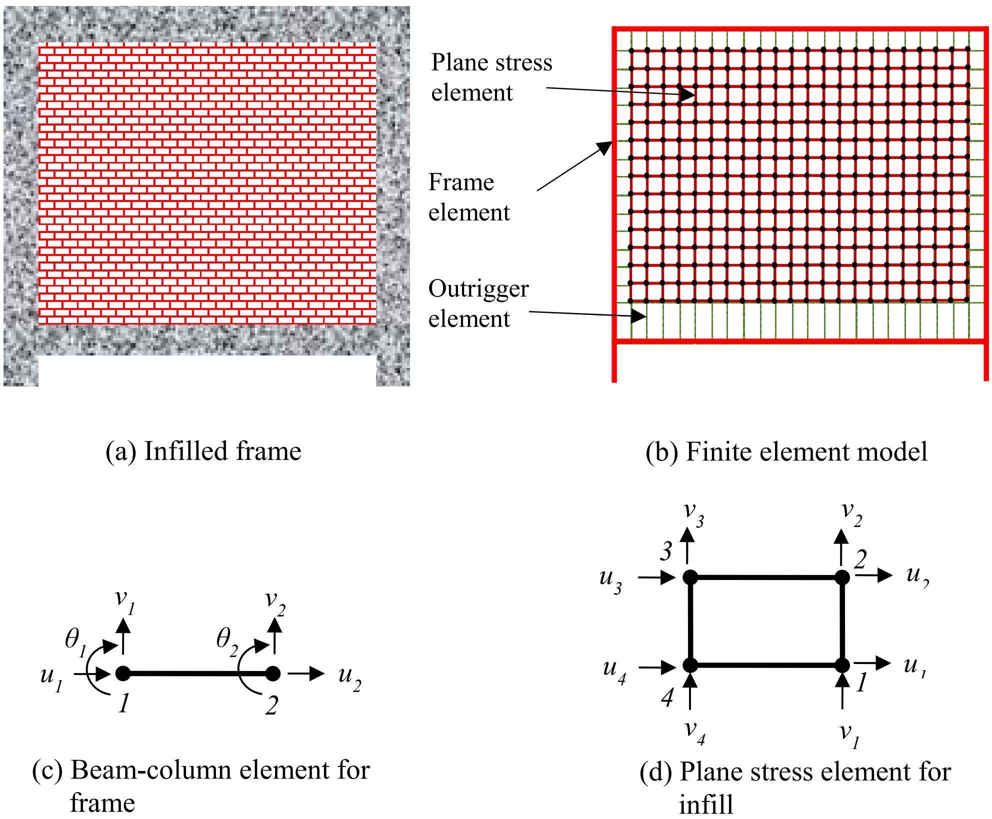
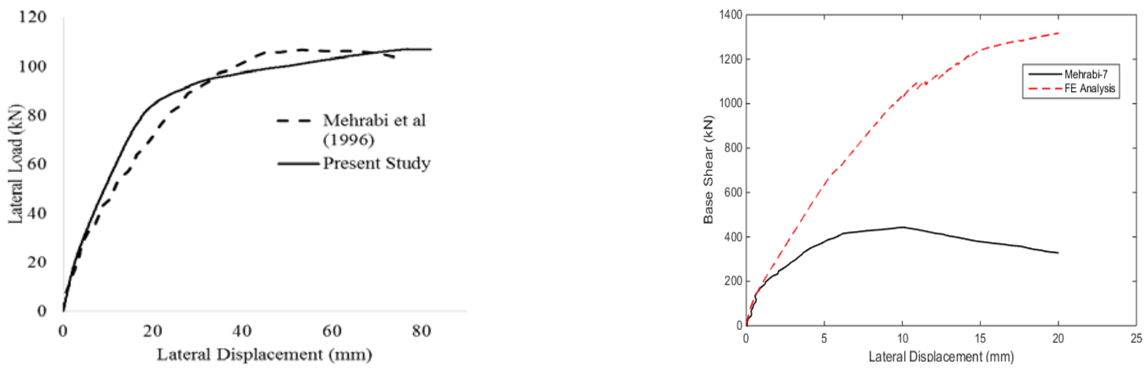


