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Study on failure mechanism of multi-storeyed reinforced concrete framed structures

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Abstract. Failure of a Multi-storeyed reinforced concrete framed structure occurs when a primary vertical structural component is isolated or made fragile, due to artificial or natural hazards. Load carried by vertical component (column) is transferred to neighbouring columns in the structure, if the neighbouring column is incompetent of holding the extra load, this leads to the progressive failure of neighbouring members and finally to the failure of partial or whole structure. The collapsing system frequently seeks alternative load path in order to stay alive. One of the imperative features of collapse is that the final damage is not relative to the initial damage. In this paper, the effect on the column and beam adjacent to statically removed vertical element in terms of axial force, shear force and bending moment is investigated. Using Alternate load path method, numerical modelling of two dimensional one bay, two bay with variation in storey heights are analysed with FE model in order to obtain better understanding of failure mechanism of multi-storeyed reinforced concrete framed structure. The results indicate that the corner column is more susceptible to progressive collapse when compared to middle column, using this simplified methodology one can easily predict how the structure can be made to stay alive in case of sudden failure of any horizontal or vertical structural element before designing.

Keywords: progressive collapse; static linear analysis; multistoried buildings; damage; reinforced concrete framed structure; load distribution

1. Introduction

The "Progressive Collapse" has been used to depict the extend of an initial local failure in a manner equivalent to a chain reaction that leads to partial or total collapse of a multi-storeyed building. The most important characteristic of progressive collapse is that the final state of failure is unreasonably greater than the failure that initiated the failure of structural element.

Progressive collapse first fascinated the attention of researchers from the partial failure of Ronan Point 22 storeys apartment in London, in 1968 (Pearson and Dellatte 2005). The cause of

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the failure was a gas explosion. After the event of 11 September 2001, more researchers have engaged on the causes concepts and structural robustness of progressive collapse, which have been reflected in new guidelines. The potential irregular loads that can trigger failure of structures are categorized as: aircraft impact, design and construction errors, fire, gas, bomb explosions, accidental overload, hazardous materials and vehicular collision, etc.

Among numerous different methods used to design buildings against progressive collapse, the GSA guidelines recommend Alternate Load Path method[ALP] as a threat independent methodology, which means it does not consider the cause of initial local failure rather it considers structural response after the initial failure(GSA Guidelines and DoD).The response of building against progressive collapse can be studied using the four approaches, linear static analysis, linear dynamic analysis ,non-linear static analysis and non-linear dynamic analysis.

Several investigators have identified, demonstrated and proved failure of structures by using ALP method. There is an increasing recognition for the researchers conducted on the proposed case are:

Hayes *et al*. (2005) investigated the validity of seismic strengthening schemes to mitigate the risk of blast and progressive collapse of reinforced concrete buildings It is obvious that the preventing the progressive collapse by implementing seismic strengthening schemes adopted by them represented increasing the strength of the building rather than enhancing the continuity and the ductility of that building.

Khalid M. *et al*. (2008), a realistic seismically deficient and retrofitted R.C beam-column with a reduced 1/3rd scale were treated experimentally using shake table tests and compared with analytical results, which was found to be valid when direct element removal was done.

Sasani and Sagiroglu (2008) conducted several experimental investigations and they have also shown a progressive impairment on the structured six-storey reinforced concrete frame. They have displayed the convincing data with bidirectional Vierendeel (frame) action and considered it as an excellent mechanism in redistributing the loads. They have concluded that with consistent flexural reinforcements and thereby providing excess resistance to the such collapse at high level.

