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Influence of Brick Masonry Infill Walls on Seismic Response of RC Structures

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Abstract- Finite element modelling and analysis of three bays three stories, two-dimensional reinforced concrete (RC) frame were performed to evaluate the seismic performance of structures with infill masonry assuming the structure to be constructed in the seismic zone 3, according to the building code of Pakistan. Two types of Masonry RC frames were modelled, first with full infill walls (FIF) and secondly with a soft story (SSF) at ground floor. Subsequently, the analytical results were compared with that of the performance of the bare frame (BF) model, considered as reference. FEMA and ATC 40 guidelines were used to include the effect of masonry walls. The overall performance of all three models were evaluated in terms of the fundamental modal time period, maximum inter-story drift ratio (MIDR), relative displacement (RD), stiffness, and performance points as per ATC 40 capacity spectrum method. The study confirmed that the structural performance of full masonry infill walls frame model (FIF) was better than the other two. The study also revealed that the single strut model was unable to capture the real behaviour of the infill wall in RC structures, favouring the use of multi diagonal struts macro modelling techniques.

Keywords- Stiffness, ductility, Full infill Frame, Soft Story, Bare Frame, Unreinforced Masonry (URM).

I. Introduction

Infill masonry walls in reinforced concrete (RC) frame structures are considered as non-structural elements during the modelling stage. When RC infill frame structure is subjected to seismic action, Infill walls significantly influence the seismic behaviour. These systems contribute towards stiffness and strength even at small drift levels, consequently improving the overall seismic behaviour of the structure [1]. The relative stiffness, strength between frame materials and infill panel, pre-cracking of bricks in infill walls, poor workmanship etc. are the factors which endorse the complexity of modelling infill walls thus making difficult to describe efficient approach of RC infill frame analysis. Moreover, the quality, proper arrangement of bricks and workmanship play significant role in the global seismic performance of infill panel and its failure mode [2]. Another study suggests that brick anisotropy and panel slenderness must be considered while performing design of new structures and assessment of existing structures [3]. The effect of infill wall is omitted in finite element modelling to avoid complex calculations and procedures consequently to save time and efforts [4]. Considering infill walls as non-structural elements, leads to underestimated stiffness, strength and can give higher demand for seismic design [5]. Nevertheless, the presence of infill walls has the reasonable effect on improving the stiffness and lateral bearing strength [6]. Furthermore, in RC structures non-structural masonry infill walls tend to considerably modify the global seismic behaviour, displacements and base shear of framed buildings [7]. Previous research suggests that the regular distribution of infill walls both in elevation and plan improves the seismic performance of overall structures in term of story displacement, stiffness and drift ratios [8]. Infill panel if provided in a regular fashion have beneficial influence on the global behaviour of RC buildings especially from seismic perspective with respect to strength and stiffness [9]. The response spectrum analysis of frames shows that infill panels tend to reduce the fundamental time period of the structure which leads to affect the level of the demand forces on the structure [10]. Furthermore, the structural performance of RC frames during strong ground motion improves in the presence of adequate infill walls on the other hand the soft storey causes several unpredictable and undesirable damages [11]. Besides the increase in the percentage of opening in the infill RC frame structure leads to decrease in the lateral stiffness of the infill RC frame structure [12]. Another study also concluded that the RC frames with infill walls perform satisfactory even during strong ground motions, moreover the study suggests that the infill walls with opening are more vulnerable than solid infill walls [13]. On the contrary, irregular distributions of masonry infill walls in elevation can result in unacceptably elastic displacement in the soft storey frame. Thus, unreinforced masonry (URM) should be considered both in analysis and design phase of RC structures to fully exploit their modified strength and ductility [14]. The effect of masonry Infill walls should be considered in progressive collapse design to accurately predict the stiffness strength and failure modes of infill RC frames. The experimental and analytical results also indicated that Infill walls with low height/span ratio may fail in splitting of the equivalent compressive struts prior to crushing [15]. Another experimental study that was supported by photogrammetry analysis revealed that infill walls increase the load carrying capacity of RC frames [16]. Arrangement of the infill panels over the elevation can influence the performance of RC frames. Specially infill discontinuities at ground level can cause capacity degradation [17].

