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# Prevention of collapse: Analysis and Design

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***Abstract***— ***Throughout the ages men were engaged in construction activities besides other pursuits - to build their dwellings and shelter other activities. They willed to make these structures safe and free from collapse and hence employed various methods and designs. However in spite of all precautions it is impossible to guarantee the safety from collapse and destruction due to unforeseen causes. Some of the causes could be related to human errors like: poor design, faulty construction, foundation failures, extraordinary loads, compromising on quality of building materials, workmanship for economic reasons, negligence in enforcing building codes and their compliance laxity in supervision, inspection and approval by authorities etc. the other cause could be gas explosions, soil liquefaction, terrorist attacks, material degradations etc. It is admitted that it is uneconomical to design the structure for unforeseen events unless they have a reasonable chance of occurrence. The project study "Prevention of collapse: Analysis and design" is presumedto help understand the collapse behavior of structure and accordingly design to prevent drastic, severe failures and save human lives and property. Secondly the practices employed to ensure safety and prevent collapse are to incorporate redundancies in structure in the form of detailing, ductile designs, tying of elements at particular locations, provision of hinges and their connections. However this study is limited to understand the outcome of failures for G+5 buildings for column loss on different storeys, the adjacent beams, the increased loads on columns and footings studied and its resistances to failures and accordingly some measures are noted to prevent further collapse and danger.***

***Index Terms***— ***axial loads, column removal scenario, collapse resisting mechanisms, load redistribution***

## I. INTRODUCTION

In everyday experience we note, whenever there is an impact of an unexpected action on a structure there is proportionate damage. This damage can either be stopped/brought to a halt or it progresses to reach a higher level of damage. Structures built according to the current design codes showed that they are not robust under the action of accidental/unexpected loads and fail sequentially. When the structure losses one or more vertical load bearing members it fails. In determinate structures, loss of single element causes larger damage whilst incase of indeterminate structures it is not so, as other elements compensate the local damage and distribute the load of damaged element to the undamaged nearby members. The structural robustness is a function of its degree of redundancy i.e. the structures ability to redistribute the loads. The mitigation of progressive collapse in buildings became an urgent demand in structural engineering environment. Aiming to provide the designers with wider overview on collapse to minimize the consequence of progressive collapse in buildings after the event of column loss, this study analysis the collapse behavior for different column loss locations. Emphasis on reinforcement details, recommendations for steel in vulnerable members and some measures to incorporate robustness in buildings is the main objective.

## II. UNDERSTANDING COLLAPSE

Failure of structure to maintain its structural integrity is referred to as collapse. Any failure starts when the element is stressed beyond its strength limits causing fracture or excessive deformation. Mechanism of collapse is the crushing of joint concrete followed by the fracture of the steel bar. The state of beams in proximity to the damaged column changes from compressive arch action to cantilevering and the disconnection of horizontal with the vertical ones causes the final collapse. Survey on building collapse presented by Starossek [1] divided the failures into six types namely: Pancake, Zipper, Domino, Section type, Instability and Mixed type. As a result of the consequences of these collapses many research institutes target on improving and revising the design guidelines to prevent the damage from spreading and increase the buildings resistance to collapse. All these guidelines [2,3] converge to three basic methods of collapse prevention: a) Event control where the structure is protected and isolated from any accidental events; b) Direct design which focuses on providing resisting mechanisms like Alternate Load Paths (ALP's) transferrin the loads to the intact regions through Vierendeel and Catenary/ Membrane actions, Specific Local Resistance (SLR) providing strength to the vulnerable elements to withstand unforeseen loads. C) Indirect Design approach promising minimum level of strength, ductility and continuity of building elements depending on plan layout, horizontal and vertical tie systems and seismic ductile detailing.

## III. MODELLING PROCEDURE

A G+5 storey RC building structure with bay width 20m along X and 15m along Y direction [see fig 1] with each floor height of 3.2m and slab thickness of 125 mm is modelled to check the potential of the building to collapse. Grade of concrete used is M30 for beams columns and slabs, grade of steel Fe 415 for main reinforcement. All beams are

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300x450mm and columns 300x450mm. Loadings were assigned using LL- 3kN/m$^2$, FL- 1kN/m$^2$ and wall load of 12.65 kN/m$^2$. Fixed support conditions were assigned and the structure was analysed under Indian Standards loadings 1.5(DL +LL). Twenty one models were prepared using similar procedure. Column loss was initiated by just a delete command and analysis were carried out.