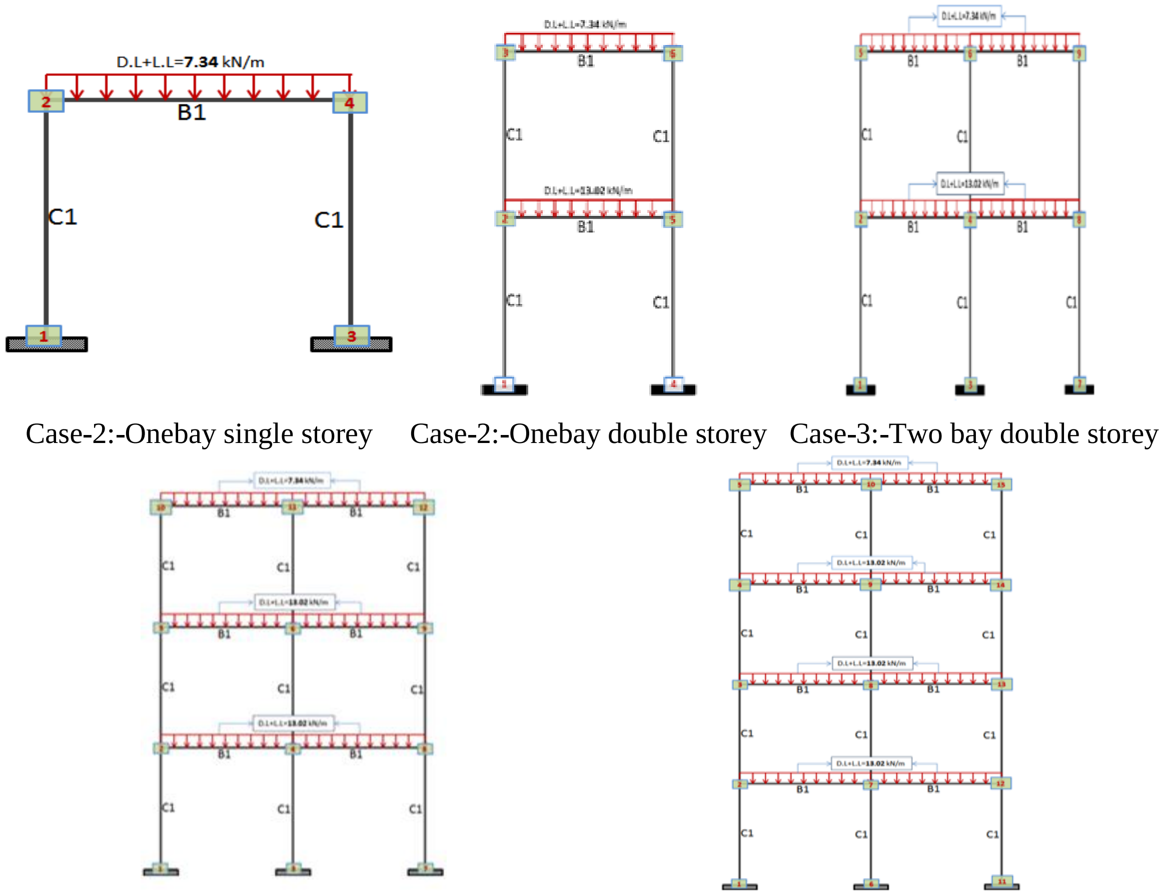
YihaiBao and Shashi K Kunnath (2010) developed a shear wall model for various seismic zones and calculated the behaviour due to collapse of shear wall at first storey. Their study made it evident that frames designed to resist seismic loads were more robust compared to frames designed without seismic loading.

Sasani *et al*. (2011) hypothesized and analysed eleven-storied hotel namely RC Crown Plaza in Houston, USA. This was subjected to resist primary damage at experimental location. The results revealed that it is more prominent to frame similar model for elastic strength and axial stiffness at the base or the floor elements. This is precisely advocated for partial affect in the performance of in-plane floor.

Tsai and Huang (2011)) studied the efficacy on the level of performance and their respective response of a building equipped with reinforced concrete via three kinds of infilled walls. They have gained some profound data with the resistance of the experimental buildings against raised collapse followed by sudden column loss and resistance increased markedly via wing-type walls. The bending potential of the structure was found to be minimized with the usage of exteriorly non-structured walls.

Rohit b *et al*. (2014) found that precast connections were most capable in resisting higher loads in comparison to monolithic connections. Ductility of precast connection is more under column collapse scenario compared to monolithic connections.

