P-Δ Behaviour of Three Dimensional Single-Storey Infilled R.C. Frame with SLAB

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Abstract
An equivalent static experimental study described to investigate the behaviour of a three-dimensional reinforced concrete frame with slab and infill. Load deflection and failure of the model building taken into account in this research. Two three-bay frame with central brick infill bay along the sides and one long single-bay plain frame at the middle and single-story one-third scale model representing a three-dimensional structure taken. An RCC slab covered the entire top of the frame. Constant vertical loads applied on the top surface of the slab using steel solid blocks to apply the gravity load. Lateral applied by loading frame and hydraulic jacking system and load-deflections and the failure of the three-dimensional frame studied. The frame collapse, defined in this study as the failure of bonding, column-beam joints, failure of anchorage, brickwork failure, beam failures and column failure

Keywords: 3d-frame, Deflection, Infill Bay, Plain Bay, Slab, Cracks, Load Carrying Capacity.

Introduction

Influence of brick infill and RCC slab can use while designing three-dimensional R.C. Frames thereby the cross-sectional area of beams and columns and the measure of reinforcements in the columns and beams can reduce. This research describes the behaviour of the model when the redesigned three-dimensional frame subjected to cyclic loading. An experimental investigation carried on a three-dimensional single storey RC infilled frame. Three dimensional frame consists ten columns covered by beams and slab on top and it has two three-bay brick infilled frames at the ends and one long single plain bay frame at the middle along loading direction. Brickwork constructed at the middle bay of three-bay frames.

Whole frame subjected to lateral cyclic loading. Brick infilling and slab cause increased load carrying capacity. Cyclic loads applied in the experimental study whereas monotonic loads applied in the analytical study up to maximum loads. Six cycles of loading applied in the post cycling. In this research IS: 1893 code used to load calculations. [Alessandra Fiore et al. 2012] studied the effect of infills in the global (stiffness) and local response (effects on the frame) of a building under earthquake loads. [Altun F, et al. 2012] conducted test on a 1:3 scaled, three-storey, FRP (Fiber Reinforced Polymer) retrofitted reinforced concrete model structure whose behaviour and crack development were identified experimentally in the laboratory and it was investigated analytically.

[Cengiz Dundar et al. 2007] developed a rigid diaphragm model for the three dimensional analysis of reinforced concrete frames with cracked beam and column elements. ACI, CEB and probability-based effective stiffness models are used for the effective moment of inertia of the cracked members. In the analysis, shear deformations, which can be large following crack developments, are taken into account and the variation of the shear rigidity due to cracking is considered by reduced shear stiffness models. [Fariborz Barzegar et a. 1997] presented a three-dimensional (3D) model for finite-element (FE) analysis of reinforced concrete (RC) based on smeared cracking approach The constitutive model for plain concrete has been presented and verified in a companion paper; a simple hypoelastic formulation with modification to approximate the postpeak behavior in compression was used. [Fiore A. et.al, 2012] presented a paper reports the results of the non-linear static assessment performed for two RC existing buildings located in a high seismic hazard area. Both buildings are characterized by regularity in plan and elevation, but while the first one is a low rise construction, the second one is relatively tall (7-storey). Thence, there is the possibility of considering two different and interesting situations. [Ilker Fatih Kara et al. 2010**]** developed a computer program based on the iterative analytical procedure for the three-dimensional analysis of reinforced concrete frames with beam, column and shear-wall elements in cracked state. The iterative analytical procedure provided an accurate and efficient prediction of deflections of reinforced concrete structures due to cracking under service loads. [Manos, G.C, et.al, 2012] presented systematic study aims to propose valid numerical models that can realistically approximate the shear behavior of masonry assemblages and the hysteretic behavior of masonry infilled reinforced concrete (R/C) frames when they are subjected to combined vertical and horizontal cyclic loads. [Matjaz Dol sek, et.al, 2008] studied the effect of masonry infills on the seismic response of a four-storey reinforced concrete frame using the N2 method. The method was based on pushover analysis and the inelastic spectrum approach. It was recently extended in order to make it applicable to infilled reinforced concrete frames. [Meng-Hao Tsai, et.al, 2008] evaluated following the linear static analysis procedure recommended by the US General Service Administration (GSA), the potential of an earthquake-resistant RC building for progressive collapse. Nonlinear static and nonlinear dynamic analyses were conducted to estimate the progressive collapse resistance of the building subjected to column failure. Under an approximate deflection demand, different collapse resistances are obtained. [Pujol, S, et.al, 2010] were tested a full-scale three-story reinforced concrete structure with and without infill walls made out of solid clay bricks. During the test without the walls, the structure experienced a punching shear failure at a slab–column connection. After this first test, infill walls were built with solid bricks. The walls filled completely full bays and ran continuously from the foundation to the roof. It was observed that the walls increased the stiffness and the strength of the structure. [Rafael Sacks et al. 2008] studied the Impact of three-dimensional parametric modeling of buildings on productivity in structural engineering practice. [Uva, G et.al, 2012] were performed a number of non-linear static (pushover) analyses on proper structural models of the building, considering both the bare framed structure and the infilled one, in order to appraise the influence of infill walls on the failure mechanisms. [Uva, G, et.al, 2012] studied, an existing RC framed building for which a good level of knowledge was available, including a wide experimental database. A reference frame was considered for performing nonlinear static analyses aimed at investigating some significant aspects of the modeling of the infill and the relapse induced by the related computational choices on the structural response. [Yihai Baoa, B, at.al, 2010] investigated a macro model-based approach to enable post-event progressive collapse analysis of reinforced concrete (RC) frame–wall structures. A simplified shear wall model was developed to simulate the inelastic behavior of a multi-story frame–wall system due to the sudden loss of a significant portion of the shear wall at the first story. Two perimeter frame–wall systems designed for different seismic zones were modeled using the proposed approach and numerical simulations following the sudden loss of a portion of the shear wall at the lowest story are compared and evaluated. [Yi, Wei-Jian, (2008] were tested a four-bay and three-story one-third scale model representing a segment of a larger planar frame structure. The frame collapse, defined in this study as the rupture of tension steel bars in the floor beams, occurred at a vertical unloading displacement of 456 mm (18 in.) that corresponds to a beam drift angle (rotation with respect to the horizontal) of 10.3 degrees. Based on the experimental observations, the mechanical behavior of the model frame was analyzed and the redistribution and transition of the load resisting mechanisms were discussed. [Yong Lu, 2002] conducted a comparative study of the nonlinear behavior of reinforced concrete (RC) multistory structures is carried out on the basis of measured response of four six-story, three-bay framed structures, namely a regular bare frame, a discontinuous-column frame, a partially masonry-infilled frame, and a wall-frame system.

