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ANALYTICAL STUDY ON NONLINEAR PERFORMANCE OF RC TWO BAY THREE STOREY FRAMES WITH INFILL

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ABSTRACT

The reinforced concrete (RC) moment-resisting frames with masonry infill walls is widely used in buildings. In this study, two-bay and three-storey RC Bare Frame (BF), RC Infill frame (IF) with Cement mortar (CM) interface combinations scaled to a factor (1:6) are analyzed. The objective is achieved by analytical studies. To investigate this, we modelled the behavior of frame structures with masonry IF in two ways such as a linear method and Pushover (PO) method. It is found that with the addition of masonry infill wall rigidly connected to the frame, the lateral strength, the stiffness of the BF RC frame increase significantly while the displacement ductility ratio decreases significantly. Numerical simulation of the BF and the IF frames is done with SAP2000 (Structural Analysis Package) a Finite Element Method (FEM) based software.

Keywords: Bare frame; infill frame; interface; linear; nonlinear; lateral stiffness.

1. INTRODUCTION

Masonry Infill RC frames are very commonly seen in most of the part of the world. Primary reasons for the same are easily available construction materials, good insulation properties of masonry wall against heat and electricity, and the traditional practices in some cases. Under the lateral loads, caused by earthquakes, the response of such structures may be quite unpredictable, owing mainly to the brittle nature of IF walls.

Past earthquakes have demonstrated the vulnerability of IF RC frames such as short-column effect, soft-storey effect, torsion and out-of-plane collapse. It is evident that the presence of infill walls can significantly enhance the lateral stiffness and strength of RC frames and result in a good energy dissipation capacity of the structure. The IF walls are not considered in design as the final distribution of these elements may be unknown to the engineers, or because masonry walls are regarded as non-structural elements.

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Separation between masonry walls and frames is often not provided and, as a consequence, walls and frames interact during strong ground motion. This leads to structural response deviating radically from what is expected in the design. These are some of the negative effects of using IF frames. The IFs may cause a devastating effect if their arrangement results in a soft storey, especially in the ground floor. In addition, interaction between frame and IF may result in shear failure in frame members depending on the relative strength of frame and IF.

A very strong IF may result in a brittle post-peak behaviour besides causing shear failure in frames. However, force deformation behaviour of frames with stronger IF may be better than weak IF even if shear failure takes place in columns.

The following potentially negative effects of infill walls on the failure mode of RC frame structures should be considered: torsional effects induced by irregular arrangement in plane, soft-story effects induced by irregularities in elevation, short-column effects due to openings, and concentration of forces in elements of the frame due to the connection with the infill wall. The failure modes referred from [1] which may occur in infill during lateral loading is shown in Fig. 1. and Fig. 2.

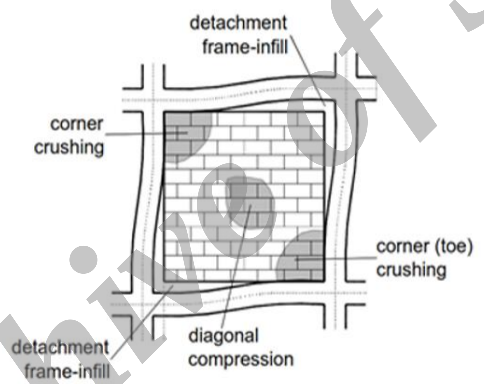

Figure 1. The corner crushing (CC) mode the diagonal compression (DC) mode

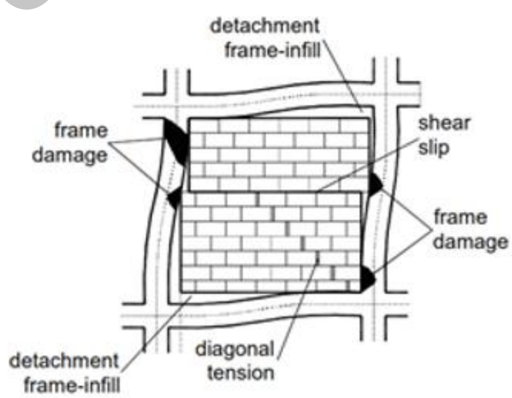

Figure 2. The sliding shear (SS) mode, the diagonal cracking (DK) mode, The Frame Failure (FF) mode

2. SUMMARY OF LITERATURE

In order to access and to critically evaluate the research work done on the IF frames, a detailed review of literature has been undertaken. From the literature survey it is evident that IF improves the strength and reduce the ductility behavior of the structure. Jiang [2] has said that the Seismic performance of the IF frame with flexible interface falls in between the BF and IF frame with rigid interface. Leslie [3] has clearly explained the pushover analysis theoretically and practically using SAP2000 as the analysis tool for a multistoried building. Niruba [4] has found that treating RC frames as ordinary frames without regards to IF leads to underestimation of base shear. For different scaled models the base shear increases with rigidity of the IF. Asteris [1] has indicated that the failure modes of the in-filled frames can be classified into distinct modes (Crack patterns). Satyanarayanan [5] has shown in his Thesis that a one-sixth scale model of three-storeyed, two-bay three dimensional frame model has been experimented and analyzed for linear analysis. Bose [6] has found that IFs also influence the hysteretic dissipation capacity of the frames. Cavaleri [7] studied a strategy for assessment of the cyclic response of IF frame systems were. Energy dissipation curve during repeated straining can be measured from a load–deformation curve. SAP 2000 is used to get the load deformation values. Hence the Energy dissipation curve can be prepared. Kaushik [8] said that the influence of IF plays a major role in the seismic response of the building. For scaled models struts need not be used as IF walls acts as a strut in modeling. Umarani [9] has found that the strength, stiffness and energy absorption capacity of the infilled test units are much higher than those of the bare RC frame. She also stated that the stiffness decrease rapidly following the cracking in frame and infills.