Fig. 1 – Details of finite element modelling of infilled frame

In reality, separation and sliding may take place at the frame-infill interface during in-plane lateral loading. In order to simulate such behavior, the frame-infill interfaces were modelled using node-to-node zero-length frictional contact element available in OpenSees [9]. The formulation of these elements is based on penalty method. This element was developed based on the Mohr-Coulomb frictional criteria and can only be connected between two nodes sharing the same space and with the same numbers of degrees of freedom (DOF) [9]. Since at the interfaces, nodes of infill had 2-DOF and the corresponding frame nodes had 3-DOF, interface elements could not be connected directly to the nodes of infill and frame. Therefore, a set of dummy nodes with 2-DOF each was introduced at the frame-infill interfaces. The interface elements were connected to the infill nodes and corresponding dummy nodes and frame nodes were connected with these dummy nodes using equal-DOF constraints in both X and Y directions. Performance of the interface elements depends on the value of two penalty parameters, K_N for normal penalty, and K_T for tangential penalty. These parameters are required to have very high values in order to reduce the penetration of infill nodes into nodes of beam and columns or vice versa, and to idealize rigid-plastic slip during sliding. Such high values may induce numerical instability in solving the global system. On the other hand, low values of these parameters results in excessive penetration and unreasonably high amount of separation and sliding. Therefore, some finite values of the parameters are needed to reduce the penetration to an acceptable tolerance and to achieve convergence in separation and sliding. Based on some iterations it was observed that values of K_N and K_T should be in the order of 10^6 to 10^8. Friction coefficient between brick-mortar and RC frame was taken as 0.75 [16].

3. Verification of finite element model

Finite element model was verified with the experimental specimen 1 and specimen 7 of Mehrabi *et al.* [16]. These specimens are half-scale model tested in the laboratory of University of Colorado, Boulder; specimen 1 is a bare frame (without infill wall) and specimen 7 is a fully infilled frame. These specimens represented the interior bay at the bottom story of the prototype frame and were designed in accordance with *ACI* 318-89 [17]. The specimen was analyzed for monotonic lateral loading in combination with the gravity load. The geometric and material properties of these frames can be found elsewhere [16]. Lateral load versus lateral displacement curves obtained from the FE analysis were compared with those obtained from the experiment (Fig. 2). Fig 2a shows that for bare frame numerically obtained load-deformation curves matches satisfactorily with experimentally obtained curve. Numerical lateral stiffness was found only 4.84 % less than the experimental value observed by Mehrabi *et al.* [16]. In case of fully infilled frame, a good agreement was observed between experimental lateral stiffness and numerically obtained lateral stiffness Fig 2b. However, the strength estimated from the numerical analysis was found to be significantly more than that obtained from the experimental study by Mehrabi *et al.* [16]. This is because the nonlinear behavior of infill wall was not modelled in the present study. Thus the present FE model can satisfactorily predict the lateral stiffness of infilled frame. This model is used to analyze the partially infilled frame.



(a) (b)

Fig. 2 – Lateral load versus lateral deflection curves of (a) bare frame (b) infilled frame

4. Analysis of partial infilled frame

For the analysis, a one-bay three-storey RC frame was designed in STAAD Pro. V8i [18] following the Indian seismic design code IS: 1893-Part-1 [19] and ductile detailing was done as per IS: 13920 [20]. The building frame was designed to be located in Zone III and rested on medium soil. Height of ground storey and two upper stories were taken as 3.53 *m*. and 3*m*, respectively. Bay width of the frame was taken as 4.674 *m*. Thickness of the infill wall was taken as 100 mm. Infill wall was considered as non-structural element. However, appropriate mass of the infill wall was considered during the design of RC frame. Design details of the frame have been shown in Fig.3.

Analysis was done for ground floor of the RC frame. Vertically downward point load of 112.5 *kN* was applied on both columns and 1.535 *kN* load was applied on each node of beam to consider the effect of upper stories on the ground storey. In the analysis, height of the infill was varied to obtain the effect of infill height on the response of partially infilled frame. Therefore, 0%, 25%, 50%, 75% and 100% height of infill were considered.