Research significance

Performance of three-dimensional RC frame with RCC slab and brick infill, evaluated in this research. The primary aim of this study is to investigate the effects of slab and brick infill the lateral load displacement relationship, crack pattern, and failure mechanism of the frame by a comparison of the results. This study can help the structural engineer to design effectively the new buildings and accurately evaluate the ability to existing buildings to mitigate progressive collapse.

Experimental Program

Specimen preparation: A three-dimensional RC frame constructed on the test floor of structural engineering laboratory. Raft slab constructed on the test floor followed by construction of ten columns 100 mm x 100 mm size. 70mm x 90 mm beams and 50 mm slab casted on the top of columns. Brickwork constructed with 1:4 mix.

Test setup: Whole three-dimensional RC frame erected on the test floor. The three-dimensional frame model, columns positions, Schematic diagram of the test setup and full three-dimensional frame shown in Fig. 1 (a) to 1 (d)

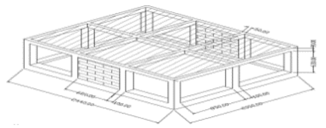

Fig. 1(a): Model of 3-D frame

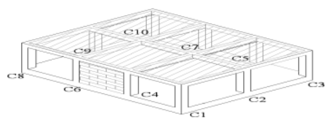

Fig. 1(b): Positions of columns

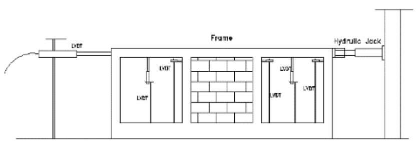

Fig. 1(c): Schematic diagram of test set-up (Side View)

Fig. 1(d): Full 3-D Frame

Loading arrangements: Lateral cyclic loading applied at storey level through the loading frame in line with the beams (Figure 2). The Jack operated by a hydraulic pump and the Jack controlled by a common console. Reaction frame, which used for loading arrangements, fixed to the test floor. Single acting hydraulic jack of capacity 300 kN in capacity used at the required level. Loads applied from the jack at the top storey level of the frame. A pressure gauge used to measure the applied load. Point load applied to the loading frame which converts the point load to line load in the frame. The hydraulic jack placed at one end and the LVDTs placed on the opposite side to read the displacements. One LVDT placed at the midpoint of slab bottom to read center point deflection of the slab. Other three LVDTs placed at the infill bay alone and at the columns tops of C_1 and C_4.

Fig .2: Fixing of loading frame

Testing Procedure: In-plane cyclic loading, stroke-controlled pushover tests performed on the frame to find horizontal displacements of the frame. Load-Displacements and cracking behaviour of three-bays infilled frame, long single plain bay frame, infill bay alone and columns C_1 and C_4 performed. Three-dimensional frame subjected to lateral static cyclic loading. Load applied gradually with increment of 2.5 kN at each cycle. Deflections at storey level measured using LVDTs and deflectometer at each increment or decrement of the load. Formation and propagation of cracks hinge formation and failure pattern recorded. Initial crack found at 12.5 kN in the fourth cycle. Ultimate base shear of 18.0 kN reached in the seventh cycle of loading. Post ultimate cycles performed in the frame till the final collapse of the frame.

Loading and load - Deflection Behaviour (P–Δ): Thirteen load cycles imposed on the frame. The frame was gradually loaded by increasing the load level in each cycle. After reaching the ultimate load, post-ultimate cycles performed to study its non-linear behavior.