Tavakoli *et al*. (2014) performed Nonlinear static analysis and investigated the response of



Case-2:-Onebay single storey Case-2:-Onebay double storey Case-3:-Two bay double storey

Case-4:-Two bay three storey Case-5:-Two bay four storey

Fig. 1 Different types of 2D reinforced concrete frames considered for Analysis

various lateral loads under presence of infill walls against shear strength and seismic performance. They came up with vital information against seismic safety of reinforced concrete frames. E. Brunesi *et al*. (2015) conducted analytical study on Fragility models for low rise RC bare frame structures under gravity load and earthquake load. This result revealed that the earthquake resistant design frame was resistant to progressive collapse also when compared to frame designed only for gravity loads.

Pham Xuandat *et al*. (2015) carried out experimental tests on beam-slab sub-assemblages and checked analytically applying yield line method. If continuous reinforcement or extra lap length is provided in the bottom part of joints. Such joints were found to mitigate collapse of RC structures.

Yi *et al*. (2016) evaluated the performance in reinforced concrete model. The considerable frame with a measure of 1/3 scale at lower three storeys of a prototype eight-storey reinforced concrete building designed according to the code of China. Only three storeys and four bays plane frame of the building model was considered in the investigations. On the other hand, a simple analytical analysis was conducted based on the plastic mechanism of the frame model. They concluded that adopting plastic limit design provides safe and conservative results. Also, it was concluded that the catenary action is the alternate resistance path beyond the flexural load path.

Abbasnia *et al*. (2016) calculated the sustainability of beams and their vertical displacements under accidental loading. A theoretical approach was actuated, and these results were validated with experimental results. The ability to withstand collapse against sudden loading due to element loss was also explained.

In recent years, Emanuele Brunesi and FalvioParisi (2017) suggested new fragility models on basis of push down analysis for reinforced concrete bare framed structures designed as per European code. Their study revealed that secondary beams designed to resist self-weight more stiffness under column loss.

As huge experimental set-up is needed to validate the simulation results, modelling procedures are mostly preferred to understand the failure mechanism scenario. In this paper, only the effect of initial local failure is investigated so that one can clearly understand the difference between not considering local failure and considering structural response after the initial failure.

2. Methodology

For the analysis, a total of five cases are considered as shown in Fig 1. The height of each storey is taken as 3 m. To observe the probable capacity for progressive damage with different reinforced framed structures symmetrical about x-axis or y-axis or about both x and y-axis by using a linear static analysis, and removal state and conditions with two required columns considerably as:

1) Failure of Corner Column.
2) Failure of Middle Column.

Frame structures are hypothetically designed by employing FE model as per IS 456:2000 and IS 1893 load combinations. Linear Static Analysis is performed for each case of column removal. In this analysis, column is removed and separated from the location and the effect on various parameters such as axial force, Shear force and Bending moment are determined. The amounts of changes in those parameters before and after column failure are investigated in order to understand the failure mechanism. These changes are presented in tabular form.

3. Model description

In this paper, reinforced concrete framed structures of one bay single storey, one bay double storey, two-bay double storey, two-bay three storey and two-bay four storey frames having each floor of height 3m, with square plan and typical bays of width 3 m were simulated using FE model.

3.1 Material and sectional property

These models were designed and checked as per Indian Standard codes (IS 875-Part1, Part2). The dimensions of columns and beams for all stories are 230 mm x 230 mm. Material properties used for the structures are M25 for beams and M30 for columns. The elasticity modulus of steel and concrete are 200000 MPa and 25000 MPa (beams) to 27000 MPa (columns) respectively. In addition to the self-weight of structural elements, the Dead load (DL) of 5.08 kN/m for the roof

Table 1 Case - 1

Case No.	Axial Force on Adjacent Column (kN)			Axial Force on Adjacent Beam (kN)		
Case-1	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Column	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Beam
	19.01	32.47	1.7	2.29	0	0
	Shear Force on Adjacent Column (kN)			Shear Force on Adjacent Beam (kN)		
	2.29	0	Decreases by 2.29 times	13.46	26.91	2
	Bending Moment in Adjacent Column (kN-m)			Bending Moment in Adjacent Beam (kN-m)		
	4.6	40.37	8.8	5.50	40.37	7.35