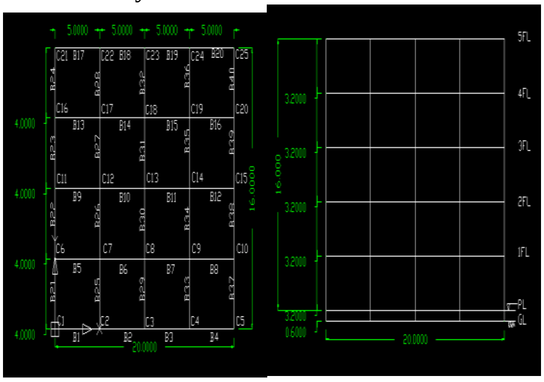

**Fig 1. Architectural plan and elevation view.**

## IV. ANALYSIS FOR COLUMN LOSS SCENARIOS

According to literature column is the most critical element in a structure. When a structure fails, the remaining structural elements provide an alternative path that redistributes the loads of the structure. After redistribution, each element will support the new loads. If this new load exceeds the load carrying capacity of any member, it will cause another failure. These sequential failures can propagate through a structure, and if the structure loses too many members, it may suffer partial or total collapse, therefore the study of loads coming on adjacent columns after certain column loss is of great importance.

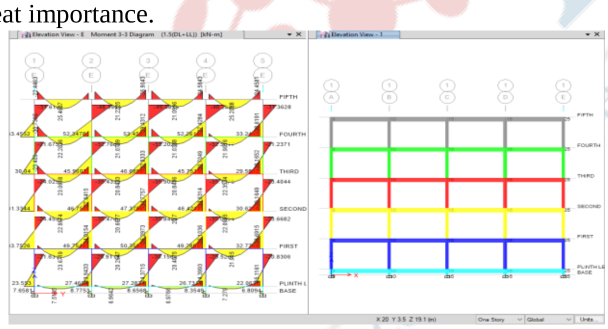

**Fig 2: Image of bending moement diagram for NCS case**

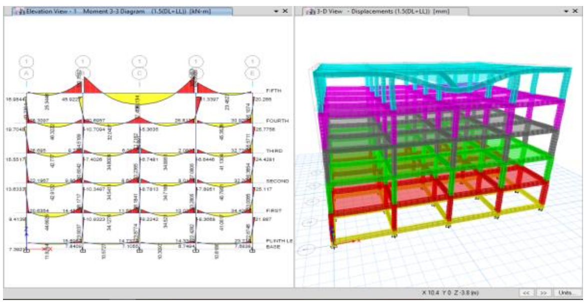

**Fig 3: Image of bending moment diagram for fourth floor long edge column loss case (CFFEL)**

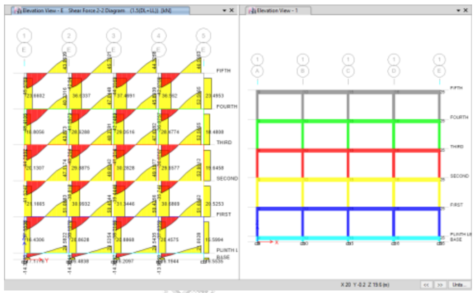

**Fig 4: Image of shear force diagram for NCS case**

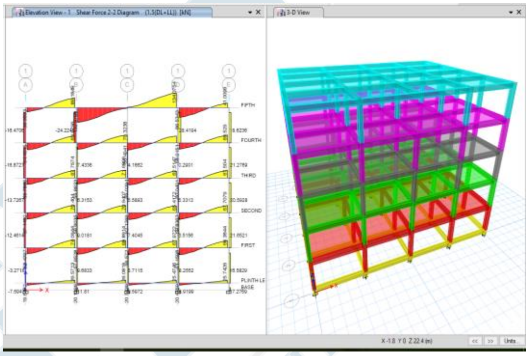

**Fig 5: Image of shear force diagram for CFFEL case**

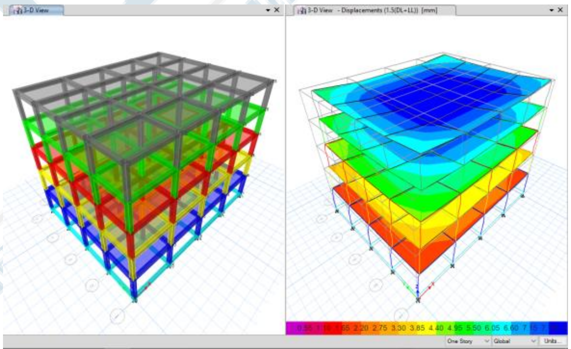

**Fig 6: Image of displacement resultant diagram for NCS case**

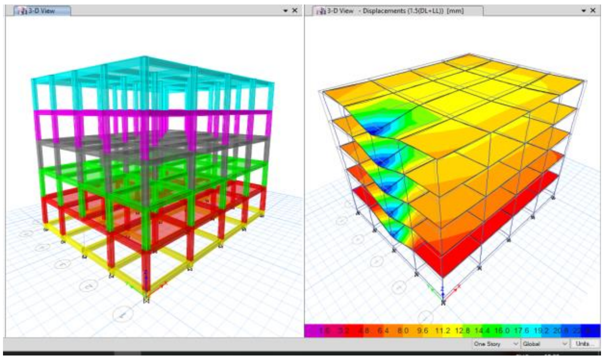

**Fig 7: Image of displacement resultant diagram for column loss on ground floor alon short edge (CGES) case**

On interior column loss the structure undergoes different stages [4], It observes an increase in bending moment in the reversed direction due to duplication of span of the beam above the damaged/lost column [see fig 2]. Therefore the

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regions previously designed to resist negative moments now have to encounter positive moments. The structure can resist the collapse through different mechanisms. The most important mechanisms are:

1. *Vierendeel action*: On duplication of spans, bending moments are enlarged while others are changed to elements opposite sides therefore uniform reinforcements is to be provided in every horizontal member. Main stresses in columns for intact structures/ no column loss (NCS case) are compressive in nature. On removal of column it initiates the formation of significant moments, which in turn develops tensile stresses due to vierendeel action, thus causing different straining actions in different storeys. Special transverse reinforcement at beam column joint locations and the use of seismic reinforcement detailing in lower storeys thus helps in improving structures resistance to collapse.
2. *Compressive Arch Action*: The axial horizontal restraints provided by beams and slabs supported by the damaged column resist further collapse through this action until reaching specific vertical displacements. The horizontal constraints decrease when the beams and slabs are at higher deflection values as compared to its thickness i.e. CAA can increase loading capacity of axially restrained beams depending on higher beam tensile steel ratio and lower span to depth ratio.
3. *Catenary Action*: At large deflection, the axial force in the beam or slab is converted to tensile action, this tensile force in the member has a vertical component due to high deflection which helps to resist increased loads due to column loss. This action is developed at large displacements because the amount of vertical force is directly related to the rotation angle. Elements with continuous reinforcements and proper anchorage detailing at joints with high rotation capacities are to be provided to increase structures resistance.
4. *Other RC slab mechanisms and contribution of non-structural elements such as external walls and partitions:* Considering membrane actions improves its performance in terms of achieving higher cracking and ultimate loads before failure however it is effective only in case of interior column loss while its contribution is less for exterior or corner column loss.