Guidelines [16,17,18,19,20] covers some procedures for calculations of infilled frame stiffness, which can be done by modelling infill walls as "equivalent diagonal strut method". The nonlinear static pushover analysis which is described in references [18],[19] and [21] are now very useful tools for professional and structural experts for estimating seismic demands of RC buildings.

This paper incorporates the current state of knowledge to explore the further aspects of modelling infill masonry and RC frames together. Finite element modelling of three types of frames: Full Infill Walls (FIF), Bare Frame (BF) and Soft Story (SSF) was performed. Non-linear static pushover analysis was performed to evaluate structure behaviour in terms of fundamental mode, inter storey drifts, relative displacements, stiffness, performance points, and target as well as global ductility. Consequently, the study suggests that by considering the effect of infill masonry in finite element modelling of RC frame smarter, safer and cost-effective structural designs can be obtained.

II. METHODOLOGY

The aim of the study is to investigate the seismic performance of RC infilled frame structure and the influence of masonry infill walls in seismic performance of structure. Moreover, it also concludes the reliability of single compression model described in refence [21] for infill wall modelling.

In this study non-linear static pushover analysis as per reference [22] capacity spectrum approach was performed on three types of frames to investigate the performance point of individual model.

Furthermore, to capture non-linear behaviour backbone curves as provided in SAP2000 software [23] were used for all structural elements. Performance of each model was than evaluated in terms of fundamental mode, inter storey drifts, relative displacements, stiffness, performance points, and target as well as global ductility.

III. MODELLING

This section elucidates various aspects of modelling and analysis.

A. Model Description and Loading

An interior 2D frame is extracted from a three-storey frame structure having overall plan dimensions of 10m x 8m. Constant inter story height of 3m and the columns apart from each other in X direction with the spacing 4.5m, 2m and 3.5m respectively. Whereas the columns are spaced at equal distance of 4m in the orthogonal i.e. Y direction as shown in Figure 1.

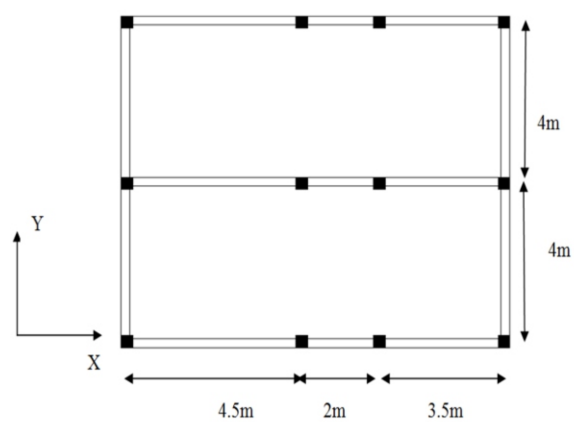

Figure 1: Floor plan of the prototype building

The frame was modelled with three options as shown schematically in Figure 2. Full infill masonry (FIF) was modelled to study the effect of masonry infill. Another frame was modelled without incorporating the masonry effect at ground floor level and was named as soft story frame (SSF). A bare frame (BF) without masonry was modelled and analysed as reference for comparison purpose.

In all frames Cross-sectional dimensions of beams and columns were 30×50cm and 30×30cm respectively. Beams were reinforced with two sets of three 18mm plus two 12mm diameter longitudinal bars each on top and bottom face. Furthermore, as a shear reinforcement 6mm diameter stirrups were provided at 150mm spacing. Columns were reinforced with four 18mm diameter main bars and confined with 6mm diameter ties at 150mm spacing.

Applied loads on structure and materials properties both for frame and brick masonry infill walls material are shown in Table 1.