Table 2 Case - 2

Case No.	Axial Force on Adjacent Column (kN)			Axial Force on Adjacent Beam (kN)		
Case-2	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Column	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Beam
	49.96	94.36	1.88	1.51	11.98	7.9
	Shear Force on Adjacent Column (kN)			Shear Force on Adjacent Beam (kN)		
	2.27	0	Decreasesby2.27	25.39	63.79	2.5
	Bending Moment on Adjacent Column (kN-m)			Bending Moment on Adjacent Beam (kN-m)		
	4.55	133.21	29.3	10.59	90.37	8.5

floor and 10.77 kN/m for other floors. Live load (LL) of 2.25 kN/m was taken for roof floor and other floors.

4. Results and discussions

This current study is to investigate the possible action on the adjacent columns and beams in terms of axial force, shear force and bending moment after the removal of corner Column and middle Column. In this context, linear static analysis has been performed to assess the effects with an increase in storey and bays of structure while removing column only at ground storey. One of the considerable significant effects with the column removal phenomenon is that the forces with respect to its adjacent columns and beams are notably altered. The total load of the impaired elements was transferred to adjacent columns in the form of impact load. Collusively, these extra forces imparted on to the columns must be estimated to enquire whether the structures could maintain a balance as bridging platform over the notionally removed corner column. Accordingly, five cases have been analysed to investigate extra axial force, shear force and bending moment imposed on adjacent columns and beams. So that the failure mechanism can be easily understood for better performance of structures.

After removing the corner column C1 with nodes (3,4) in the ground storey of one bay single storey as shown in Fig. 2 and Table1: case-1, the axial compressive forces, shear force and bending

Case-1: One bay single storey reinforced concrete framed structure

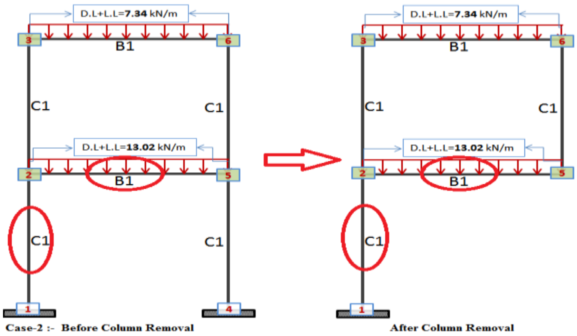


Fig. 2 Location of elements of one bay single storey 2D Reinforced Concrete Framed Structure for Analysis, Red Color Circles specify the structural elements, the effect of column removal are examined on these elements

Case-2: One bay double storey reinforced concrete framed structure

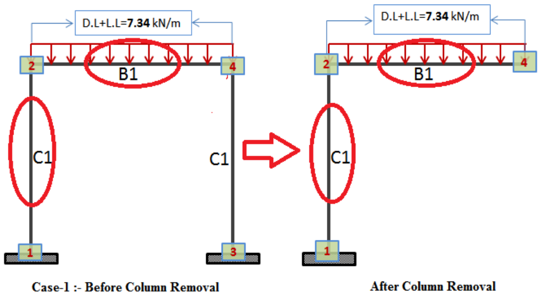


Fig. 3 Location of elements of one bay double storey 2D Reinforced Concrete Framed Structure for Analysis, Red Color Circles specify the structural elements, the effect of column removal are examined on these elements