## V. RESULTS AND SUMMARY

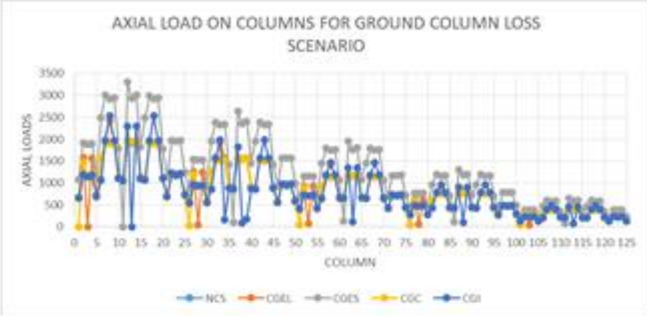


**Fig 8. Graph showing the axial loads on columns after ground floor column loss**

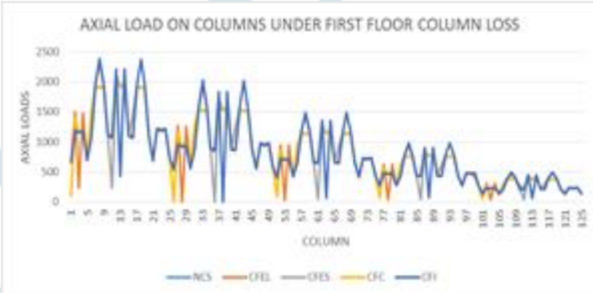


**Fig 9. Graph showing the axial loads on columns after first floor column loss**

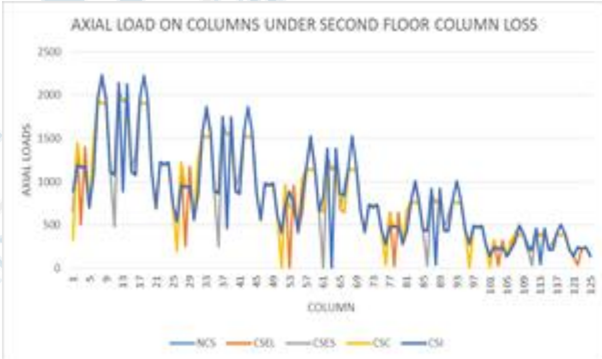


**Fig 10. Graph showing the axial loads on columns after second floor column loss**

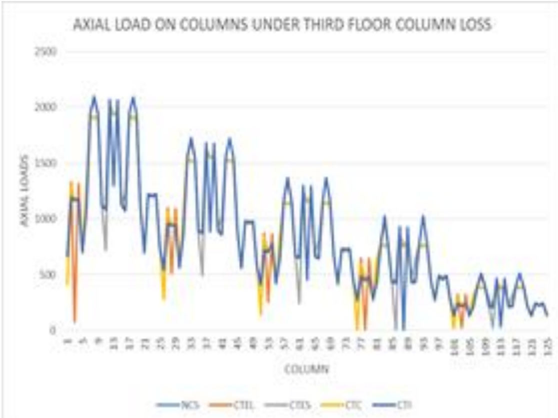


**Fig 11. Graph showing the axial loads on columns after third floor column loss**

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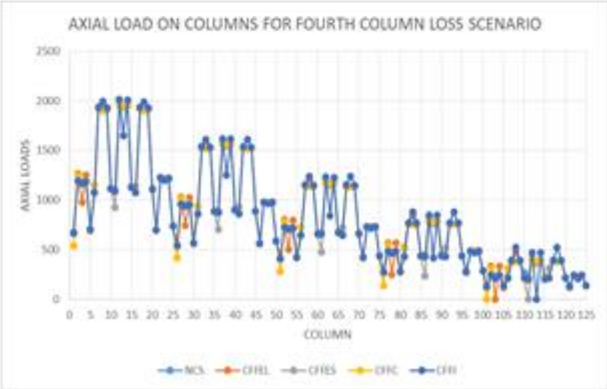


**Fig 12. Graph showing the axial loads on columns after fourth floor column loss**

Although, most of the columns are loaded higher for NCS case as compared to the other cases, it was seen that incase of ground floor short edge column loss all the ground columns were loaded higher i.e. 60% higher than the load during NCS case. Also it is to be noted that interior column loss at different storeys too have major effect on the ground columns as compared to corner and edge column losses.

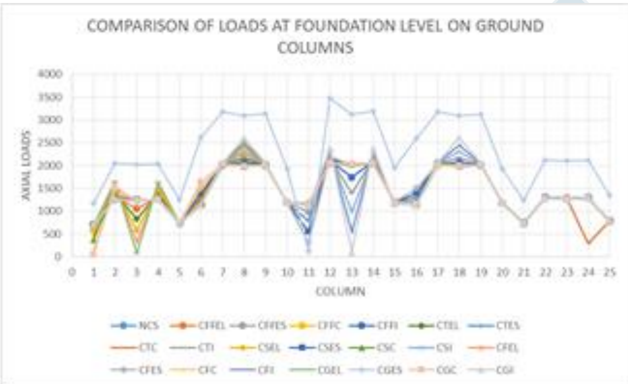


**Fig 13. Graph showing the comparison of axial loads on ground columns for different cases**

For long edge column removal B1, B2, B3, B4, B 29, B30, B31 and B32 are studied. For short edge column removal B21, B22, B23, B24, B 9, B10, B11 and B12 are studied. For corner column removal B1, B2, B3, B4, B21, B22, B23, B24 are studied. For interior column removal B 9, B10, B11, B12, B 29, B30, B31 and B32 are studied. After edge and interior column removal the beam span doubles, the bending moment changes so the beam which was earlier designed for negative moment near the column is now to be designed for sagging moments i.e. steel increases to resist positive moment. In case of corner column loss the beams are to be designed as cantilevers.