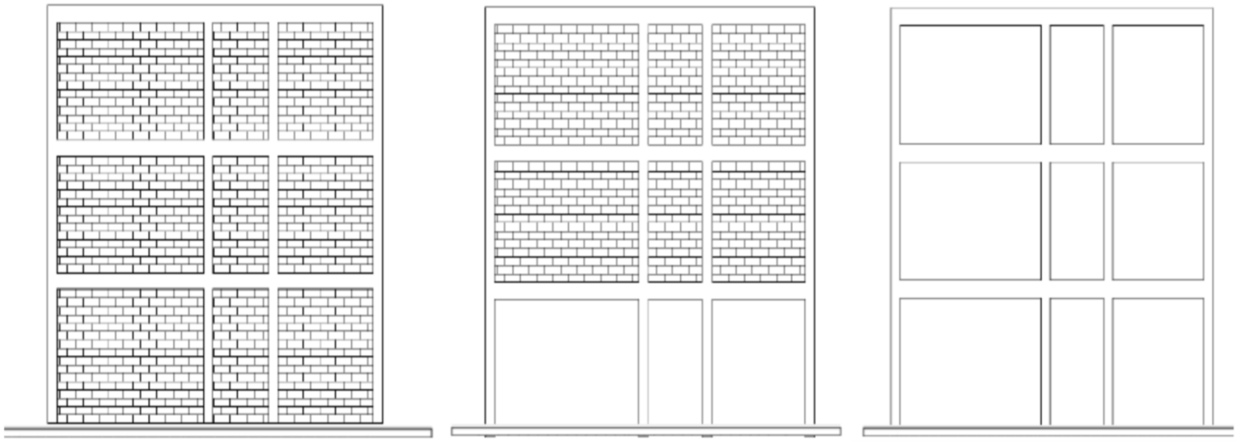

Figure 2: Left to right. Option 1(FIF) option 2(SSF) and Option 3(BF) type frame

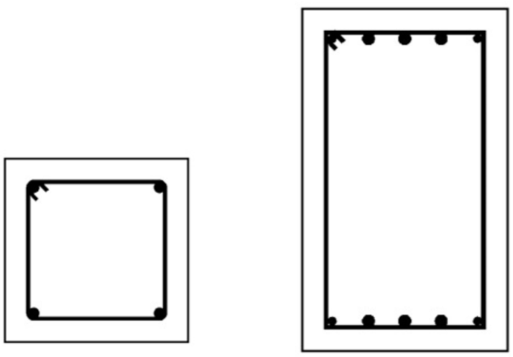

Figure 3: (a) Cross Section of square column 30 x 30 cm (b) Cross section of beam 30 x 50 cm, having concrete cover for all columns and beams 3.81 cm

Table 1: Applied loads and material properties

Type of Load	(KN/m)
Live load	3
Dead load including masonry load	42
Dead load on the top floor beams	28.6
Materials Properties	
Elastic Modulus E_{fe} for steel	29 GPa
Compressive strength of concrete	15.52 MPa
Compressive strength of masonry	4.14 MPa
Modulus of elasticity of masonry	2277 MPa
Rebars used in columns and beams were plain bars having yield strength	0.14 GPa

B. Codes Recommendations

The *Eurocode 8* (EC 8) [24] advices that the fundamental time period of the structure to be used for calculating base shear should be the average of the bare frame and infilled frame. Frame members demand are then calculated by treating the frame structure without infill walls. It also addresses the irregularities both in plan and elevation.

References [18,21] contains method to evaluate the seismic response of the structures with infill walls. According to the procedure, masonry infill panel should be replaced by equivalent diagonal strut, place either eccentrically or concentrically in order to evaluate the effect of infill walls on the adjacent columns. These documents also provide the acceptance criteria of deformation of masonry infill panels.

C. Guidelines for finite element Modelling of infill walls

The FEMA 356 [21] guidelines propose the geometry property of a strut having an area equivalent to the thickness "t" time of the width "a" of the infill wall panel as presented in equation 1,2 and 3, in equal units. Moreover, the term λ_1 is dimensionless

$$a = 0.175(\lambda_1 h_{col})^{-0.4} r_{inf}$$

$$V_{ine} = A_{ni} f_{vie} \quad V_{ine} = A_{ni} f_{vie} \tag{4}$$

Where;

h_c = Height of columns

h_{inf} = Infill wall height

E_{fe} = Elastic Modulus of frame material

E_{me} = Elastic Modulus of infill wall material

I_{col} = Columns' Moment of inertia about the axis perpendicular to the loading direction

L_{inf} = Infill panel Length

r_{inf} = Diagonal length of infill panel

t_{inf} = Thickness of infill panel and equivalent strut,

θ = Angle in radian of the infill panel of equivalent strut

A_e = Cross section area of infill

A_{ni} = Net area mortar/grouted section across infill panel

f_{vie} = Expected shear strength of masonry infill not to exceed the expected masonry bed-joint Shear strength v_{me} as defined in Equation (5)