2.1 Research significance

During earthquakes the real situation is that the masonry IF walls will resist some lateral forces. When an IF frame is subjected to lateral loading, the IF behaves efficiently as a strut along its compression diagonal to brace the frame. Hence it is necessary to study the influence of different IF materials on the properties of IF frames. The behaviour of RC IF frames with Brick Masonry IF under lateral loads is studied experimentally and analytically by a number of researchers in the past [10]. The present codes unfortunately don't have adequate guidance for the analysis and design of masonry IF frame structures. The analytical approach in introducing interface in IF has to be made. Linear and nonlinear analysis is done in BF and IF frame and then the modelled results are compared.

3. METHODOLOGY

The objective of this research work is to study the IF behavior of two bay three storeyed RC BF and IF. The scope of this analytical study is achieved by using SAP2000 (FEM based software) for 1:6 scaled RC 2D IF and BF. Numerical analysis of models will be carried out. IF forms a major role in seismic response of a building since not much knowledge is yet gained on the topic. Hence, this topic is chosen. Theoretical knowledge about the topic and the work to be done is gained from reading several journals [11]. The modelling of BF and IF frame is done in FEM based software. The material properties for modelling are achieved from experimental data achieved from the testing of the specimens. Linear analysis is done for both the BF and the IF frames. Nonlinear analysis using Push over analysis is done for better clarity of the frame behavior.

3.1 Creating model in CAD

The Dimensions of each member is given in Table 1. The CAD drawing showing IF frame details are given in Fig. 3.

Table 1: Member specifications

Member of frame	Dimension, mm		
	Height	Width	Depth
Column of ground floor	400	100	75
Column of other floor	325	100	75
Beam on other floors	75	325	75
Beam on top floor	75	425	75
Beam on ground floor	300	1400	250

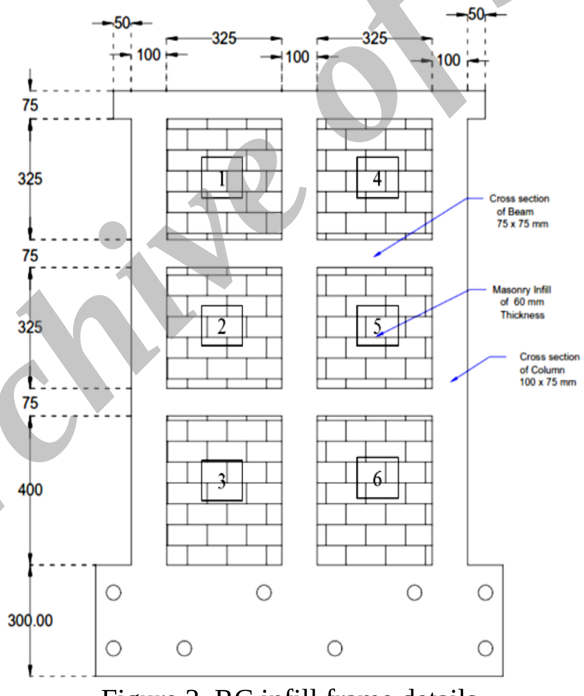

Figure 3. RC infill frame details

3.2 Properties of specimens

Companion Specimen Testing works are undertaken for calculating the material property to be used in the FEM based software. The mix design is carried out for a characteristic compressive strength of 20 N/mm^2 at 28 days using Indian Standard method, IS 10262 - 2009. The mix proportion used is 1: 1.435: 2.782 by weight of cement, sand and coarse aggregate with water cement ratio 0.55 for casting all the specimens. For CM IS 4326 recommends minimum 1:6 mix proportion of cement and sand.

The compression test of cubes was done in Compression testing machine and it is found to be 23.49 N/mm^2. The Modulus of elasticity of concrete cylinders was done using an Extensometer with a dial gauge arrangement and it is found to be 19.549x10^9 N/m^2. The modulus of elasticity of brick masonry was found using DEMEC strain gauge and it is found to be 18.635x10^9 N/m^2. The compression test of cylinders, prisms and their graphical representation is given in Fig. 5 and Fig. 6 respectively. The test setup and snaps taken during the Companion Specimen Testing is shown in Fig. 4.