**Table1: Comparison of steel to beams adjacent to ground floor damaged columns.**

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FIRST FLOOR | | | | | | | | | | | | | |
| | | B1 | | | B2 | | | | B3 | | | B4 | | |
| | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS |
| CASE 1: NCS | T | 209 | | 419 | 249 | | 382 | | 234 | | 392 | 251 | | 309 |
| | B | | 296 | | | 295 | | | | 295 | | | 295 | |
| | | LHS | MIDDLE | RHS | LHS | | | MIDDLE | | RHS | | LHS | MIDDLE | RHS |
| CASE 2: CGEL | T | 209 | 209 | 744 | 1398 | | | 394 | | | 1575 | 547 | 209 | 228 |
| | B | | 295 | 372 | | 699 | | 1176 | | 788 | | 273 | 295 | |
| | FIRST FLOOR | | | | | | | | | | | | | |
| | | B29 | | | B30 | | | | B31 | | | B32 | | |
| | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS |
| CASE 1: NCS | T | 209 | | 269 | 209 | | 300 | | 209 | | 298 | 209 | | 297 |
| | B | | 296 | | | 295 | | | | 295 | | | 295 | |
| | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS |
| CASE 2: CGEL | T | 422 | | 1689 | 469 | | 209 | | 209 | | 255 | 209 | | 248 |
| | B | 940 | | 844 | | 295 | | | | 295 | | | 295 | |
| | FIRST FLOOR | | | | | | | | | | | | | |
| | | B21 | | | B22 | | | | B23 | | | B24 | | |
| | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS |
| CASE 1: NCS | T | 209 | | 209 | 209 | | 209 | | 209 | | 209 | 209 | | 211 |
| | B | | 295 | | | 295 | | | | 295 | | | 295 | |
| | | LHS | MIDDLE | RHS | LHS | | | MIDDLE | | RHS | | LHS | MIDDLE | RHS |
| CASE 3: CGES | T | 209 | 214 | 705 | 2163 | | | 584 | | | 2337 | 462 | 209 | 281 |
| | B | | 295 | 353 | | 1082 | | 2226 | | 1168 | | 231 | 295 | 140 |
| | FIRST FLOOR | | | | | | | | | | | | | |
| | | B9 | | | B10 | | | | B11 | | | B12 | | |
| | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS |
| CASE 1: NCS | T | 262 | | 649 | 478 | | 601 | | 454 | | 621 | 483 | | 452 |
| | B | | 498 | | | 432 | | | | 434 | | | 481 | |
| | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS |
| CASE 3: CGES | T | 526 | | 2105 | 1032 | | 821 | | 637 | | 986 | 716 | | 697 |
| | B | 722 | | 1052 | | 406 | | | | 525 | | | 613 | |
| | FIRST FLOOR | | | | | | | | | | | | | |
| | | B1 | | | B2 | | | | B3 | | | B4 | | |
| | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS |
| CASE 1: NCS | T | 209 | | 419 | 249 | | 382 | | 234 | | 392 | 251 | | 309 |
| | B | | 296 | | | 295 | | | | 295 | | | 295 | |
| | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS |
| CASE 4: CGC | T | 313 | | 1252 | 471 | | 316 | | 218 | | 397 | 257 | | 302 |
| | B | 520 | | 626 | | 295 | | | | 295 | | | 295 | |
| | FIRST FLOOR | | | | | | | | | | | | | |
| | | B21 | | | B22 | | | | B23 | | | B24 | | |
| | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS |
| CASE 1: NCS | T | 209 | | 209 | 209 | | 209 | | 209 | | 209 | 209 | | 211 |
| | B | | 295 | | | 295 | | | | 295 | | | 295 | |
| | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS |
| CASE 4: CGC | T | 356 | | 1426 | 362 | | 209 | | 209 | | 209 | 209 | | 209 |
| | B | 942 | | 713 | | 295 | | | | 295 | | | 295 | |
| | FIRST FLOOR | | | | | | | | | | | | | |
| | | B9 | | | B10 | | | | B11 | | | B12 | | |
| | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS |
| CASE 1: NCS | T | 262 | | 649 | 478 | | 601 | | 454 | | 621 | 483 | | 452 |
| | B | | 498 | | | 432 | | | | 434 | | | 481 | |
| | | LHS | MIDDLE | RHS | LHS | | | MIDDLE | | RHS | | LHS | MIDDLE | RHS |
| CASE 5: CGI | T | 250 | | 1002 | 1667 | | | 454 | | | 1816 | 808 | | 387 |
| | B | | 432 | 501 | | 833 | | 1054 | | 908 | | 404 | 393 | 295 |
| | FIRST FLOOR | | | | | | | | | | | | | |
| | | B29 | | | B30 | | | | B31 | | | B32 | | |
| | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS | | LHS | MIDDLE | RHS | LHS | MIDDLE | RHS |
| CASE 1: NCS | T | 209 | | 269 | 209 | | 300 | | 209 | | 298 | 209 | | 297 |
| | B | | 296 | | | 295 | | | | 295 | | | 295 | |
| | | LHS | MIDDLE | RHS | LHS | | | MIDDLE | | RHS | | LHS | MIDDLE | RHS |
| CASE 5: CGI | T | 209 | | 596 | 1938 | | | 510 | | | 2040 | 459 | | 232 |
| | B | | 295 | 298 | | 969 | | 2089 | | 1020 | | 229 | 295 | 116 |