V_{ine} =Shear strength of masonry infill panel

$$v_{me} = 0.75\left(v_{te} + \frac{P_{CE}}{A_n}\right) \tag{5}$$

Where;

v_{te} =Average shear strength of bed-joint

P_{CE} =Expected gravity compressive force applied on

the URM infill wall
A_n = Net area of infill wall with mortar
Moreover, the guidelines presented in reference [21] also describe the nonlinear maximum drift ratio "d" with respect to the unexpected loss of the horizontal strength of infill wall. The drift "d" is defined corresponding to the height of the infill for different values of infill aspect ratio as well as infill to frame shear strength ratio.
Non-linear behaviour of elements (beam columns and infill struts) was captured by assigning backbone curve (Non-linear hinges) to them as per refence [21]. For beams and columns SAP2000 software [23] automatically generates code compliance hinges. The backbone curves for beams and columns is shown in Figure 4 and for infill walls in Figure 5.

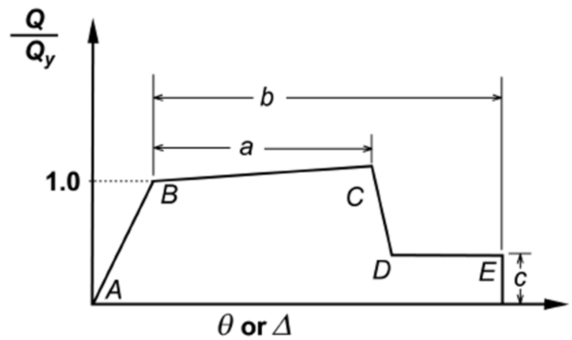

Figure 4: Plastic Hing Property/ Nonlinear back bone curve for beam and columns by FEMA 356 [21]

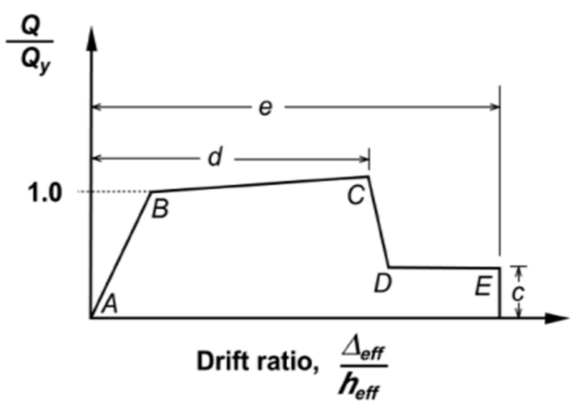

Figure 5: Plastic Hing Property /Nonlinear back bone curve for the infill compression strut model by FEMA 356 [21]

Displacement control parameters are described in Table 2, for elements like beams, columns and infill masonry. Acceptance criteria for beams and columns elements are plastic rotation, and plastic deformation respectively. Whereases for infill strut the acceptance criteria is plastic displacement. Corresponding values for immediate occupancy (IO), life safety (LS) and collapse prevention (CP) are also provided in table 2.

Table 2: Program auto-generated non-linear hinge Properties

Point	Beam		Column		Infill strut	
	Moment /S.F[4]	Rotation /SF	Moment /S.F	Rotation / SF	Moment /S.F	Rotation / SF
E-	-0.2	-0.05	-	-	0	-1
D-	-0.2	-0.025	-	-	0	-1
C-	-1.1	-.0.025	-	-	-1	-1
B-	-1	0	-	-	-1	0
A	0	0	0	0	0	0
B	1	0	1	0	1	0
C	1.1	0.025	1.1	0.05	1	1
D	0.2	0.05	0.2	0.015	0	1
E	0.2	0.05	0.2	0.025	0	1
			Acceptance criteria			
IO[1]		0.01		3.00×10^{-3}		0.3782
LS[2]		0.02		0.012		0.7563
CP[3]		0.025		0.015		0.85

Immediate Occupancy[1], Life Safety[2] ,Collapse Prevention[3] Scale Factor[1]

It is pertinent to mention here that, due to high variability of walls section type and materials properties of masonry infill walls, automatic generation of nonlinear hinges properties for infill walls in finite element structural program i.e. SAP2000 [23] is not possible. In order to capture the nonlinear behaviour of the infill walls, a user defined back bone curve in compliance to FEMA 356-2000 [21] was assigned to infill struts in the finite element model. The value of different points of A, B, C, D and E must be symmetric both in positive as well as negative axis but with different user defined performance levels i.e. immediate occupancy, life safety and collapse prevention with respect to compression loading as shown in Table 2.

