Study on Progressive Collapse Failure in a Multistory Structure

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Abstract - *When major structural load carrying members are removed suddenly, the remaining structural elements cannot support the weight of the building and it fails. This failure leads to a progressive collapse failure in the structure. The bombing of the Murray Federal Building in Oklahoma City is a typical example of progressive collapse failure. The basic characteristic of the progressive collapse that the end state of the destructions is disproportionately greater than the failure that made the collapse.*

In the theoretical part of the paper the main issue was to reveal and describe the term and the types of the progressive collapse, then to find out the reasons, appearance and effects from this event. Also a linear static analysis based on the static removal of a major structural element using SAP has to be carried out.

***Key Words*: progressive collapse, Column removal, DCR, GSA, Alternative path method**

1. INTRODUCTION

The progressive collapse of building structures is initiated when one or more vertical load carrying members (typically columns) is removed. Once a column is removed due to a vehicle impact, fire, earthquake, or other man-made or natural hazards, the building's weight (gravity load) transfers to neighboring columns in the structure. If these columns are not properly designed to resist and redistribute the additional gravity load that part of the structure fails. The vertical load carrying elements of the structure continue to fail until the additional loading is stabilized. As a result, a substantial part of the structure may collapse, causing greater damage to the structure than the initial impact. Progressive collapse occurs when a structure has its loading pattern or boundary conditions changed such that some members are loaded beyond their intended capacities. The residual structure is then forced to seek alternate load paths to redistribute the out-of balance loads from damaged members. As a result, other neighboring members surrounding the residual structure may also fail shedding some applied loads. The redistribution of loads is a dynamic process and will continue until a new equilibrium position is reached by the residual structure, either through finding a stable alternate load path or through further shedding of loads as a consequence of collapsed members.

Most of the published progressive collapse analyses are based on alternative load path method with sudden column loss as recommended in mentioned guidelines. In most of the published numerical studies of progressive collapse, open source or commercial nonlinear FE packages are used, such as Abaqus, SAP2000 and Open sees. Most of the considerations are confined to 2D frames using beam element. Detailed 3D numerical study using shell element is rare due to required computational times and poor pre-processing ability of general purpose finite element packages

2. CAUSES OF PROGRESSIVE COLLAPSE

The potential abnormal loads that can cause the progressive collapse are categorized like that:

A. Pressure Loads

- Internal gas explosions
- Blast
- Wind over pressure
- Extreme values of environmental loads

B. Impact Loads

- Aircraft impact
- Vehicular collision
- Earthquake
- Overload due to occupant overuse
- Storage of hazardous materials

3. TYPES OF PROGRESSIVE COLLAPSE

There are five types of progressive collapse-Pancake type, Zipper type, domino type, Instability type and section type destruction.

4. OBJECTIVES AND SCOPE

A. To describe the term and the types of progressive collapse.
B. To find out the causes and effects of progressive collapse.
C. To perform linear static analysis based on the static removal of a major structural element using SAP 2000.

5. DESIGN GUIDANCE

As per USA General Service Administration (GSA) guidelines, it is recommended that the following structural characteristics should be considered in the initial phases of structural design.

A. Redundancy

The use of redundant lateral and vertical force resisting systems are highly encouraged when considering progressive collapse. Redundancy tends to promote an overall more robust structure and helps to ensure that alternate load paths are available in the case of a structural element(s) failure.

B. Tie forces

In the Tie Force approach, the building is mechanically tied together, enhancing continuity, ductility, and development of alternate load paths. Tie forces can be provided by the existing structural elements that have been designed using conventional design methods to carry the standard loads imposed upon the structure. There are three horizontal ties that must be provided: longitudinal, transverse, and peripheral. Vertical ties are required in columns and load bearing walls.

C. The use of detailing to provide structural continuity and ductility

It is critical that the primary structural elements (i.e., girders and beams) be capable of spanning two full spans (i.e., two full bays). This requires both beam-to-beam structural continuity across the removed column, as well as the ability of both primary and secondary elements to deform flexurally well beyond the elastic limit without experiencing structural collapse. Hence, correct detailing of connections shall be required in the design to ensure discrete *beam-to-beam continuity* across a column, and to ensure *connection redundancy and resilience.* Loading such as that encountered for the case of a structural element(s) failure.