Case-3: Two bay double storey reinforced concrete framed structure

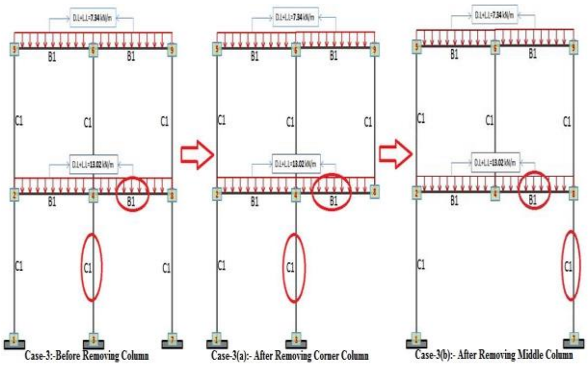


Fig. 4 Location of elements of two bay double Storey 2D Reinforced Concrete Framed Structure for Analysis, Red Color Circles specify the structural elements, the effect of column removal are examined on these elements

Table 3 Case-3a

Case No.	Axial Force on Adjacent Column (kN)			Axial Force on Adjacent Beam (kN)		
Case-3a	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Column	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Beam
	100.53	186.09	1.85	1.43	14.44	10.09
	Shear Force on Adjacent Column (kN)			Shear Force on Adjacent Beam (kN)		
	0	2.1	Increases by large no	28.91	52.87	1.82
	Bending Moment in Adjacent Column (kN-m)			Bending Moment in Adjacent Beam (kN-m)		
	0	10.52	Increases by large no	15.16	55.99	3.69

Table 4 Case-3b

Case No.	Axial Force on Adjacent Column (kN)			Axial Force on Adjacent Beam (kN)		
Case-3b	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Column	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Beam
	50.84	98.13	1.93	1.43	11.81	10.09
	Shear Force on Adjacent Column (kN)			Shear Force on Adjacent Beam (kN)		
	2.15	8.54	3.97	28.91	51.29	1.77
	Bending Moment in Adjacent Column (kN-m)			Bending Moment in Adjacent Beam (kN-m)		
	4.33	17.11	3.94	15.16	45.79	3.02

Table 5 Case-4a

Case No.	Axial Force on Adjacent Column (kN)			Axial Force on Adjacent Beam (kN)		
Case-4a	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Column	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Beam
	162.21	312.37	1.93	1.83	12.55	6.85
	Shear Force on Adjacent Column (kN)			Shear Force on Adjacent Beam (kN)		
	0	3.05	Increases by large no	28.73	54.81	1.91
	Bending Moment in Adjacent Column (kN-m)			Bending Moment in Adjacent Beam (kN-m)		
	0	13.04	Increases by large no	14.89	60.54	4.06

and (2.29 kN, 13.46 kN, 5.50 kN-m) on the adjacent beam respectively.

After the support was lost the compressive axial force, shear force, bending moment obtained from structural analysis were (32.4 kN, 0 kN, 40.37 kN-m) on the adjacent column and (0 kN, 26.91 kN, 40.37 kN-m) on the adjacent beam. According to gained results, the compressive axial force increases by 1.7 times, shear force decreases by 2.28 times and bending moment increases by 8.8 times in the adjacent column after column removal. On the adjacent beam the compressive axial force decreases to 0, shear force increases by 2 times and bending moment increases by 7.35

Case-4: Two-Bay Three Storey Reinforced Concrete Framed Structure

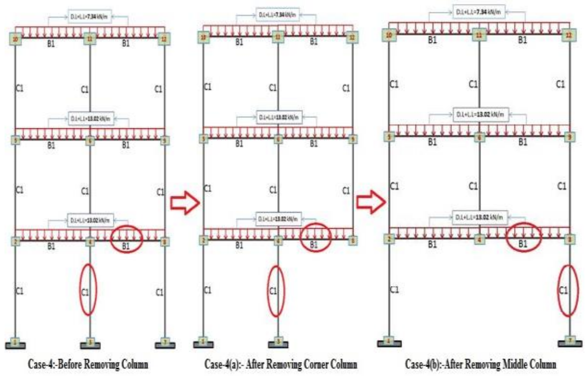


Fig. 5 Shows the Location of elements of two bay three storey 2D Reinforced Concrete Framed Structure which are to be Analyzed, Red Color Circles specify the structural elements, the effect of column removal are examined on these elements

times after column removal.