D. Analysis
Based on nonlinear static pushover analysis, capacity curves were developed for all three models. These curves along with the Hing locations are shown in figures 6, 7 and 8 for bare frame, soft storey and full infill frame respectively. Performance points for BF were 47mm and 116kN. Additionally, the BF frame was ductile but less stiff compared to SS type frame.

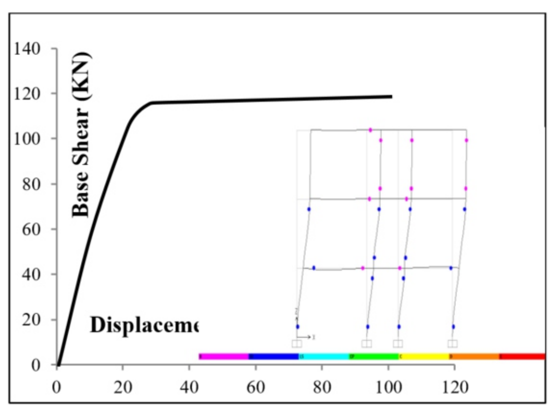

Figure 6: Pushover Curve of Bare Frame Model

According to figure 7, roof displacement for SSF type was 53mm at 126 kN base shear. Furthermore, overall failure of the model occurred as soon as the shear capacity of ground floor columns exhausted. Although columns must take same amount of load as in case of BF frame but due to absence of infill walls at ground floor level and resulting soft story mechanism the "K" value was 69% higher than that of BF type frame.

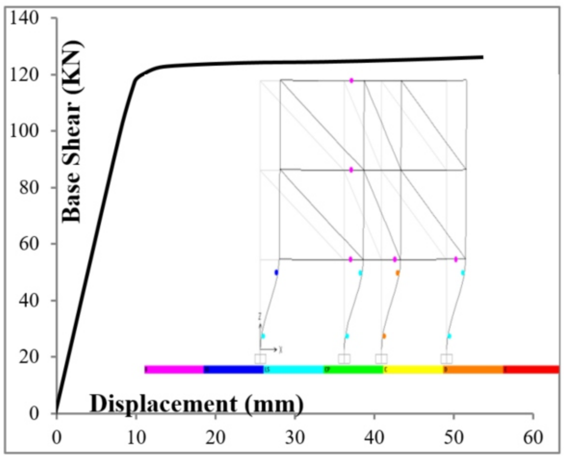

Figure 7: Pushover Curve of the Soft Story Frame Model

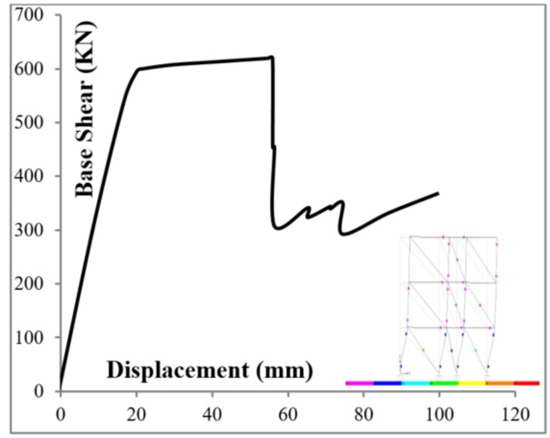

Figure 8: Pushover Curve of the Full infill Frame

Figure 9 compares the performance curves of all frames with the demand spectra proposed by ATC- 40 [19]For the same seismic loading, the behaviour of FIF type frame was fragile and stiffer than the other two cases due to additional strength imparted by masonry struts. Consequently, the stiffness value was 7.74 and 4.6 time the values of BF and SS type frames.