D. Capacity for resisting load reversals

It is recommended that both the primary and secondary structural elements be designed such that these components are capable of resisting load reversals for the case of a structural element(s) failure.

E. Capacity for resisting shear failure

It is essential that the primary structural elements maintain sufficient strength and ductility under an abnormal loading event to preclude a shear failure such as in the case of a structural element(s) failure. When the shear capacity is reached before the flexural capacity, the possibility of a sudden, non-ductile failure of the element exists which could potentially lead to a progressive collapse of the structure.

6. ANALYSIS CONSIDERATIONS AND LOADING CRITERIA

The following analysis considerations shall be used in the assessment for progressive collapse for typical structural configurations.

A. Exterior considerations

The following exterior analysis cases shall be considered
1. Analyze for the instantaneous loss of a column for one floor above grade (1 story) located at or near the middle of the short side of the building.

2. Analyze for the instantaneous loss of a column for one floor above grade (1 story) located at or near the middle of the long side of the building.

3. Analyze for the instantaneous loss of a column for one floor above grade (1 story) located at the corner of the building.

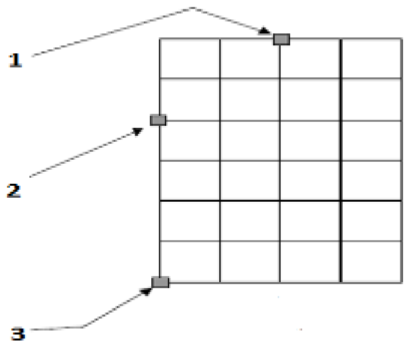

Fig-1:Plan view (from GSA Guideline)

B. Interior Considerations

Buildings that have underground parking and/or uncontrolled public ground floor areas shall use the following interior analysis case

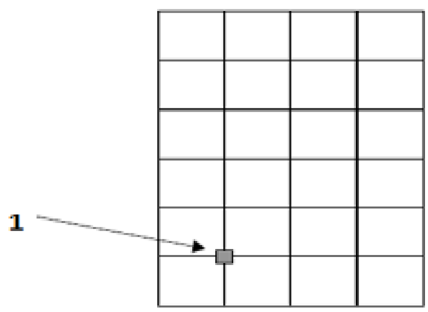

Fig-2:Plan view

1. Analyze the building for the instantaneous loss of one column that extends from the floor of the underground parking area or uncontrolled public ground floor area to the next floor (1st story). The column considered should be interior to the perimeter column lines.

C. Analysis Loading

For static analysis purposes the following vertical load shall be applied downward to the structure under investigation:

$$\text{Load} = 2(DL + 0.25LL) \quad (1)$$

where,

DL = dead load

LL = live load

D. Acceptance Criteria

An examination of the linear elastic analysis results shall be performed to identify the magnitudes and distribution of potential demands on both the primary and secondary structural elements for quantifying potential collapse areas. The magnitude and distribution of these demands will be indicated by **D**emand-**C**apacity **R**atios (*DCR*).

Acceptance criteria for the primary and secondary structural components shall be determined as:

$$DCR = \frac{Q_{UD}}{Q_{CE}} \tag{2}$$

where,

Q_{UD} = Acting force (demand) determined in component or connection/joint (moment, axial force, shear, and possible combined forces)

Q_{CE} = Expected ultimate, un-factored capacity of the component and/or connection/joint (moment, axial force, shear and possible combined forces)

Using the *DCR* criteria of the linear elastic approach, structural elements and connections that have *DCR* values that exceed the following allowable values are considered to be severely damaged or collapsed.