## CONCLUSION AND SCOPE FOR FUTURE WORKS

Though we cannot eliminate these failures totally we can at-least reduce their chance of occurrence. So if the probability of occurrence of these unforeseen events is high then they are to be designed for anti-collapse, either by increasing the cross sectional dimensions or by increasing the

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reinforcement. Detailing of reinforcement and tying of elements also contributes to redistribution of forces which can prevent failure. The key findings that have been carried out in this study are as follows.

- The study of the cases around the world over suggests the failures and collapses of many buildings is due to several reasons: some related to human negligence and a case of unexpected explosion and some due to ageing or degradation of materials.

- The cases of human negligence is in areas like faulty geotechnical investigation in foundation works, faulty design and planning, selection of poor quality building materials, use of unqualified contractors and workmen, inadequate project monitoring and approval by relevant authorities, failure to ensure compliance of regulations by government agencies. All these irregularities are just to maximise profit with reduced cost.

- From the analysis it was observed that when the column was removed, bending moment of the adjacent beams increases approximately four times due to doubling of spans. The moment over the missing column reverses the direction positive where the beam was designed for negative moment. In-case of corner column loss the beam is to be designed as a cantilever, this is shown in the form of tables in results.

- The study of axial forces showed that interior loss of column was having great impact on the remaining columns, a practical example could be interior column loss for aesthetics or basement parking etc. it was observed that column C12 was heavily loaded in-case of NCS and C_ES, while C8 was loaded more in C_EL condition and C18 in C_I condition. Therefore only if these columns were designed for that particular load it would be safe and would help in maintaining structural integrity.

- Comparison of loads at foundation level is all shown, this will give a general idea of the redistribution of loads on footings.

- To ensure work will not compromise stability, strict guidelines and competent personal is to be consulted before adding and making changes and at every level and stage of construction. Appointment of qualified and expert building professionals, architect and engineers by building clients. Considering the magnitude of human loss during building collapse and the ineffectiveness of the emergency management there is a need for immediate review of practical policy guidelines by the government that should be carried out to safeguard human living. Implementation of planning regulations, acts, bye-laws and codes in the processing of building permit, actual construction, post occupancy follow up will help to improve the standards of construction.

Lack of proper guidelines in collapse analysis and management is hindering the design framework evolution. Non-availability of fibre modelling open sources soft-wares handicaps the students in understanding the collapse mechanism at micro level. The present study is limited to medium structure there is vast scope left out for very tall structures.

This study of collapse pertains to loss of single column and nothing about multiple column loss at a time. The study deals with static loads but there is need to widen the scope to include dynamic effects. Lots need to be done to determine the time stamp of collapse which would enable evacuation of people living in. The study pertains to effect of damaged columns on adjacent beams, but there is need to see the effect on other beams.

Research in innovative joints and member reinforcement details is needed to achieve resistance against progressive collapse. Buildings lacking monolithic actions like in precast and pre-stressed buildings frequently used incase of long spans and heavy loads are to be investigated as these are more prone to collapse.

The present study is for uniform placement of columns and beams throughout the stories and there is a need to see the effect of collapse on non-uniform beam alignment at every floor. Finally I must admit in all sincerity that this is a humble contribution which might be useful for research in future.

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