Figure 4. Companion specimen testing snaps

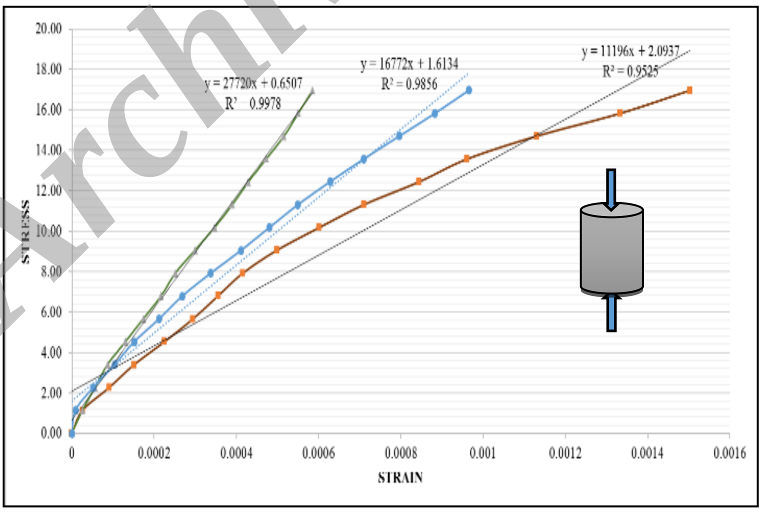

Figure 5. Modulus of elasticity of cylinders

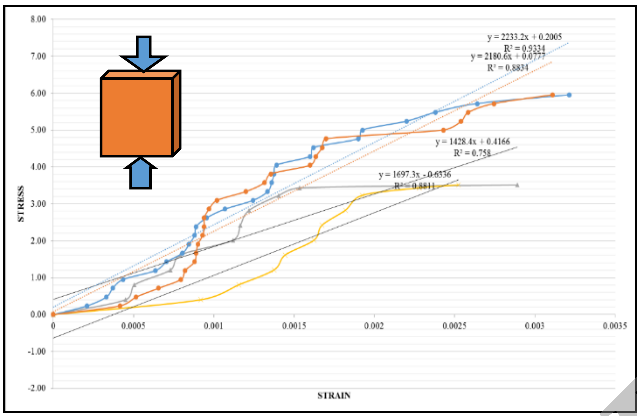

Figure 6. Modulus of elasticity of Prism

4. ANALYTICAL STUDIES

Finite element analysis can also be used to model the behavior numerically. Finite element analysis, as used in structural engineering, determines the overall behavior of a structure by dividing it into a number of simple elements, each of which has well-defined mechanical and physical properties. Modeling the complex behavior of RC, which is both non homogeneous and anisotropic, is a tedious task in the finite element analysis. Hence for simplified modelling, finite element based software is used.

4.1 Modelling of bare frame

Material properties and frame member properties are assigned. The beams and columns are assigned as line elements. The base beam column joints are assigned with fixed restraints. The BF is two bay, three storeyed RC frame. The model created is a scaled model of an actual prototype building scaled to a factor of 1:6. The reinforcement details are inputted appropriately in frame properties for beams and columns. The 3D BF modelled in sap is shown in Fig. 7.

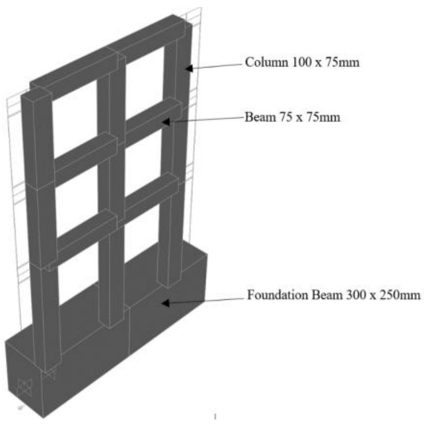

Figure 7. 3D bare frame

4.2 Modelling of infill frame

The bare frame modelled before is taken. The IF is modelled in the FEM based software by discretizing the area element in the three storeys with 8 x 8 divisions. The interface at top and bottom of an area element is divided as 8x1 and the interface at left and right of the brick masonry IF as 1x8 divisions. The brick masonry and the BF RC frame has to be connected with link elements with a stiffness value of 100 N/m based on the convergence. In this case springs with a are used for effective transfer of stresses from frame to the IF. Without the links the frame and the interface, the IF combination is unique and doesn't act as a single unit .The models are discretized to understand the behavior of the frame with more clarity. This discretization is done in other FEM based software packages by meshing. The 3d IF frame and IF with interface modelled in sap is shown in Fig. 8.

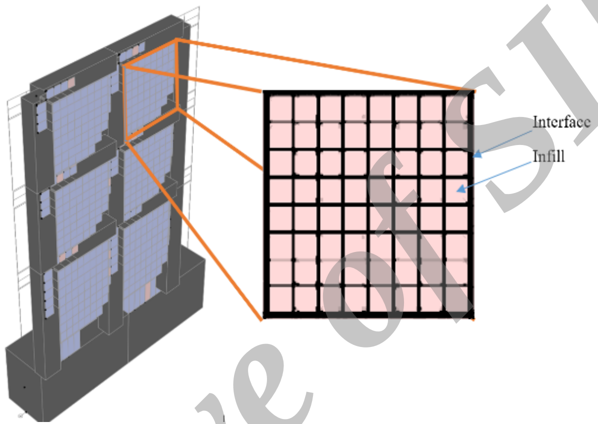

Figure 8. 3D infill frame

5. LINEAR ANALYSIS

RC members are detailed (as per IS:13920) to confirm its ductile capacity. The drawback is that the response beyond the limit state is neither a simple extrapolation nor a perfectly ductile behavior with pre-determinable deformation capacity.

This drawback is due to Change in stiffness of members due to cracking and yielding, P-delta effects, Change in the final seismic force estimated (due to Change in time period 'T' and effective damping ratio 'ζ'. Linear analysis is done by applying dead load and live load on the frame. The Dead load and Live load is applied with a scale factor of 1. Live Load is applied at the top left joint (joint 4) and the deflection is calculated at the top right joint (joint 7) in FEM based software. The load and deflection values are noted down.