The allowable *DCR* values for primary and secondary structural elements are:

- *DCR* < 2.0 for typical structural configurations
- *DCR* < 1.5 for atypical structural configurations

7. MODERN METHODS AND APPROACHES

Nowadays exist two approaches to ensure sustainability for progressive collapse, they are the indirect method and the direct methods. The indirect method is a prescriptive approach of granting the minimum level of links between different structural components and little additional structural analysis is required by the designer. Basically instead of calculations which show the effects of abnormal loads on buildings, the constructor can use an implicit design method that includes measures to improve the overall reliability of the structure. But the direct methods are strongly dependent on the structural analysis, designer obviously considering the ability of the structure to resist the influence of an abnormal event load.

A. Indirect method

Indirect method is a prescriptive approach that can be used to improve the overall reliability of the structure during the process of design through provision of minimum levels of strength, continuity and ductility. Thus the indirect method will probably be the basic method used to increase the robustness of the building. Indirect design approach has the explicit advantage as the easiest way to use and provide uniformity of compliance in all projects. Although this event is an independent approach and does not rely on detailed calculations of the structural response to an abnormal load, this leads to a continuous tied reinforcement for the concrete frame structure in order to develop more of their potential when exposed to abnormal loading conditions. Although the vertical load is not effectively resisting horizontal ties, loads, which were originally supported by corrupted parts of the structure, will be redistributed to the intact structure elements. So the indirect approach is for the regular layout design of buildings that do not contain significant transfer mechanisms and structures and which do not correspond to higher importance categories.

B. Direct method

In the direct design methods, resistance from progressive collapse is made by increasing the strength of the main construction elements to avoid the failure under accepted abnormal loads or making the structure so that it can cover the local failure area. But on the other hand, the direct design methods need more complicated analyses compared with the ordinary gravity and lateral load analyses used in regular design.

- Specific local resistance
- Alternative path method

8. SAP2000 MODELLING AND ANALYSIS

The building considered for the study is twelve storey symmetrical R.C. building.

The structure consists of six bays of 5 m in the longitudinal direction and four bays of 5 m in the transverse direction. Typical floor-to-floor height is 3.1 m and for the first story it is 3.4 m. Wall having 115 mm thickness is considered on all the beams. Slab thickness considered is 150 mm. Beam size is taken for twelve storey's as 300 × 550 mm. Column sizes are 500x500, 600x600 & 900x900 mm are considered for building. Loading considered on the building for the study are as follows.

- Dead load
- Live load
- Seismic loading as per IS: 1893

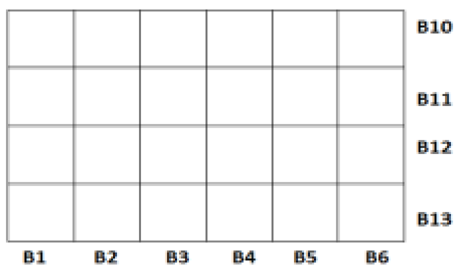

Fig-3: Plan of the building

A. Linear static progressive collapse analysis

To evaluate the potential for progressive collapse of a twelve storey symmetrical reinforced concrete building using the linear static analysis three column removal conditions is considered. First building is designed in SAP 2000 for the IS 1893 load combinations. Then separate linear static analysis is performed for each case of column removal.

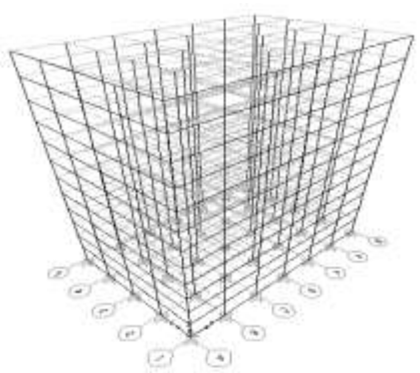

Fig-4: 3D model generated in SAP 2000

B. Calculation of Demand Capacity Ratio

Demand capacity ratio for flexure at all storeys is calculated for all three cases of column failure. Capacity of the member at any section is calculated as per IS456:2000 from the obtained reinforcement details after analysis and design. Demand capacity ratio after removal of column is found out considering the member force for the load combination as per GSA guidelines. Member forces are obtained by analysis results carried out in SAP 2000.