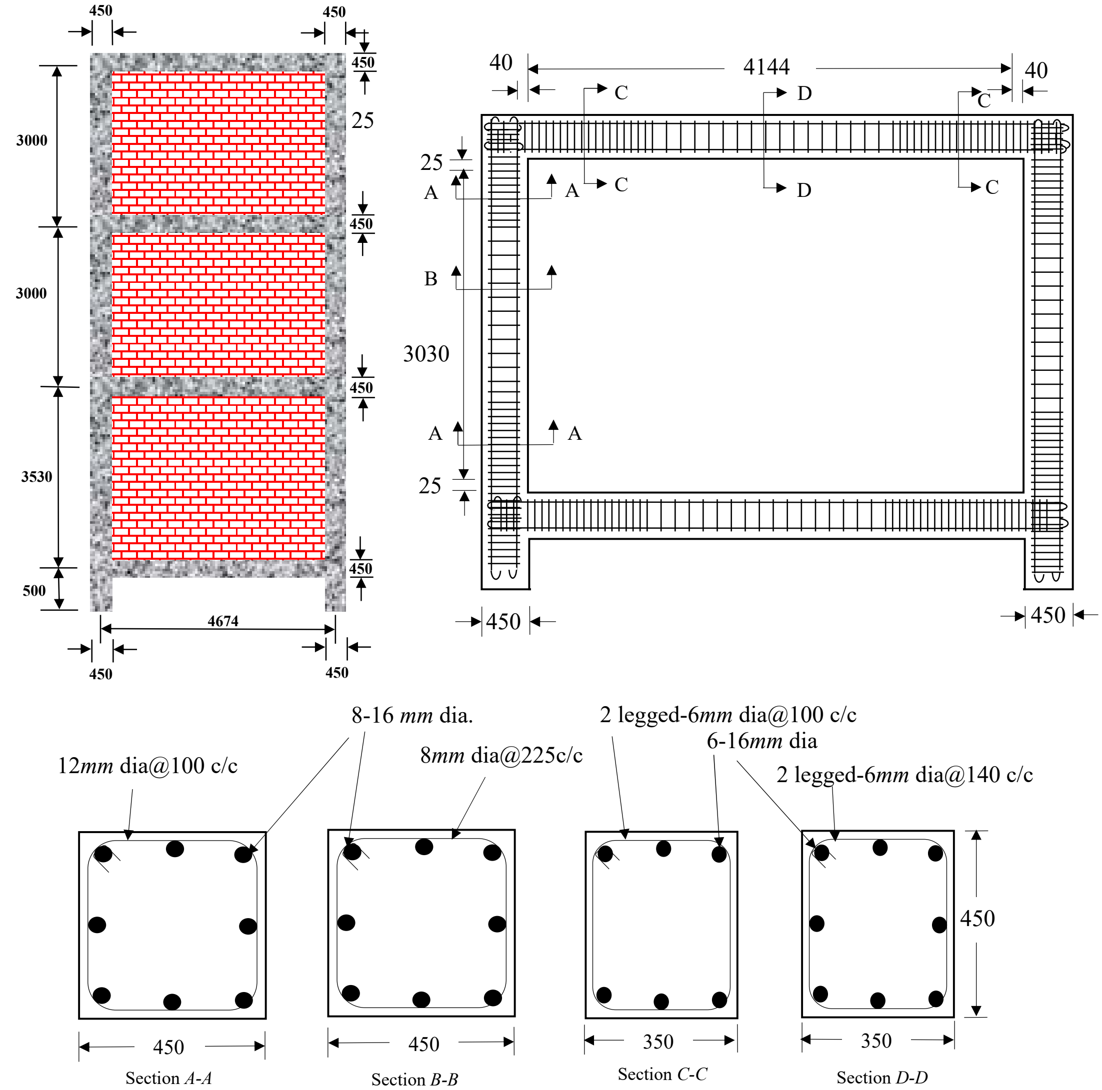


Fig. 3 – Details of one-bay, three-storey RC frame (all dimensions are in *mm*)