6. NONLINEAR ANALYSIS

Nonlinear analysis of RC structures has become increasingly important over the last decade. Although elastic analysis gives a good indication of elastic capacity of structures and shows where yielding will first occur. It cannot predict the redistribution of forces during the progressive yielding that follows and predict its failure mechanisms. The problem of developing a good material model for RC frame and IF frame is probably the most difficult task.

Pushover analysis (PO) is a non-linear analysis procedure to estimate the strength capacity of a structure beyond its Limit State up to its ultimate strength. It can help demonstrate how progressive failure in buildings most probably occurs, and identify the mode of final failure. The method also predicts potential weak areas in the structure, by keeping track of the sequence of damages of each and every member in the structure. PO analysis uses a non-linear computer model for the analysis. This is done by incorporating hinges. These are points on a structure where one expects cracking and yielding to occur in relatively higher intensity so that they show higher flexural/shear displacement, under loading.

Now select a lateral load pattern apply unit lateral point load. In this pattern the monotonic increasing lateral load will be applied to your structure until failure. Assign hinges to beams and columns on both the ends (SAP has inbuilt hinge properties of beam and column as per FEMA356/ASCE-41). The locations where one expects to see cross diagonal cracks in an actual building structure after a seismic mayhem would be at either ends of beams and columns, the 'cross' being at a small distance from the joint. This is where hinges are inserted in the corresponding computer model as in Fig. 9.

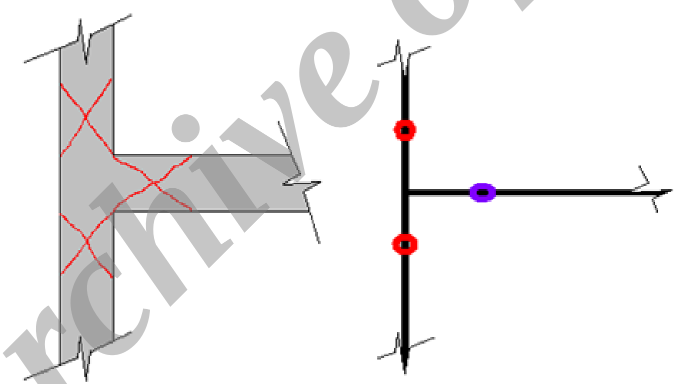

Figure 9. Location of hinges and crack formation

The flexural and shear hinges are inserted into the ends of beams and columns. Typical Moment Hinge property has AB which represents the linear range from unloaded state (A) to its effective yield (B), Followed by an inelastic but linear response of reduced (ductile) stiffness from B to C. CD shows a sudden reduction in load resistance, followed by a reduced resistance from D to E, and finally a total loss of resistance from E to F as shown in Fig. 10. These hinges have non-linear states defined within its ductile range as 'Immediate Occupancy' (IO), 'Life Safety' (LS) and 'Collapse Prevention' (CP).

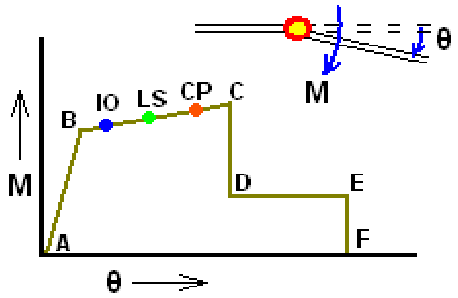

Figure 10. Typical moment hinge property

The analysis is done with gravity, dead and push load cases. Now run analysis. Each point on the PO curve or capacity curve obtained is consecutively checked to see whether the Sa-Sd at that point intersects the Response Spectrum curve known as Demand curve. For each point on the Capacity curve, the Demand curve has to be checked for intersection with the Response Spectrum curve. When the curves intersect, that meeting point is known as the Performance Pt. For the performance point the effective period is noted down and the steps coming under the effective period is checked if the frame exhibit any disastrous hinge behavior. The performance point is kept as references and all the steps with nearby time period is checked to be safe from hinge failure.

7. RESULTS

7.1 Linear analysis results for bare frame

For the increase in load the deflection at the joint opposite to the load applied is noted and load vs deflection graph is plotted to get the stiffness which is the slope of the curve. The Fig. 11 shows the deformation at Joint 7 when Load is applied at Joint 4 in BF. The load Vs Deflection graph for BF subjected to Linear Static Loading is shown in Fig. 12. The maximum Shear force and Bending Moment of 24.61 KN and 7070.39 Nm occurs in the center column at the foundation beam column junction and the center column of the middle storey respectively. The Fig. 13 shows the Shear Force and Bending Moment of the BF for the applied load.