Three-Bays with central bay infilled frame: The frame subjected to cyclic loading in experimental study and monotonic loading considered in analytical study. Relationships established for estimating the lateral loads, and the total deflection of the building might have experienced from the residual deflection at the top level. Storey deflection versus base shear represented as hysteresis loop in Figure 3 (a) up to the failure of the frame. Variation of greatest storey deflection with respect to applied lateral load (Base Shear) presented in Figure 3 (b). Maximum base shear versus top storey deflection graph of each cycle plotted. Load-deflection curve exhibited considerable pinching and stiffness degradation during same-drift repeat cycles. This behaviour is characteristic of most RC frame connections and attributed to the reinforcement bond slip through the joint region, concrete cracking, and/or reinforcement yielding. When each beam and column bars yielded, based on reinforcing steel strain gauge data measured in the beams and columns and has an effective beam depth shifted from the interfaces. Bottom beam bars and rods in the tension faces of the columns undergone an increase in strain (and yielded earlier) than the top beam bars. Maximum lateral load sustained during each cycle highlighted as part of a load-drift envelope superimposed on the hysteresis plots. These envelopes referred as backbone curves and plotted for the frame in Figure 3 (b) to facilitate comparison. Load and deflection values tabulated in Table 1. Function of the backbone curve from first cycle to eighth cycle is:

$$y = -3E\text{-}08x^6 + 5E\text{-}06x^5 - 0.0004x^4 + 0.0118x^3 - 0.2207x^2 + 2.5803x + 0.3935 \quad (R^2 = 0.9983) \qquad (1)$$

and the function from eighth cycle to final cycle is:

$$y = 2E\text{-}08x^4 - 5E\text{-}06x^3 + 0.0007x^2 - 0.1129x + 22.02 \quad (R^2 = 0.9903) \qquad (2)$$

Table 1
Load cycle, load and deflection
(Three Bay Frame with Central-Bay Infill)

Load cycle No.	Load, kN	Deflection, mm
1	0.00	0.0
2	2.50	0.6
3	5.00	2.3
4	10.00	5.9
5	12.50	9.3
6	15.00	15.2
7	17.50	26.4
8	18.00	43.1
9	17.50	50.3
10	16.5	61.6
11	15.5	76.3
12	15	88.7
13	13.5	102.2
14	13	118.9
15	12.00	160.8

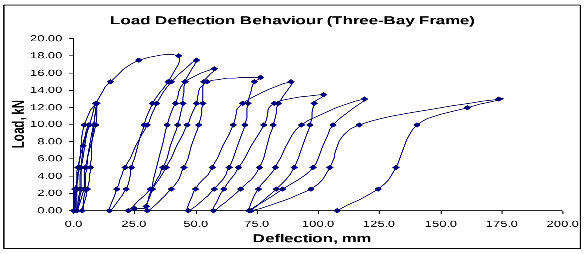

Fig. 3(a): Base Shear vs storey deflection of three-bay frame with center bay infill

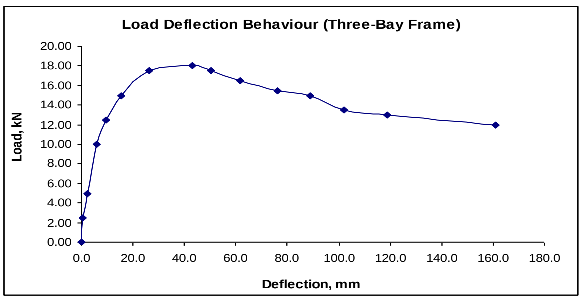

Fig. 3(b): Base shear vs storey deflection of three-Bay frame (Back-Bone Curve)

Fig. 3(c): Three bay frame

Long single plain bay frame at middle: The variation of maximum storey deflection with respect to applied lateral load (Base Shear) presented in Figure 4 (a). The deflection found higher after sixth cycle and this led to higher energy set up of the frame. Infill bays reducing its stiffness, brickwork formed diagonal cracks, windward side of columns formed tension cracks and cracks enlarged at the junction of brick infill and beams at sixth cycle. Also, the column reinforcements were starting to yield and the equivalent strut effects of brick infill reduced at this cycle. These factors motivated to higher deflection and higher energy stored in the middle single long bay frame and starting stage of failure of the whole 3D frame. Sudden shear failure indicated in Figure 4 (b) by sudden drop in lateral load capacity at 8th cycle. Deflection found increased in post cycles and severe damages found in 3-D frame and brick infill became inactive and was spalling at this cycle and also, windward columns reinforcement yielded. The variations of the values tabulated in Table 2. Equation of the backbone curve in this frame is:

$$y = 2E\text{-}12x^6 - 1E\text{-}09x^5 + 9E\text{-}08x^4 + 5E\text{-}05x^3 - 0.0116x^2 + 0.8159x + 0.7324 \quad (R^2 = 0.9845) \tag{3}$$

Table 2
Load cycle, load and deflection of middle long single bay frame

Load cycle	Load, kN	Deflection, mm
1	0.00	0.00
2	2.50	1.00
3	5.00	5.70
4	10.00	14.30
5	12.50	22.50
6	15.00	26.50
7	17.50	28.90
8	18.00	69.40
9	17.50	88.30
10	16.50	92.9
11	15.50	100.2
12	15.00	115.0
13	13.50	143.3
14	13.00	210.90
15	12.00	238.60