In the analysis, the unit weight of concrete and masonry were taken as 25 kN/m^3 and 19 kN/m^3, respectively. The modulus of elasticity of masonry and reinforcing steel were taken as 9080 *MPa* and 2×10^5 *MPa,* respectively. The yield strength and ultimate strength of reinforcement were taken 415 *MPa* and 485 *MPa*. Characteristic compressive strength (f_{ck}) of concrete is taken as 30 MPa and modulus of elasticity of concrete (E_c) is estimated using the formula as per IS 456: 2000 [21]:

$$E_c=5000\sqrt{f_{ck}}$$

The coefficient of friction between concrete and masonry is assumed to be 0.75. Poisson's ratio of concrete and masonry is taken as 1.3. Other relevant properties of reinforcement and concrete are shown in Table 1. Point mass of beam column element were applied on each node for self-weight of element. Mass of 2D element was applied on each node as lumped mass.

Table 1 – Concrete properties of all models

Sl. No.	Material	Secant Modulus *(MPa)*	Compressive strength *(MPa)*	Strain at peak stress	Modulus of rupture *(MPa)*	Ultimate strain	Shear Modulus *(MPa)*
1	Concrete	27386	30	0.003	5.13	0.006	10533.1

To evaluate the effect of height of infill wall on the response of frame, five different cases of RC frame specimen were considered. These include 0%, 25%, 50%, 75% and 100% height of infill. The case with 0% infill indicates a bare frame and that with 100% infill indicates a fully infilled frame. FE models of each of these frames are shown Fig.4. Pushover analysis of all these frames has been conducted and the results are discussed in the following section.

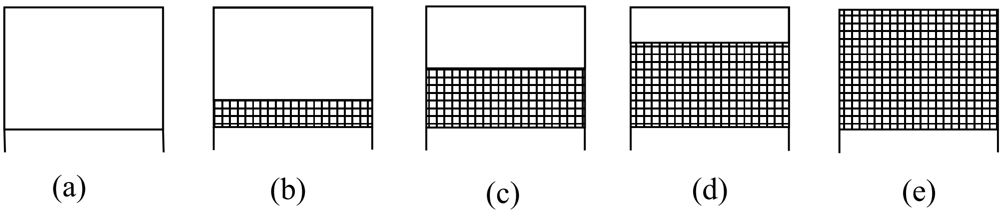


Fig. 4 – Finite element model of infilled frame: (a) 0 % infill height, (b) 25 % infill height, (c) 50 % infill height, (d) 75 % infill height, and (e) 100 % infill height

5. Results and discussion

5.1. Response of Bare Frame

Fig.5 shows the pushover curve of bare frame indicating its ductile behaviour. Lateral stiffness of the frame was found to be about 7.0 *kN/mm*. Lateral stiffness estimated here is the secant stiffness and is defined as the slope of the line connecting the origin of the pushover curve and the point at which 50% of the maximum base shear was first reached [16]. The numerical results indicate that the maximum lateral strength of bare frame was found to be about 225 *kN*. As expected, the failure of frame was found to be due to formation of plastic hinges in beams and columns.

5.2. Response of Fully and Partially Infilled Frame

Frame-infill interaction during lateral loading (earthquake load and wind load, *etc*.) involves complicated material and interface nonlinearities such as separation and sliding. It is often perceived that the interface nonlinearity has appreciable effects on the response of infilled frame. Therefore, in the FE analysis, two sets of FE models of infilled frame were prepared. In one set of models, separation and sliding at the frame-infill interface were considered and another set these were neglected. In the former case, interface was modelled using interface elements and in latter case perfect contact between frame and infill was assumed. Results of these two sets of models are compared to study the effect of separation and sliding on the lateral stiffness of infilled frame. Fig.6 shows the deflected shape of fully infilled frame with separation and sliding at the tension corners of the infill frame interfaces. Formation of compression strut along the loaded diagonal was also observed when separation and sliding was considered. Severe damage can be observed in left side column due to captive column effect. The damage accumulates with increase in lateral drift.