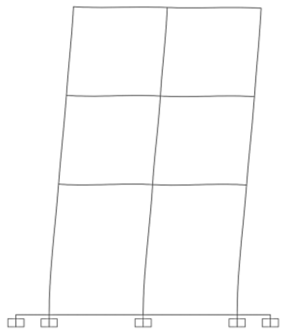

Figure 11. Deformation of bare frame

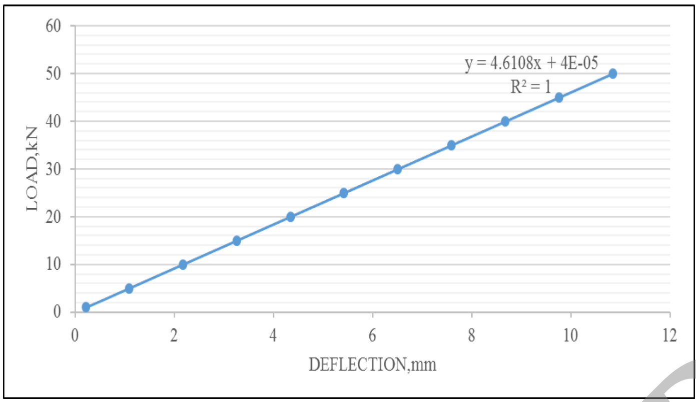

Figure 12. Load Vs deflection for bare frame

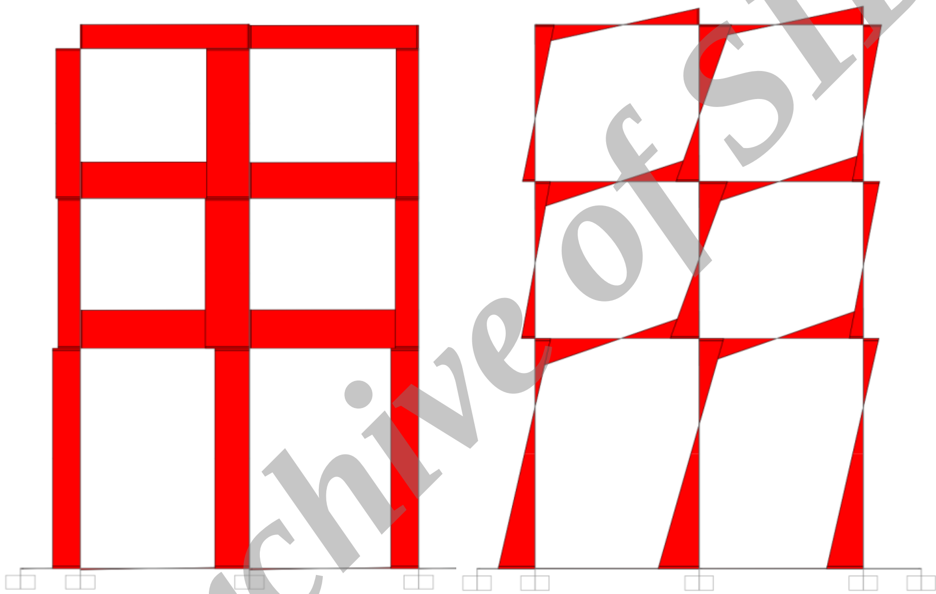

Figure 13. Shear force and bending moment bare frame

7.2 Linear analysis results for infill frame

For the increase in load the deflection at the joint opposite to the load applied is noted and load vs deflection graph is plotted to get the stiffness which is the slope of the curve. The Fig. 14 shows the deformation at Joint 7 when Load is applied at Joint 4 in IF. The Load Vs Deflection graph for IF subjected to Linear Static Loading is shown in Fig. 15. The maximum Shear force and Bending Moment of 27.06 KN and 2666.67 Nm occurs in the center column at the foundation beam column junction and the center column of the middle storey respectively. Fig. 16 shows the Shear Force and Bending Moment of the IF.