Behavior of infill bay: The variation of maximum storey deflection with respect to the applied lateral load (Base Shear) shown in Figure 5(a). This bay is a composite of RCC frame and brick infill and the behavior of this bay was heterogeneous. Brick infill has given additional lateral support as diagonal strut to the windward column of this bay up to the maximum load. Diagonal cracks found in the infill during load increment and the brick infill loses its diagonal effect. Incremental loads transferred to the columns and beams after breaking the infill and it contributed to higher deflection and widening the loops in hysteresis curve. Load-deflection curve exhibited considerable pinching and widening in each loop and it is due to the combined properties of concrete columns and brick infill. Due to the complex behavior of concrete and infill, the windward column and the leeward column of this bay behaved differently. Variations of the values tabulated in Table 3. The backbone curve shown Fig. 5(b) and the equation of the backbone curve is:

$$y = 3E\text{-}08x^6 - 3E\text{-}06x^5 - 8E\text{-}06x^4 + 0.0082x^3 - 0.3169x^2 + 4.2949x + 0.4454 \quad (R^2 = 0.9858) \tag{4}$$

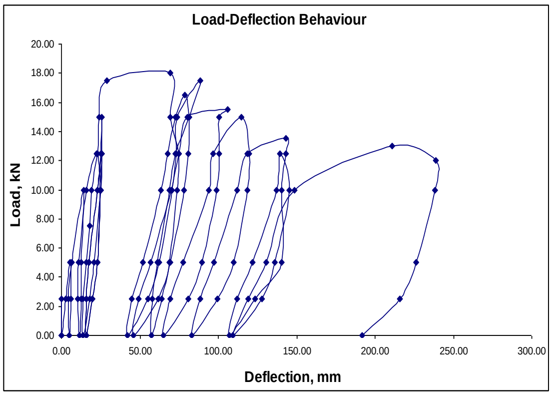

Fig. 4(a): Base shear Vs storey deflection of middle long single-Bay frame

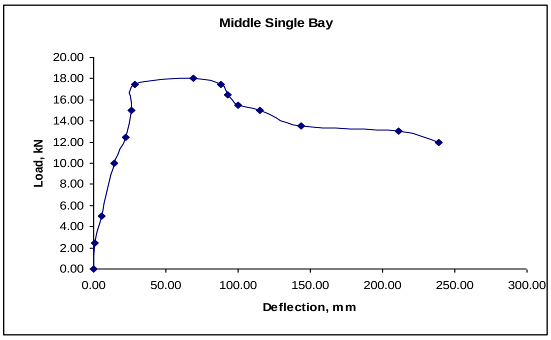

Fig. 4(b): Base shear vs storey deflection of middle long single-Bay frame (Back Bone-Curve)

Load-Deflection Behaviour of Column C_4: Column C_4 placed at windward side of infill bay in the three bay infill frame. Brick infill contributed additional load carrying capacity and stiffness to this column up to its failure. Deflections found higher after the formation of diagonal crack in the brick infills and column reinforcements yielded. This led to a shear flexural crack in this column. Variation of maximum storey deflection with respect to the applied lateral load (Base Shear) presented in Figure 6 (a). The loops in cyclic curves were narrow and pinching upto the failure of infill due to its equivalent strut action of the infill. Loops in hysteresis graph widened after the failure of infill. Load resisting capacity of the column reduced due to losing its diagonal strut effect of the infill. Variations of load and deflection values shown in Table 4. Backbone curve shown Figure 6 (b) and the equation of the backbone curve is:

$$y = -2E\text{-}10x^6 + 8E\text{-}08x^5 - 1E\text{-}05x^4 + 0.0011x^3 - 0.0583x^2 + 1.6029x + 0.22 \quad (R^2 = 0.9971) \qquad (5)$$

Table 3
Load cycle, load and deflection (Centre Infill Bay)

Load cycle No.	Load, kN	Deflection, mm
1	0.00	0.00
2	2.50	0.21
3	5.00	1.54
4	10.00	2.70
5	12.50	3.95
6	15.00	4.46
7	17.50	6.16
8	18.00	8.25
9	16.50	23.36
10	15.50	27.61
11	15.00	38.72
12	13.50	46.53

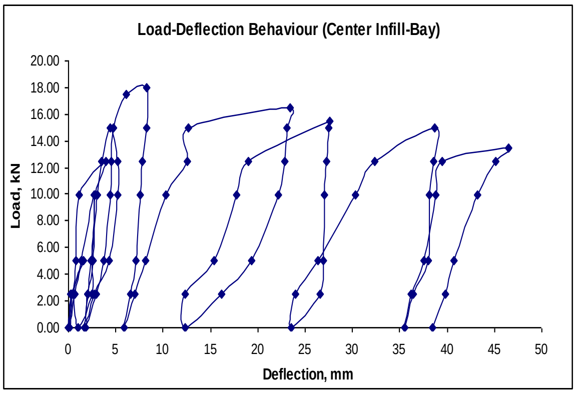

Fig. 5(a): Base shear Vs storey deflection of infill bay

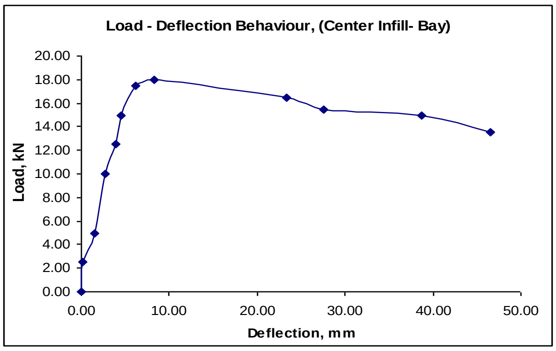

Fig. 5(b): Base shear Vs storey deflection of infill-bay (Back-Bone Curve)