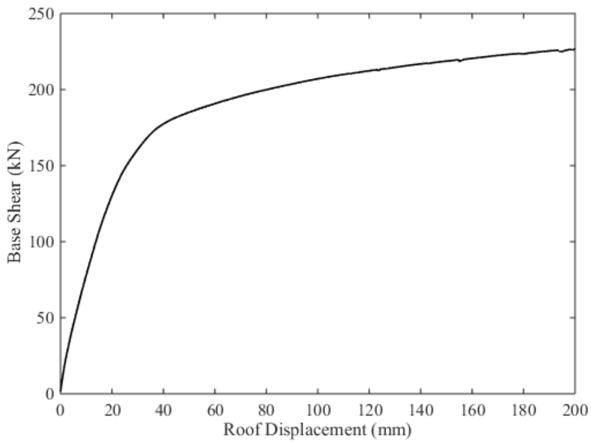


Fig. 5 – Pushover curve for RC bare fame

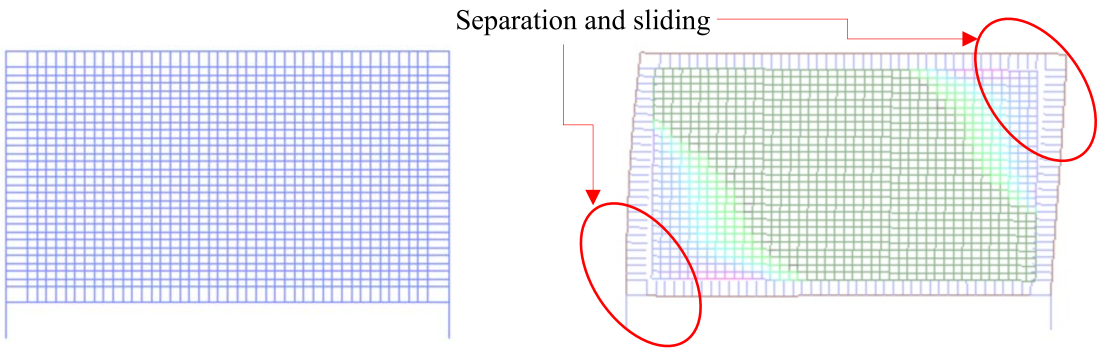


Fig. 6 – (a) Deflected shape of fully infilled frame at the instant of roof displacement of 30 *mm*

5.2.1. Effect of Separation and Sliding

The effect of interface nonlinearity on the pushover curves of 25%, 50%, and 75% infill height are shown in Fig.7a to 7c. The lateral stiffness of frame considering perfect contact at the frame-infill interfaces was obtained from pushover curve and compared it with same frame considering separation and sliding (Table 2). Lateral stiffness of fully infilled frame (100% infill) with perfect contact was found to be unrealistically high; about 11.0 times more than the same frame with interface nonlinearity. In other words, separation and sliding at frame-infill interfaces has an important role in reducing stiffness of infilled frame. However, numerical results of other frames indicate that the effect of separation and sliding on the lateral stiffness of frame reduces with reduction in infill height. Lateral stiffness of partial infilled frames with 75%, 50% and 25% height of infill considering perfect contact were found to be 3.5, 3.0 and 1.4 times stiffer as compared to that of the same frame considering interface nonlinearity. Fig.7d shows the damage level in frames at different levels of base shear in partially infilled frame with 75% infill height. The red colour in the frame elements indicates that the damage starts in the elements.