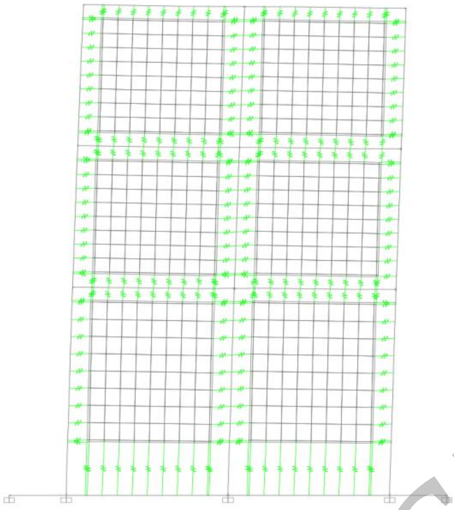

Figure 14. Deformation of infill frame

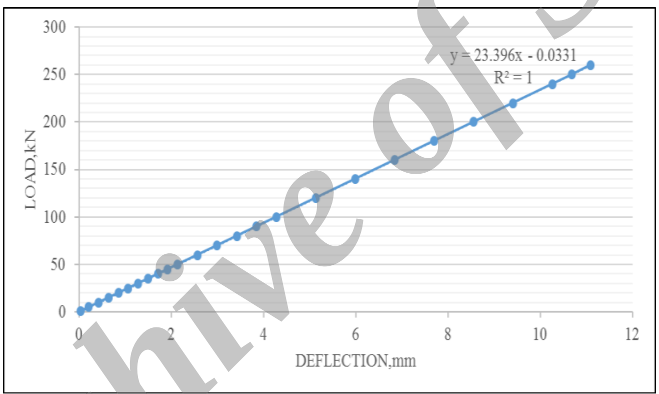

Figure 15. Load Vs deflection for infill frame

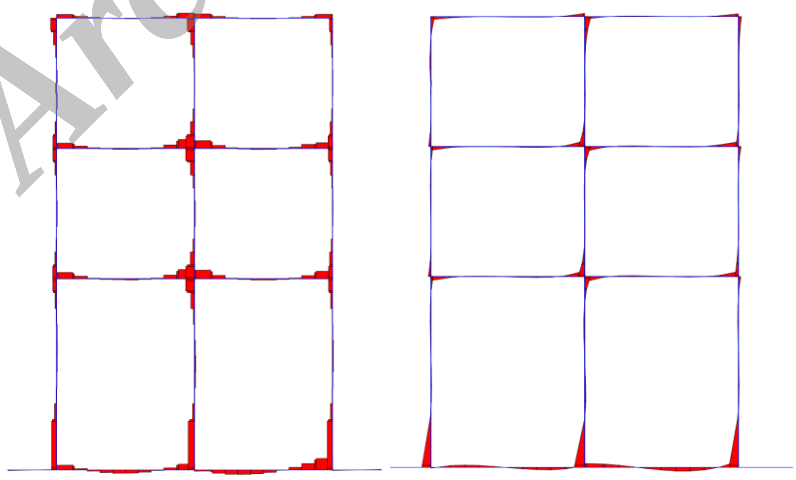

Figure 16. Shear force and bending moment infill frame

7.3 Nonlinear results for bare frame

The PO analysis is done for displacement controlled mechanism where steps are saved up to a maximum displacement of 31.5mm for accuracy. The Capacity curve, the Demand curve has to be checked for intersection with the Response Spectrum and the point where they intersect or meet is the performance point. For BF the performance point is found to be at a Time Period of 0.017 seconds. This Static PO curve shown in Fig. 17. Based on the Performance point the hinge formation between step 90 and step 103 in has been checked for safety. The Hinge formation for BF at step 103 is shown in Fig. 18. The Hinge formation for BF at step 403 is collapse as shown in Fig. 19. The Shear force and Bending Moment diagram for BF is shown in Fig. 20.