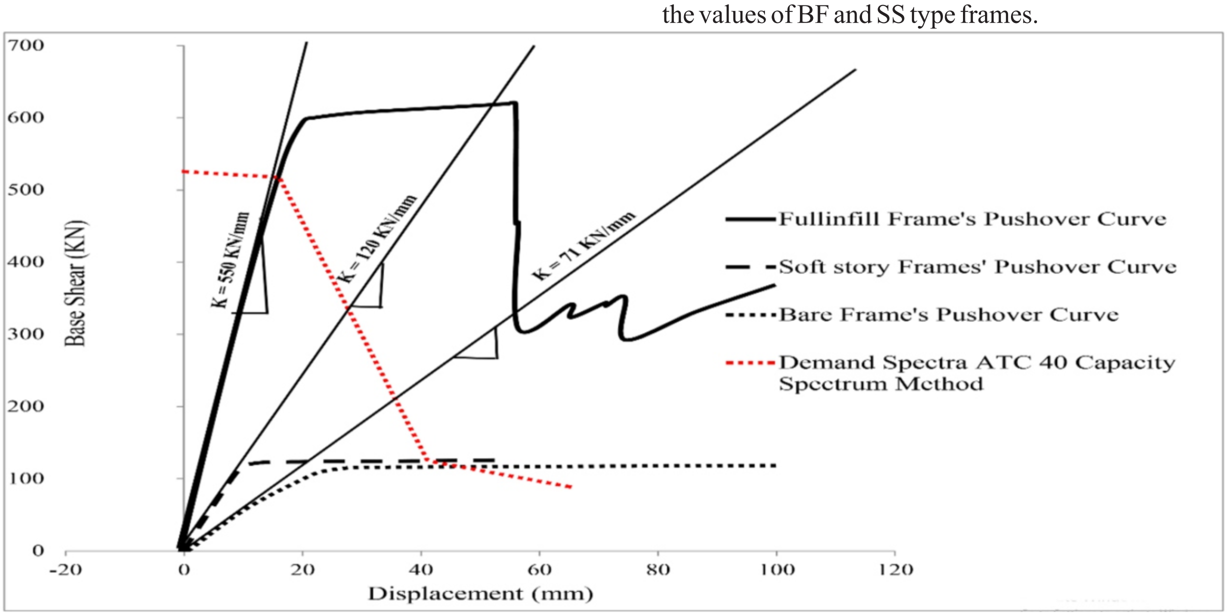

Figure 9: Combined Pushover Curve of three Different Frames Models

Pushover Curve for full infill walls frame model is shown in figure 8. The initial stiffness and strength of the model was 7.75 and 4.47 times the BF type frame owing to infill affect yet the curve shows the fragile behaviour. Further study of the results revealed that the significance loss of the capacity curve was due to the failure of infill walls at the ground storey level after 9th step of load increment in the pushover analysis. Likewise, according to ATC-40 capacity spectrum method the structure performed well up to 16 mm roof displacement at the base shear of 519 KN.

This concludes that the structure can be redesigned with more economical elements using smaller member cross-sections and lesser steel area. Additionally, considering RC frames as normal frame i.e. neglecting infill walls, leads towards underestimation of the base shear because structure with infill walls reduces the fundamental time period of the structure therefore have higher lateral force attraction.

The infill walls at ground level with symbols left side (L), middle (M) & right-side infill wall (R) as shown in figure 10 are found critical because the failure of these

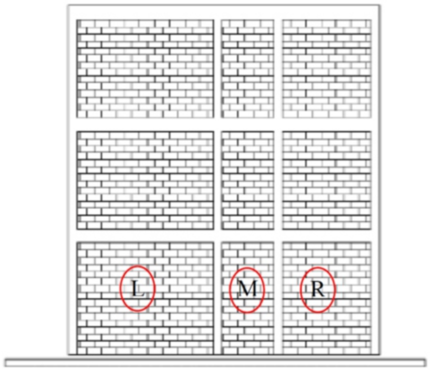

Figure 10:: Critical Infill walls at the base of FIF model, R= Right side infill walls, M=middle infill walls and L=Left side infill walls

infill walls. The influence of infill walls in the overall seismic performance of frame is further discussed and highlighted in the figures 11 and 12.

Figure 11 shows the relationship between accumulative axial forces taken by the critical infills walls at the base of FIF model, and corresponding roof displacements.

Analysis results show that the wall displacement increased with the increase in axial force. Eventually the frame failed due to failure of left side wall at 312kN force and 56mm displacement. The fragile failure (sudden drop of the pushover curve shown in Fig. 8) of the FIF model causes the failure of the infill wall.

The contribution of infill walls in form of axial force taken by the critical infill walls at the base of FIF model and corresponding shear force in columns at each load increment step is shown in Fig. 12. The values of shear force for the base columns are presented in positive quadrant and the corresponding values of axial force taken by infill walls are presented in the negative quadrant. As shown in Fig. 12, the load path shifted from infill to columns after the increment of lateral loads at 9th step of pushover analysis.