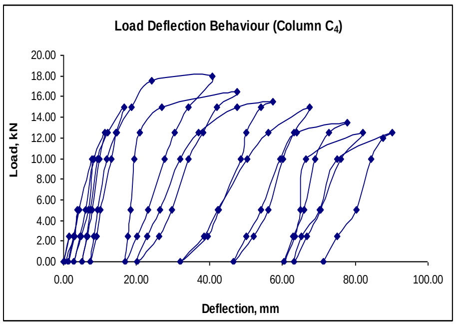

Fig. 6(a): Base shear vs. storey deflection of column C_4

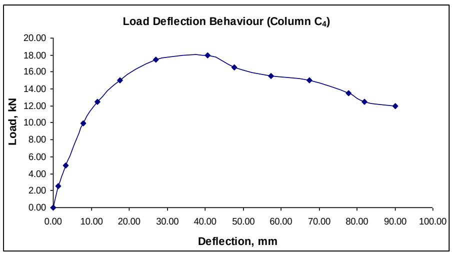

Fig. 6(b): Base shear vs. storey Deflection of column C_4 (Back-Bone Curve)

Table 4
Load cycle, load and deflection of column C_4

Load cycle No.	Load, kN	Deflection, mm
1	0.00	0.00
2	2.50	1.40
3	5.00	3.31
4	10.00	7.92
5	12.50	11.66
6	15.00	17.54
7	17.50	27.06
8	18.00	40.7
9	16.50	47.66
10	15.50	57.34
11	15.00	67.39
12	13.50	77.74
13	12.50	82.00
14	12.00	90.16

Load-deflection Behaviour of column C_1: This is the first column of the frame and placed in the open bay of the three bay frame. Load and corresponding deflection values are in Table 5. The variation of maximum story deflection with respect to applied lateral load (Base Shear) presented in Figure 7 (a). At the initial stage, the deflection of column C_1 was 48.72% higher than the column C_2. At yielding, the deflection of column C_2 was 32.27% lower than the column C_2. Appreciable widening in the cyclic loops has occurred after the failure of infill. Whole 3-D frame and the column C_1 lose their lateral load resisting capacity at the maximum load and the deflections found higher in the column C_1. This led yielding of column reinforcements and cracks propagation in the concrete at post-cycling. Anchorage failure occurred at the bottom of this column during collapse stage of whole frame. Load-displacement graph shown in Figure 7(b). The trend equation of the backbone curve is:

$$y = -2E\text{-}07x^6 + 3E\text{-}05x^5 - 0.0018x^4 + 0.0543x^3 - 0.8441x^2 + 6.3487x + 0.1594$$
$$R^2 = 0.9987 \quad (6)$$

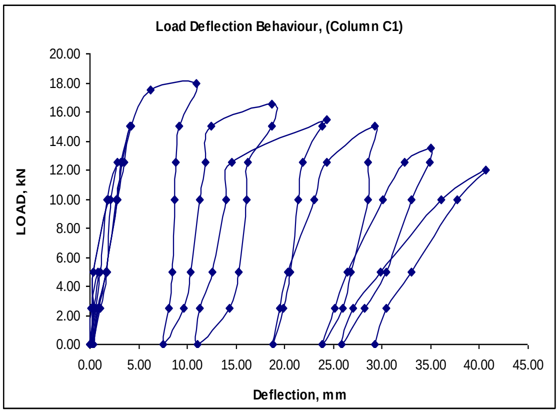

Fig. 7(a): Base shear Vs storey deflection of Column C_1

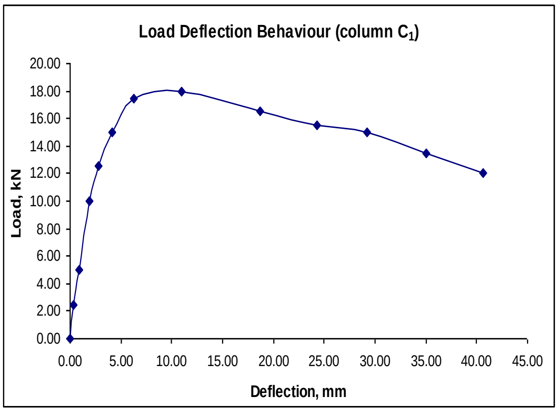

Fig. 7(b): Base shear Vs storey deflection of column C_1 (Back-Bone Curve)

Table 5
Load cycle, Load and deflection of column C_1

Load, kN	Deflection, mm.
0.00	0.00
2.50	0.20
5.00	0.81
10.00	2.21
12.50	3.73
15.00	5.46
17.50	5.22
18.00	17.90
16.50	22.83
15.50	43.56
13.50	52.52
13.00	54.73
12.00	66.58