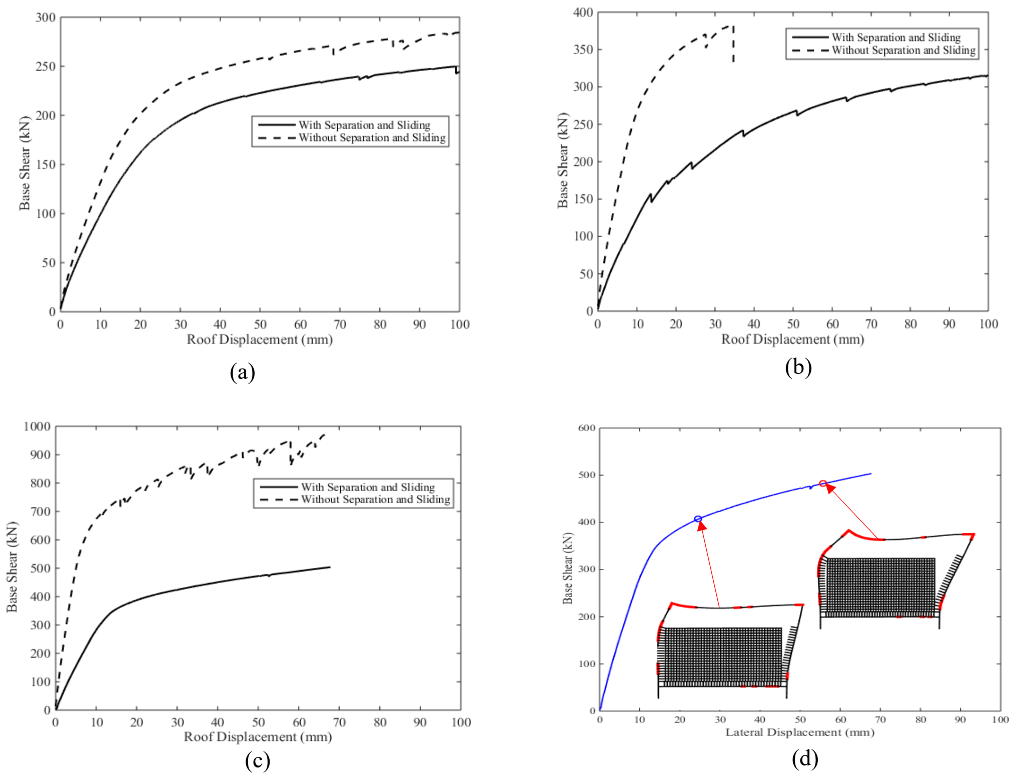


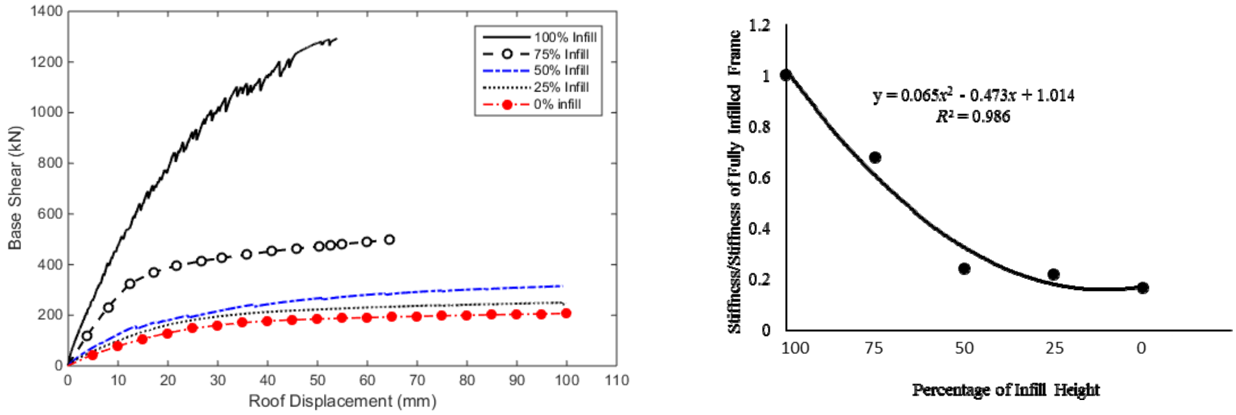
Fig. 7 – (a) Pushover curves of RC frame considering perfect contact and interface nonlinearity with: (a) 25% infill height, (b) 50% infill height and (c) 75% infill height (d) Damage level in partially infilled frame (75% infill height) at specific points on pushover curve