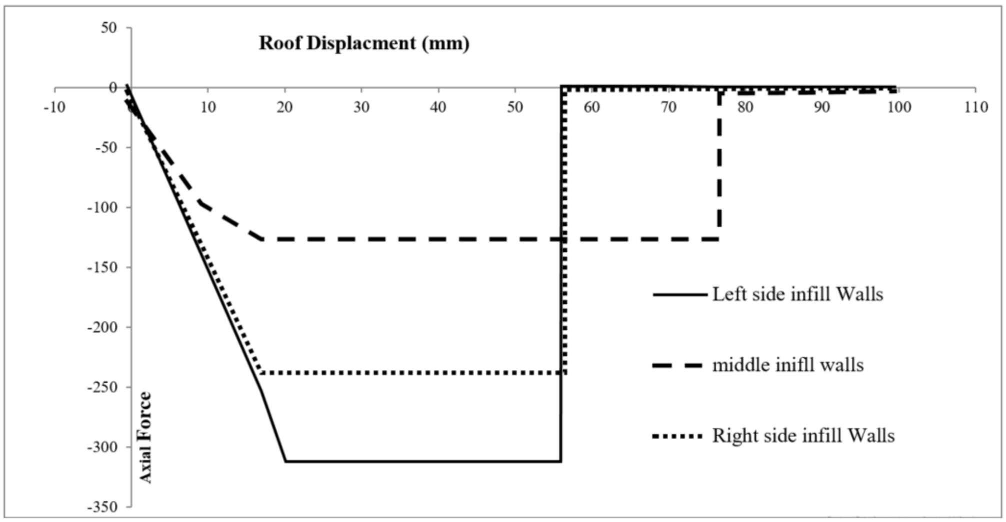

Figure 11: Axial Forces in the Critical Infill walls

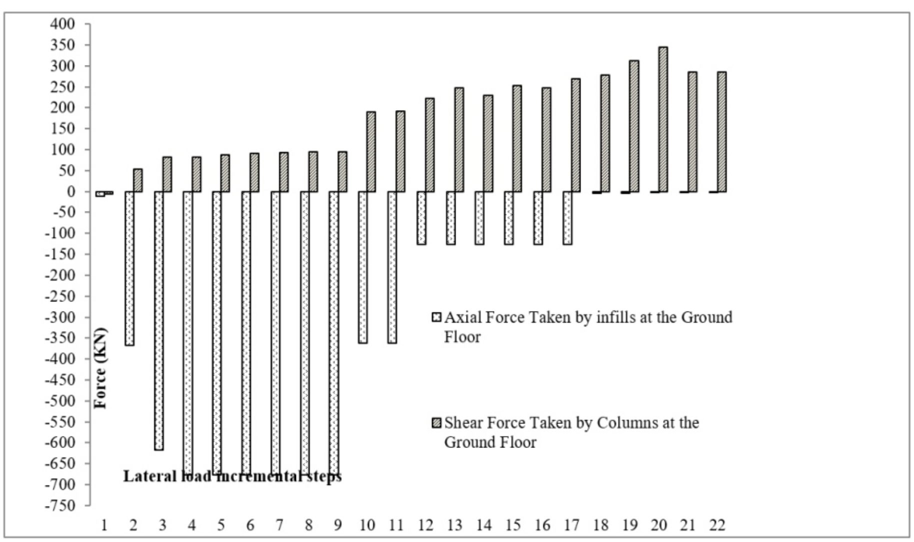

Figure 12: Axial Force Taken by infill and Shear Forces taken by columns at Ground Floor

VI. Summary and Analysis

This section discusses the performance of each type of frame in terms of fundamental mode, inter storey drifts, relative displacements, stiffness, performance points, and target as well as global ductility discretely.

A. Fundamental Mode
Correct estimation of time period of structures is important because it forms bases for the calculation of base shear and afterwards determination of seismic lateral forces for the structure. Indeed, Infill masonry has considerable effect on the fundamental mode period. The value for FIF was 0.38 seconds which was 57% less than that of BF and 47 % lesser than that of the value of SSF.

B. Maximum Inter-story Drift Ratio (MIDR)
Due to soft story effect SSF type frame showed maximum drift ratio of 1.7% at first floor level and minimum for FIF type frame i.e. 0.235%. Whereas for BF it is 4.5 time the FIF type frame and its value is 1.05%. Furthermore, due to soft story effect the observed MIDR in SSF was 7.2 times the BF.