Load-Deflection behaviour of column C_2: The column C_2 placed in the middle of frame in transverse direction at loading face and this is the windward column of the middle long plain bay. Loads transferred to this plain bay frame and corresponding deflections were higher than the columns C_1 and C_4. This is the middle column on the windward side so that it subjected to double the lateral load than the end columns. Because of higher lateral load and high yielding of steel, this column subjected to higher deflections. Variation of maximum storey deflection with respect to applied lateral load shown in Figure 8 (a). At yielding, the deflection of column C_2 was 24.40% higher than the column C_2; at this stage, the rate of yielding of reinforcements of column C_2 was higher, this led to higher deflection in this column. This column subjected to considerable amount of pinching in the initial stage. Sudden drop of load resisting capacity found in the column C_2 and the flexural shear had occurred in this column. Slope of curve varied in each loop during each cycle. Load versus deflection graph shown in Figure 8 (b). and corresponding values are in Table 6. The equation of the trend curve is:

$$y = -2E\text{-}08x^6 + 4E\text{-}06x^5 - 0.0004x^4 + 0.0184x^3 - 0.4347x^2 + 4.6927x + 1.0046$$
$$(R^2 = 0.9832) \quad (7)$$

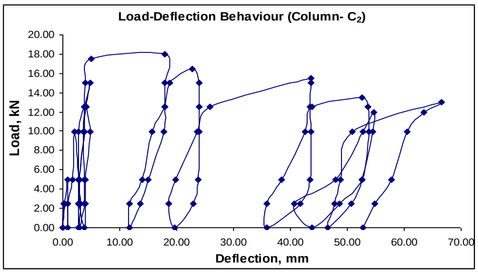

Fig. 8(a): Base shear Vs storey deflection of column C_2

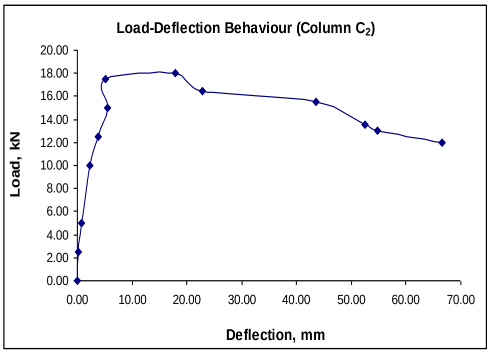

Fig. 8(b): Base shear Vs storey deflection of column C_2 (Back-Bone Curve)

Behaviour of SLAB with Beams ON 3-D Frame: The presence of floor slab (Figure 9) with beams affects the behaviour of whole three-dimensional frame in two ways: One way, it increases the flexural capacity of beams and the other way, it imposes torsional moment on transverse beams that can affect the confinement of joints. The torsion induced in the transverse beams may cause them to crack and reduce their ability to confine the joint.

Table 6
Load cycle, load and deflection (Column C_2)

Load cycle No.	Load, kN	Deflection, mm
1	0.00	0.00
2	2.50	0.39
3	5.00	0.86
4	10.00	1.90
5	12.50	2.82
6	15.00	4.14
7	17.50	6.27
8	18.00	10.96
9	16.50	18.64
10	15.50	24.27
11	15.00	29.24
12	13.50	35.05
13	12.00	40.68

Fig. 9: RCC Slab in Three-Dimensional Frame

Lateral load -vertical deflection behaviour of slab: The slab constructed with end tie beams and two transverse beams and one longitudinal beam at the middle of slab. The slab with beams subjected to combined gravity and lateral load. Strength envelopes obtained from the load - vertical deflection behaviours. Lateral load versus vertical deflection hysteretic loops of slab is in Figure 10(a). Maximum lateral load sustained during each cycle highlighted as a part of a load-deflection envelope superimposed on the hysteresis plots. Sudden shear failures indicated in Figure 10 (b) during 8th and 10th cycles. The slab deflected upward during 2nd, 3rd and 4th cycles. The slab stiffened in all the sides and in the middle by beams. Because of the stiffening effects of beams, the slab subjected to shear compression in addition to live load and hence the slab buckled upward during these three cycles. At this stage, the lateral load was dominant than the live load. Large deflection has occurred in 9th cycle. Diagonal and interface failure of infill in the frame led to large deflection of the columns and higher deflection in the slab middle. Bond failure, yielding of reinforcements in the columns, beams and slab and propagation of cracks in components contributed higher deflections in the slab. Curve exhibited considerable pinching and widening in the loops. Load and corresponding deflection values are in Table 7.

Results and Discussion

Middle long single-bay plain frame subjected to maximum deflection than the three bay frame with central bay brick infill bay. Initial deflections of the three bay frame were lower than the middle single long bay frame due to the presence of infill bay. Infill bay contributed additional strength and stiffness to the three bay frame. Equal deflection found in both the frame at the sixth cycle of the load. Brick infill started to fail along the diagonal and was starting to lose its equivalent strut effect; consequently, the deflection was increasing and equalizes the single bay frame deflection at this cycle. Deflections found higher in both the frame in the post-cycling shown in Fig. 11 (a). Middle column C_2 subjected to higher deflection than the column C_1. The presence of infill bay the three bay frame resisted maximum lateral force than the center single long bay frame, this led to lower deflection in column C_1. The single bay frame subjected to higher deflection than the three bay frame at the maximum load. The middle two columns of the three bay frame contributed additional stiffness with beams and obviously, the deflections were lesser in three bay frame as shown in Figure 11 (b)