After removing the corner column C1 with nodes (4,5) in the ground storey of one bay single storey as shown in Fig 3 and Table 2: case2, the axial compressive forces, shear force and bending moment have increased significantly in the adjacent column and beam of the reinforced concrete framed structure shown in Fig 3 by red colour circles. The compressive axial force, shear force and bending moment computed from Linear Static Analysis before failure collapse were (49.96 kN, 2.27 kN, 4.55 kN-m) on the adjacent column and (1.51 kN, 25.39 kN, 10.59 kN-m) on the adjacent beam respectively. After the support was lost the compressive axial force, shear force, bending moment obtained from structural analysis were (94.36 kN, 0 kN, 133.21 kN-m) on the adjacent column and (11.98 kN, 63.79 kN, 90.37 kN-m) on the adjacent beam. According to gained results, the compressive axial force increases by 1.88 times, shear force decreases by 2.27 times and bending moment increases by 29.3 times in the adjacent column after column removal. On the adjacent beam the compressive axial force increases to 7.9 times, shear force increases by 2.5 times and bending moment increases by 8.5 times after column removal.

After removing the corner column C1 with nodes (7,8) in the ground storey of two bay double storey as shown in Fig. 4 and Table3: case-3a, the axial compressive forces, shear force and bending moment have increased significantly in the adjacent column and beam of the reinforced concrete framed structure shown in Fig 4 by red colour circles. The compressive axial force, shear force and bending moment computed from Linear Static Analysis before failure collapse were (100.53 kN, 0 kN, 0 kN-m) on the adjacent column and (1.43 kN, 28.91 kN, 15.16 kN-m) on the adjacent beam respectively. After the support was lost the compressive axial force, shear force, bending moment obtained from structural analysis were (186.09 kN, 2.1 kN, 10.52 kN-m) on the adjacent column and (14.44 kN, 52.87 kN, 55.99 kN-m) on the adjacent beam. According to gained results, the compressive axial force increases by 1.85 times, shear force increases by large no and bending moment increases by large no in the adjacent column after column removal. On the adjacent beam the compressive axial force increases to 10.09 times, shear force increases by 1.82 times and bending moment increases by 3.69 times after column removal.

Table 6 Case-4b

Case No.	Axial Force on Adjacent Column (kN)			Axial Force on Adjacent Beam (kN)		
Case-4b	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Column	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Beam
	83.34	161.47	1.93	1.83	7.09	3.87
	Shear Force on Adjacent Column (kN)			Shear Force on Adjacent Beam (kN)		
	2.13	10.03	4.7	28.73	52.74	1.83
	Bending Moment in Adjacent Column (kN-m)			Bending Moment in Adjacent Beam (kN-m)		
	4.27	20.13	4.71	14.89	47.27	3.17

Table 7 Case-5a

Case No.	Axial Force on Adjacent Column (kN)			Axial Force on Adjacent Beam (kN)		
Case-5a	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Column	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Beam
	207.54	409.39	1.97	1.27	13.60	10.70
	Shear Force on Adjacent Column (kN)			Shear Force on Adjacent Beam (kN)		
	0	3.05	Increases by large no	26.71	53.07	1.98
	Bending Moment in Adjacent Column (kN-m)			Bending Moment in Adjacent Beam (kN-m)		
	0	13.19	Increases by large no	13.71	59.76	4.35

After removing the middle column C1 with nodes (3,4) in the ground storey of two bay double storey as shown in Fig. 4 and Table 4: case 3b, the axial compressive forces, shear force and bending moment have increased significantly in the adjacent column and beam of the reinforced concrete framed structure shown in Fig 4 by red colour circles. The compressive axial force, shear force and bending moment computed from Linear Static Analysis before failure collapse were (50.84 kN, 2.15 kN, 4.33 kN-m) on the adjacent column and (1.43 kN, 28.91 kN, 15.16 kN-m) on the adjacent beam respectively. After the support was lost the compressive axial force, shear force and bending moment obtained from structural analysis were (98.13 kN, 8.54 kN, 17.11 kN-m) on the adjacent column and (11.81 kN, 51.29 kN, 45.79 kN-m) on the adjacent beam. According to gained results, the compressive axial force increases by 1.93 times, shear force increases by 3.97 times and bending moment increases by 3.94 times in the adjacent column after column removal. On the adjacent beam the compressive axial force increases to 10.09 times, shear force increases by 1.77 times and bending moment increases by 3.02 times after column removal.