C. Relative Displacement (RD)
In FIF frame RD increased linearly up to 1mm. In SSF the relative displacement of the ground and first storey had high variation between 20mm and 43 mm. whereas In BF type frames the Ground and first floors displace relative to each other showed variation from 10 mm to 16.5 mm respectively. Moreover, as compared to BF model, RD for SSF model increase by 254% and for full infill walls it decreased by 85%.

D. Stiffness
There is remarkable increase in the stiffness of frame if masonry infill is considered. Improvement in FIF type frame was 7.7 times and 4.6 times the stiffness of BF and SSF respectively.

E. Performance Point (PP)
Performance points (PP) for FIF type frame was significant as compared to other types of frames. The PP were determined as per ATC-40 capacity spectrum method [22]. For FIF frame PP were at 16 mm displacement corresponding to the Base Shear of 518kN. However, for SSF at 41 mm displacement corresponding Base Shear was 125kN. Furthermore, for BF type frame the PP were at 47 mm and 116kN. Base shear of soft story and full infill frame was changed significantly, and the observed increase was 7.75% and 346.55% respectively.

F. Target Displacement (TD)
Target Displacement was calculated according to FEAM-356 Coefficient method [21] and because of the presence of infill walls at each floor of FIF type frame the stiffness increases and TD value decreases 40% of the BF. The obtained values for BF, SSF and FIF type frames are 160mm, 117mm, and 96mm respectively.

G. Global Ductility (GD)
Global ductility for FIF was 2.8 and failure was due to yielding of infill and columns. In SSF type frames collapse mechanism was formed due to failure of columns at ground story and GD for this frame was 5.4. In BF type frame the collapse mechanism was due to failure of columns and beams at GD value was 9.6.

V. Conclusion

Finite element analysis was performed for three models considering three frames conditions. Bare frame (BF), Frame considering masonry effect at each floor (FIF) and frame with no masonry at ground floor level to simulate a soft story (SSF). Analysis results confirmed that incorporating the masonry in finite element modelling effects the structure behaviour in terms of fundamental mode, inter storey drifts, relative displacements, stiffness, performance points, and target as well as global ductility. Results confirm that the performance of full masonry infill walls Frames was significantly to that of bare frames and soft storey frames.

Conclusions of the study are summarized below: -

1. Time period for FIF was 0.38 seconds which was 57% and 47 % less for BF and SSF respectively.
2. MIDR for BF model was 4.5 times the FIF model. Furthermore, due to soft story effect the observed MIDR in SSF model was 7.2 times the BF.
3. As compared to BF model, RD for soft story increase by 254% and for full infill walls it decreased by 85%. Improvement in FIF type frame was 7.7 times and 4.6 times the stiffness of BF and SSF respectively.
4. From the analysis results it has been found that treating an ordinary bare frame i.e. without consideration the effects of infill walls leads underestimation of base shear. The SSF and FIF model depicted a 7.75% and 346.55% rise respectively as compared to BF model. Performance points (PP) for FIF type frame was significant as compared to other types of frames.
5. Target displacements and global ductility were also decreased in FIF model.

In conclusion, Unreinforced Masonry (URM) infill walls have great influence in altering the strength as well as ductility of the reinforced concrete frame structures. Therefore, their role must be considered for assessment of existing structures and design for new one. Due to the influence of infill walls the structure become stiffer, reduces the fundamental time period and increase the coefficient of damping which affect the level of demand forces and displacement on the structure. Due to high relative stiffness, FIF frames act as the main lateral load-resisting system and attract larger portions of the earthquake-induced inertial forces. In addition, the floor diaphragm acts as load path and transfer inertial forces to URM infilled frame however due to the presence of infill walls the level of demand forces increases both for diaphragm and frame structural elements, therefore the frame as well as floor system should be sufficiently designed for such increments of demand forces.

Though the single strut model is simple, easy to apply and requires less computational efforts, but it is clear from the analysis and results that the shear force and bending moment in the RC frame can't be sufficiently transferred to the single strut, linked with two loaded corners. Therefore, it is recommended to use multi diagonal struts macro-modelling techniques in order to capture the real behaviour of the infill wall panel when subject to earthquake loading.

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