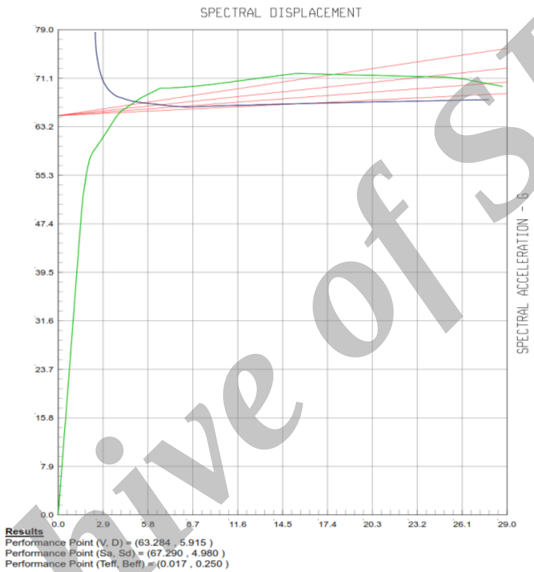

Figure 17. Static push over curve for bare frame

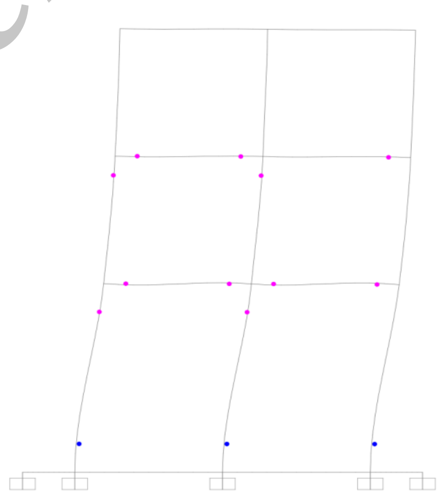

Figure 18. Hinges at performance point for bare frame

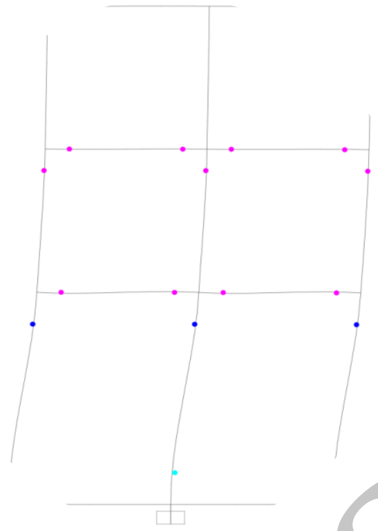

Figure 19. Hinges at collapse for bare frame

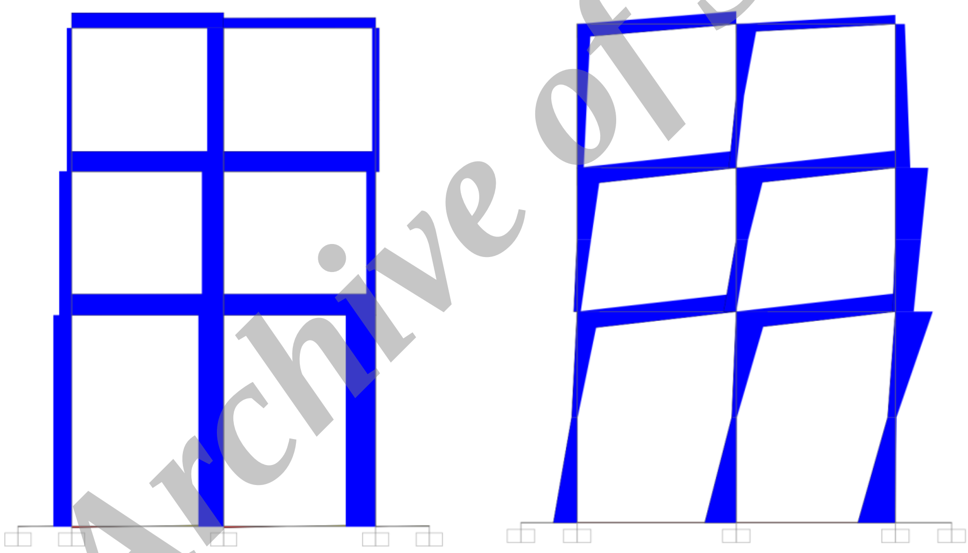

Figure 20. Shear force and bending moment BF envelope

7.4 Nonlinear results for infill frame

For IF frame the performance point is found to be at a time period of 0.020 seconds. This Static PO curve shown in Fig. 21. Based on the performance point the hinge formation between step 67 and step 73 in the IF frame has been checked for safety. The hinge formation for IF frame at step 73 is shown in Fig. 22. The hinge formation for IF frame at step 148 is collapse as shown in Fig. 23. The Shear force and Bending Moment diagram for BF is shown in Fig. 24. The link axial stress results show the transfer of stresses from the IF to the RC frame. The locations where the links effectively transfers the stress and the locations where the link stays dormant can be calculated as in Fig. 25.