After removing the corner column C1 with nodes (7,8) in the ground storey of two bay three storey as shown in Fig. 5, Table5: case4a, the axial compressive forces, shear force and bending moment have increased significantly in the adjacent column and beam of the reinforced concrete framed structure shown in Fig. 5 by red colour circles. The compressive axial force, shear force and bending moment computed from Linear Static Analysis before failure collapse were (162.21 kN, 0 kN, 0 kN-m) on the adjacent column and (1.83 kN,28.73 kN,14.89 kN-m) on the adjacent beam respectively. After the support was lost the compressive axial force, shear force, bending

Case-5: Two bay four storey reinforced concrete framed structure

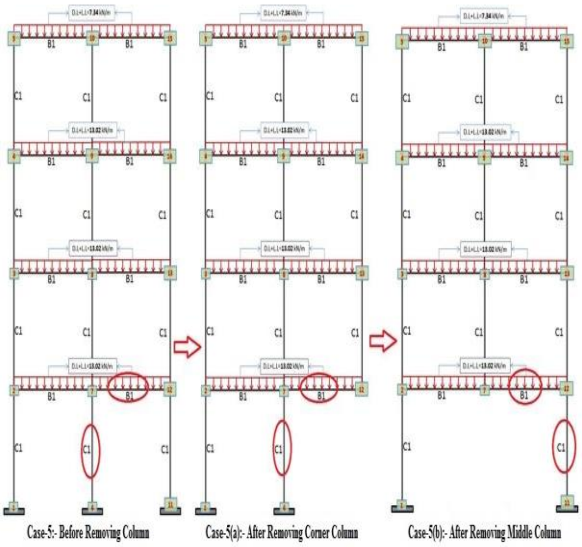


Fig. 6 Shows the Location of elements of two bay four storey 2D Reinforced Concrete Framed Structure which are to be Analyzed, Red Color Circles specify the structural elements, the effect of column removal are examined on these elements

Table 8 Case-5b

Case	Axial Force on Adjacent Column (kN)			Axial Force on Adjacent Beam (kN)		
	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Column	Before Column Removal	After Column Removal	% of Change Obtained in Adjacent Beam
Case-5b	108.83	209.83	1.97	1.27	7.73	6.08
	Shear Force on Adjacent Column (kN)			Shear Force on Adjacent Beam (kN)		
	2.02	9.58	4.74	26.71	50.58	1.89
	Bending Moment in Adjacent Column (kN-m)			Bending Moment in Adjacent Beam (kN-m)		
	4.051	19.223	4.74	13.71	46.04	3.35

moment obtained from structural analysis were (161.47 kN, 10.83 kN, 20.13 kN-m) on the adjacent column and (7.09 kN, 52.74 kN, 47.27 kN-m) on the adjacent beam. According to gained results, the compressive axial force increases by 1.93 times, shear force increases by 4.7 times and bending moment increases by 4.71 times in the adjacent column after column removal. On the adjacent beam the compressive axial force increases to 3.87 times, shear force increases by 1.83 times and bending moment increases by 3.17 times after column removal.

After removing the corner column C1 with nodes (11,12) in the ground storey of two bay four storey as shown in Fig. 6 and Table7 case5a, the axial compressive forces, shear force and bending moment have increased significantly in the adjacent column and beam of the reinforced concrete framed structure shown in Fig 6 by red colour circles. The compressive axial force, shear force and bending moment computed from Linear Static Analysis before failure collapse were (207.54 kN, 0 kN, 0 kN-m) on the adjacent column and (1.27 kN, 26.71 kN, 13.71 kN-m) on the adjacent beam respectively. After the support was lost the compressive axial force, shear force, bending moment obtained from structural analysis were (409.39 kN, 3.05 kN, 13.19 kN-m) on the adjacent column and (13.6 kN, 53.07 kN, 59.76 kN-m) on the adjacent beam.