Table 2 – Lateral stiffness of RC frame with perfect contact and interface nonlinearity

Sl. No.	**Percentage of Infill Height**	**Types of Frame**	**Percentage of Infill Height**	**Lateral Stiffness, (k_i) (kN/mm)**		**Ratio of Lateral Stiffness (k_{ip}/k_{in})**
				Perfect Contact (k_{ip})	**Interface Nonlinearity (k_{in})**	
1	100	Fully Infilled Frame	100	470.6	42.7	11.0
2	75	Partially Infilled Frame	75	100.1	29.0	3.5
3	50		50	30.8	10.3	3.0
4	25		25	12.9	9.3	1.4
5	0	Bare Frame	0	7.0		---

5.2.2. Effect of infill height

To evaluate the effect of infill height on the response of frame, pushover curves of bare frame and infilled frames with interface nonlinearity are compared in Fig.8a. The stiffness degradation of frames is observed with decrease in infill height (Fig.8a). Reduction in frame stiffness with respect to stiffness of fully infilled frames is plotted in Fig.8b. The lateral stiffness of bare frame was found to be 0.16 times of lateral stiffness of fully infilled frame. In case of partial infilled frame with 25%, 50% and 75% infill height, the lateral stiffness were found to be 0.22, 0.24 and 0.68 times respectively, as compared to fully infilled frame. The lateral stiffness of all the frames was compared with fully infilled frame and the percentage reduction of stiffness of infilled frame with respect to the fully infilled frame is shown in Table 3 and their ratio is plotted in Fig.8b. As expected, lateral stiffness of partial infilled frame were found to be less than that of fully infilled frame but more than that of bare frame. It means partial infilled frame is stiffer than bare frame but more flexible that the fully infilled frame. It can also be observed that the stiffness of partially infilled frames reduces with reduction in infill height.



(a) (b)

Fig. 8 – (a) Pushover curves of bare frame (0% Infill), (b) Stiffness degradation with decreasing infill height (Partial infilled frames with 25%, 50%, 75% and 100% infill)

Table 3 – Lateral stiffness of RC frame with different percentage of infill

Sl. No.	**Percentage of Infill Height**	**Types of Frame**	**Lateral Stiffness, ki (*kN/mm*)**	**Percentage Reduction in Stiffness** $\frac{k_{if}-k_i}{k_{if}}\times 100$
1	100	Fully Infilled Frame	42.7	0.0
2	75	Partially Infilled Frame	29.0	32.1
3	50		10.3	75.9
4	25		9.3	78.2
5	0	Bare Frame	7.0	83.6

Note: k_{if} is the lateral stiffness of fully infilled (100%) frame

6. Summary and conclusions

Infill walls in reinforced concrete framed buildings are generally considered as nonstructural elements even these are subjected to lateral loads. Sometimes infills walls are constructed up to a limited height of column to provide more lighting and ventilation especially in the corridor of public buildings like schools, hospitals, *etc*. These openings not only reduce the strength and stiffness of the frame as compared to fully infilled frame but also caused captive column and short column effect in RC frame. In the present study, finite element analysis of partial infilled frame with different height of infill are carried out in open source code OpenSees. In the analysis, nonlinear behaviour of frame elements are modelled while infills are assumed to be linear elastic. Separation and sliding at the frame-infill interfaces are also modelled.

The following conclusions are made based on the analysis in the present study:

- The partial infilled frame have more lateral stiffness and strength as compared with bare frame. The plastic hinges are formed in columns at a height of infill.
- In partial infilled frame, the lateral stiffness of RC frame decreases with decrease in infill height.
- Separation and sliding at frame-infill interfaces has an important role in reducing stiffness of infilled frame. Therefore, separation and sliding between infill and frame should be considered in the analysis of both partially infilled frame and fully infilled frame.

The present study may further be extended by considering nonlinearity in infill for better understanding the behaviour of partial infilled frame. Moreover, the rigorous analysis can be performed in 3D finite element model. Further study can be done for equivalent diagonal strut analysis of partial infilled frame.

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