Table 7
Load vs. vertical deflection of slab middle with beams

No.	Load, kN	Deflection, mm
1	0	0
2	2.5	0.3
3	5	-0.7
4	10	-0.2
5	12.5	-0.2
6	15	0.6
7	17.5	4.6
8	18	5.8
9	17.5	6.4
10	16.5	19.9
11	15.5	20.9
12	15	21.3
13	13.5	22.4
14	13	22.9
15	12.5	23.9

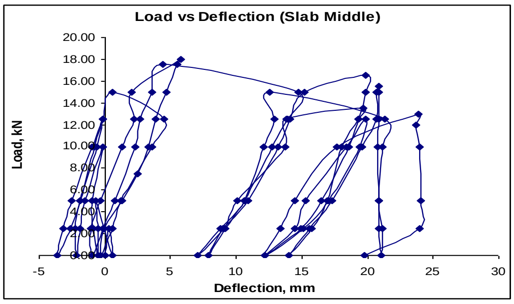

Fig. 10(a): Load vs. vertical deflection of slab middle with beams

Behavior and Mode of Failures: The first crack observed at the interface of beam and brick infill in infill bays. Minutes cracks found at beam column junction (C_5-B_3-B_5 junction) and minor cracks found in compression diagonal of brick infill in the initial stage. Diagonal crack found at beam –column joint (Figure 12 (c)) and diagonal cracks observed in all beam-column junctions in exterior and interior of the model building. Cracks in the beam - brick infill interface expanded during the fifth cycle. Compression diagonal cracks in the infill widened and separation of brick portions took place during 6th cycle. Visible hinges were found in all the junctions and the concrete cover in the exterior were starting to separate at this cycle. Line cracks found in slab and these cracks occurred in beam-slab junctions.

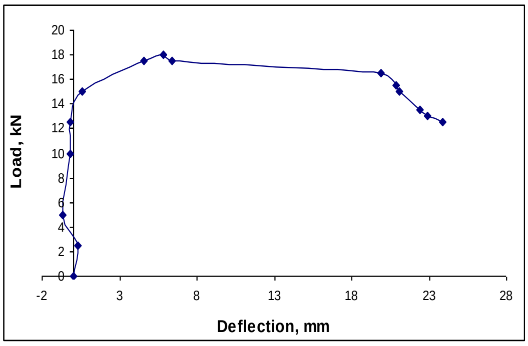

Fig. 10(b): Lateral load vs. vertical deflection of slab middle with beams (Back-Bone Curve)

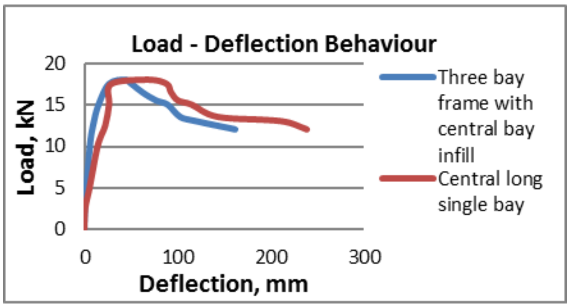

Fig. 11(a): Load-Deflection behavior of three bay frame and single long bay frame

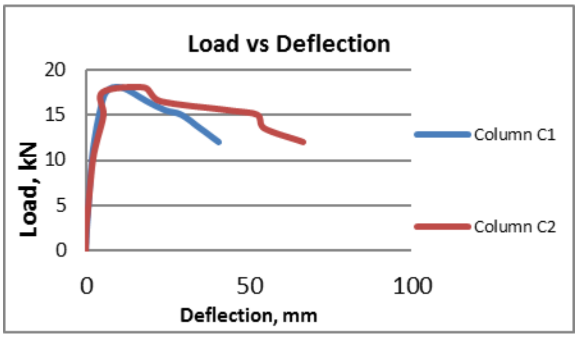

Fig. 11(b): Load-Deflection behavior of column C_1 and column C_2

Tension cracks found in the brick infill, along the tension region of brickwork at 7th cycle. Reinforcements yielded in all the columns and the brick infill crushed and lost their compression diagonal strut effect on the infill bay, finally, it collapsed at maximum load. Shear crack found in column C_6 and compression diagonal bottom of infill at maximum lateral load. Both infill compression and column compression adds and makes the column foundation suffer a failure in compression in the infill bay. Column C_2 failed by forming a typical column compression hinge (Figure 12 (g)) in post cycling. Anchorages have pulled in the column foundation junction (at column C_1, column C_8) (Figure 12 (f)). Beam-column and brickwork behaves as a monolithic unit up to first bed joint of the raft beam in the infill bay.