According to gained results, the compressive axial force increases by 1.97 times, shear force increases by large no and bending moment increases by large no in the adjacent column after column removal. On the adjacent beam the compressive axial force increases to 10.70 times, shear force increases by 1.98 times and bending moment increases by 4.35 times after column removal.

After removing the middle column C1 with nodes (6,7) in the ground storey of two bay four storey as shown in Fig. 6 and Table 8: case 5b, the axial compressive forces, shear force and bending moment have increased significantly in the adjacent column and beam of the reinforced concrete framed structure shown in Fig. 6 by red colour circles. The compressive axial force, shear force and bending moment computed from Linear Static Analysis before failure collapse were (108.83KN, 2.02KN, 4.051KN-m) on the adjacent column and (1.27KN, 26.71KN, 13.71KN-m) on the adjacent beam respectively. After the support was lost the compressive axial force, shear force, bending moment obtained from structural analysis were (209.83KN, 9.58KN, 19.223KN-m) on the adjacent column and (7.73KN, 50.58KN, 46.04KN-m) on the adjacent beam. According to gained results, the compressive axial force increases by 1.97 times, shear force increases by 4.74 times and bending moment increases by 4.74 times in the adjacent after column removal. On the adjacent beam the compressive axial force increases to 6.08 times, shear force increases by 1.89 times and bending moment increases by 3.35 times after column removal.

5. Conclusions

A. *Conclusions in terms of effect on Adjacent Columns:*

- In case of single bay 2D structures, the axial force in adjacent column for which it was designed as per IS 456:2000 increased by an average of 1.80 times after the removal of corner column.
- In case of two bay 2D structures, the axial force in adjacent column for which it was designed as per IS 456:2000 increased by an average of 1.93 and 1.94 times after the removal of middle column and corner column respectively.
- Thus, it can be concluded that axial force on the adjacent column increases on a average of two times after the removal of any vertical structural element which is in accordance with GSA guidelines.
- The effect of shear force and bending moment on the adjacent column before and after removal of first storey column was also noticed and it was found that in case of single bay 2D structures shear force on adjacent column after removal of first storey corner column decreased by large number whereas the bending moment increased by large number (8.8 times for single storey and 29.3 times for single bay-two storey 2D structures).
- In case of two bay-2D structures when corner column is removed the shear force and bending moment increases by large no and when middle column is removed it increases by an average of 4.6 times.

B. *Conclusions in terms of effect on Adjacent Beams:*

- In case of single bay 2D structures, the bending moment on the adjacent beams for which they were designed in accordance with IS 456:2000 increased by an average of 8 times after the removal of corner column. Whereas shear force increases only by an average of 2.25 times the original one.
- In case of two bay 2D structures, the bending moment in adjacent beams for which they were designed as per IS 456:2000 increased by an average of 3.3 and 4.2 times whereas shear force increases by an average of 1.9 and 1.94 times the original number after the removal of middle column and corner column respectively.
- In case of single bay 2D structures, the axial force in the adjacent beam increases by an average of approximately 8 times the original one. This effect is noticed only as the number of storey's are increased since there is no such effect observed in single storey.
- In case of two bay 2D structures, the axial force in adjacent beams in symmetrical structures (both about x-axis and y-axis) after the removal of corner column increases by an average of 10.4 times the original number and 7.6 times when the structure is symmetrical only about y-axis. On the other hand, when middle column is removed it increases by an average of 7.2 times (structures symmetric about both axis) and 4.1 times the original number (structures symmetric about only y-axis). Thus, Symmetry of the structure should also be considered while designing progressive collapse resistant structures.
- The Axial force on the beams before column removal is negligible when compared to shear force and bending moment. As beams are designed only for shear force and bending moment. Hence can be neglected.

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