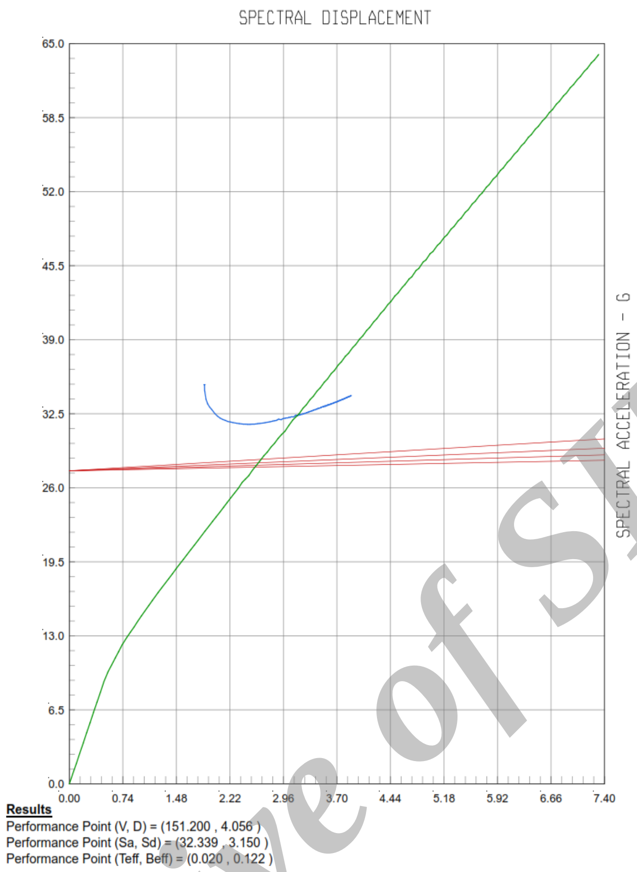

Figure 21. Static push over curve for infill frame

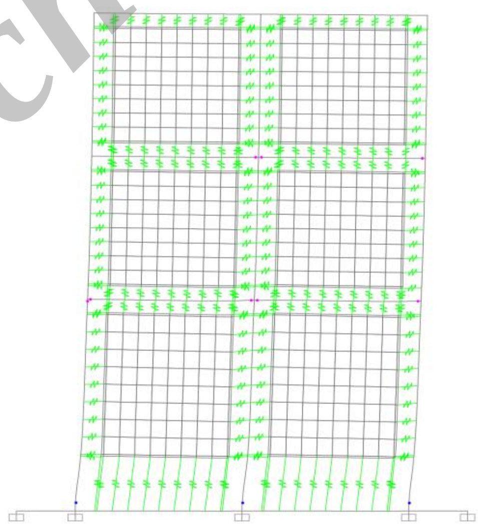

Figure 22. Hinges at performance point for infill frame

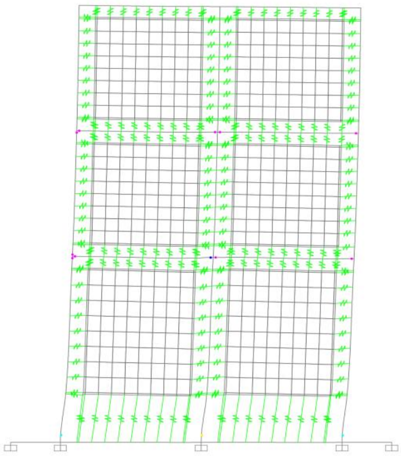

Figure 23. Hinges at collapse for infill frame

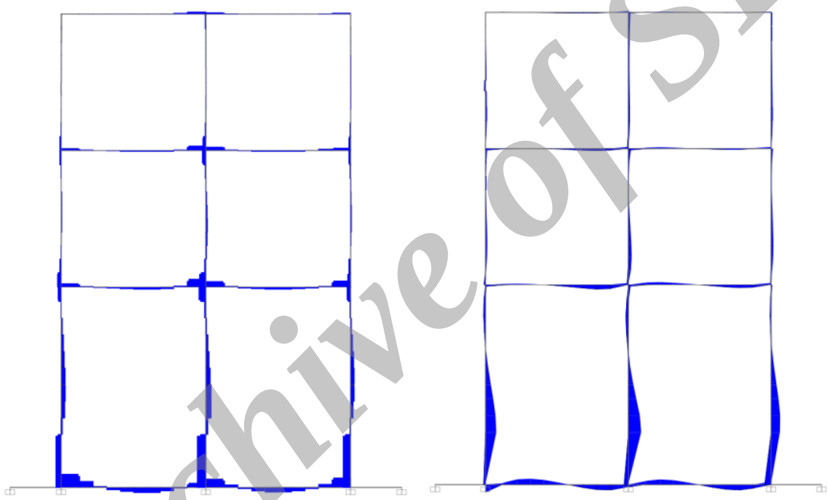

Figure 24. Shear force and bending moment IF envelope

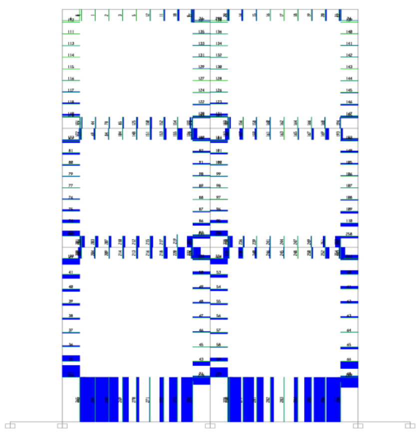

Figure 25. Link axial force for IF envelope

8. CONCLUSION AND COMMENTS

- From the linear analysis it is deduced that the stiffness of the Reinforced Concrete frame increases with the introduction of Infill.
- It is evident that for linear analysis Bending Moment envelope is more in Bare frame than the infill frame and vice versa for the Shear force in Bare and Infill frames. This, shows that with the introduction of infill the frame becomes less ductile when compared to that of the bare frame leading to material failure than structural failure.
- It is evident that for nonlinear analysis Bending Moment is more in Infill frame than the Bare frame and the same criteria for the Shear force in Bare and Infill frames. This, shows that with the nonlinear pushover analysis the bending moment has a rather greater impact on the frame behavior when compared to the linear analysis. This is due to the formation of failing hinges in the earlier steps in the analysis infill frame.
- From the Nonlinear Pushover analysis, for the Performance points of Bare Frame and Infill frame the hinge formation is found to be safe. It shows that the resistance to yielding to higher hinge states in the case of Infill frame is less when compared to that of the Bare Frame.
- In case of Bare Frame, the yielding period of the frame to collapse is long which makes the frame more ductile while in case of Infill Frame the collapse state is achieved at an earlier instant which makes it less ductile due to the increase in Stiffness.
- From the link axial force achieved it can be found that the area where link force is effectively transferred to the frame by the infill is less. This confirms that the infill area is not efficiently used. This is due to the inefficient transfer of stresses that is the energy dissipation of the stresses from the interface to the infill is not sufficient. This has to be improved for Seismic strengthening of the frame.

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REFERENCES

1. Asteris PG, Kakaletsis DJ, Chrysostomou CZ, Smyrou EE. Failure modes of in-filled frames, *Electronic Journal of Structural Engineering*, No. 1, **11**(2011) 11-20.
2. Jiang H, Liu X, Mao J. Full-scale experimental study on masonry infilled RC moment-resisting frames under cyclic loads, *Engineering Structures*, **91**(2015) 70-84.
3. Leslie R. The pushover analysis, explained in its simplicity, *National Conference (Recent Advances in Civil Engineering) RACE"13 at SAINTGITS College of Engineering, Kottayam*, 2013.
4. Niruba S, Boobalakrishnan KV, Gopalakrishnan KM. Analysis of masonry infill in a multi-storied building, *International Refereed Journal of Engineering and Science (IRJES)*, No. 3, **3**(2014) 26-31.

5. Satyanarayanan KS. Studies on the influences of different materials on the elastic behaviour of infilled frames, A Thesis of Doctor of Philosophy at SRM University, 2009.
6. Bose S, Rai DC. Behaviour of AAC infilled RC frame under lateral loading, *Tenth U.S. National Conference on Earthquake Engineering, Frontiers of Earthquake Engineering at Alaska*, 2014.
7. Cavaleri L, Di Trapani F. Cyclic response of masonry infilled RC frames experimental results and simplified modelling, *Soil Dynamics and Earthquake Engineering*, **65**(2014) 224-42.
8. Kaushik HB, Jain SK, Rai DC. Code approaches to seismic design of masonry-infilled reinforced concrete frames, *Earthquake Spectra*, No. 4, **22**(2006) 961-83.
9. Umarani G, Gnanappa SB. Structural behaviour of reinforced concrete frames with confined infill under cyclic loading, *International Journal of Earth Sciences and Engineering*, No. 6, **3**(2010) 904-11.
10. Teni M, Grubišic M, Guljaš I. Simplified approaches for modelling infilled frames, *Electronic Journal of the Faculty of Civil Engineering OSIJEK*, **5**(2014) 70-88.
11. Surana M. Nonlinear static analysis using sap 2000, Non-Linear Analysis, Department of Earthquake Engineering, IIT Roorkee.