Flexure shear cracks initiated at column C_4 bottom and infill compression strut on beam-column joint. Cover spalling due to weakness of first bed joint of brickwork taken place (Figure 12 (e)). The beam separated from columns by noticeable sway bending of beam laterally at leeward side. Frame shows severe damage at beam-column joints and severe damage in foundation column joints in final stage of test and different crack patterns developed in frame. Interface cracks observed in the beam-column joints in the interior and exterior of the frame. Windward columns in the infill bay received shear in addition to bending because of the diagonal strut effect of the infill. Hence flexural shear cracks observed in loading faces of the windward columns of the infill bays shown in Figures 12 (b) and 12 (e). At the junction of the diagonal strut, leeward columns and foundation, the leeward columns of infill bays suffered shear and local buckling. These initiated the collapse in the infill bay. Tensile and compressive forces in the plane of the slab induced shear, bending and torsion in the transverse beams that caused torsional and flexure-shear cracks in the transverse beams**.** Leeward column of middle long single bay has suffered to excessive shear due to lateral loading; this was the result of formation of plastic hinge at top. This has led to the collapse of the long single bay. Major cracks observed on the tension side of the column foundation junctions. Lateral stiffness of slab was much higher to lateral load, and minor line cracks observed in slab without severe flexural cracks. The compression diagonal length of brick infill shortened and tension diagonal extended in final stage (Figure 12 (i)). Some of cracks witnessed shown in Figures 12 (a) to 12 (h). Also, the columns tend to separate from the foundation in the final cycles

Fig. 12(a): Deflected shape of frame

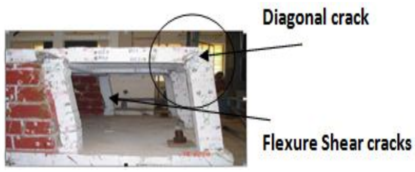

Fig. 12(b): Deflected shape of plain bay in windward side

Fig. 12(c): Crack in C_7-B_3-B_6 joint (Column - Beam Interface Crack) and spalling of concrete at beam-column junction

Fig. 12(d): Crack in C5-B3-B5 joint (Column-Beam Interface Crack) and spalling of concrete in beam-column junction

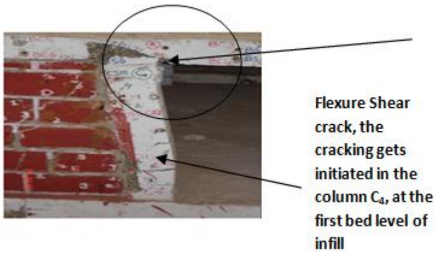

Fig. 12(e): Flexure shear crack in column C_4, crack in C_4-B_1-B_5 Joint and spalling of CONCRETE

Fig. 12(f): Cracks in foundation-Column C_1 joint

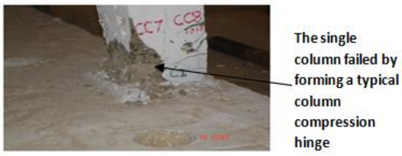

Fig. 12(g): Crack due compression in column C_2 and spalling of concrete

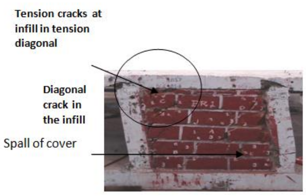

Fig. 12(h): Diagonal crack at infill in the final stage and spalling of concrete in beams and spalling of infill

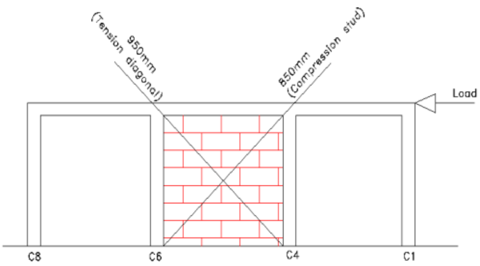

Fig. 12(i): Diagonals in tension and contraction of infill in the final stage

Conclusion

- The maximum deflection occurred in the middle long single bay frame without infill during collapse load along with slab and beams. To avoid this excess deflection, the column sections can enlarge and additional reinforcement can provide in the columns of plain bay frames.
- The three bay frames with center bay brick infill at both ends resisted a large amount of lateral load than the middle long single bay frame. In this frame, four columns and the middle brick infilled bay contributed to higher lateral load resisting capacity.
- Brick infill has given equivalent strut effect to the infill bay frame up to its failure. Brick infill failed at maximum load and loses its diagonal load resisting capacity. Windward column of infill bay subjected to shear buckling in post cycling.
- The length of the tension diagonal of the brick infill was 11.76 percent higher than the compression diagonal at collapsed condition. Windward columns of infill bay frames deflected towards windward side and leeward columns of infill bay frames deflected in the windward side in post cycling, these led to enlarge the tension diagonal length.
- The anchorages at windward columns bottom with raft slab have pulled at collapsed stage of the whole frame. This can avoid by providing additional reinforcement for anchorage at the foundation column joints.
- The hinge formation found at bottom compression side of windward column in middle long single plain bay frame. The column compression face subjected to excessive compressive force and consequently, the compression hinge found at bottom in the maximum lateral load. This can eliminate by enlarging the bottom section of the plain bays with additional confined reinforcements.
- The slab was starting to separate from the columns during post cycles and formed hinges at joints on the leeward side. This separation can resist by providing additional anchorage reinforcements at the column – beam joints.
- The brick infill damaged along the compression diagonal at maximum load and loses its diagonal strut effect. This can minimize using reinforced brick infill by providing horizontal or vertical reinforcements.
- Hinge formations and cover spalling found in beam-column joints at storey level and at collapsed load due to excessive load transferred to the joints. This hinges can reduce by enlarging the beam-column joints.
- The slab with beams contributed overall stiffness and strength to the whole three-dimensional RC frame. Little line cracks found in the slab in the collapsed condition.

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