Table-1:DCR values of beam B4 when long side column eliminated

Storey No	D.C.R-ZONE II	DCR-ZONE III	DCR-ZONE IV	DCR-ZONE V
2	4.707	3.32	1.93	1.11
3	2.966	1.9425	1.2065	0.723
4	2.4485	1.941	0.949	0.668
5	2.185	1.3917	0.8743	0.5846
6	2.13	1.172	0.7886	0.501
7	1.9569	1.139	0.6969	0.4836
8	1.775	1.046	0.692	0.441
9	1.752	0.9919	0.6526	0.4047
10	1.606	0.9895	0.63	0.395
11	1.6	0.956	0.6238	0.376
12	1.593	0.949	0.61	0.372

Table-2:DCR values of beam B11 when short side column eliminated

Storey No	D.C.R-ZONE II	DCR-ZONE III	DCR-ZONE IV	DCR-ZONE V
2	2.235	2.2	1.37	0.79
3	2.15	1.44	0.87	0.568
4	2.14	1.1	0.7534	0.4985
5	1.91	1.04	0.639	0.457
6	1.67	0.923	0.6095	0.385
7	1.55	0.8692	0.5545	0.376
8	1.47	0.83	0.5514	0.357
9	1.325	0.792	0.509	0.316
10	1.296	0.776	0.507	0.314
11	1.237	0.75	0.489	0.2977
12	1.21	0.749	0.486	0.296

Table-3:DCR values of beam B4 when corner column eliminated

Storey No	D.C.R-ZONE II	DCR-ZONE III	DCR-ZONE IV	DCR-ZONE V
2	3.34	2.25	1.538	0.951
3	2.107	1.64	1.52	0.669
4	1.476	1.45	0.98	0.6294
5	1.17	0.9097	0.913	0.611
6	1.17	0.8159	0.7692	0.6106
7	1.306	0.765	0.659	0.516
8	1.038	0.719	0.635	0.474
9	0.991	0.674	0.6252	0.465
10	0.977	0.646	0.58	0.429
11	0.955	0.646	0.568	0.409
12	0.949	0.6087	0.526	0.398

C. Graphical Representation of DCR

After getting all the DCR values for critical cases of column removal, for all zones graph is plotted DCR Vs Storeys.

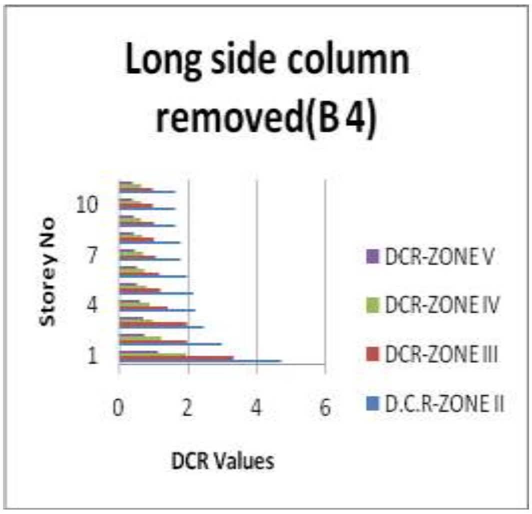

Chart-1:Long side column removal

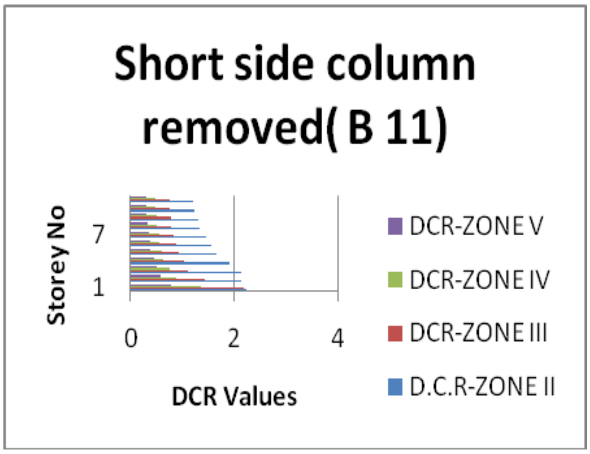

Chart-2: Short side column removal

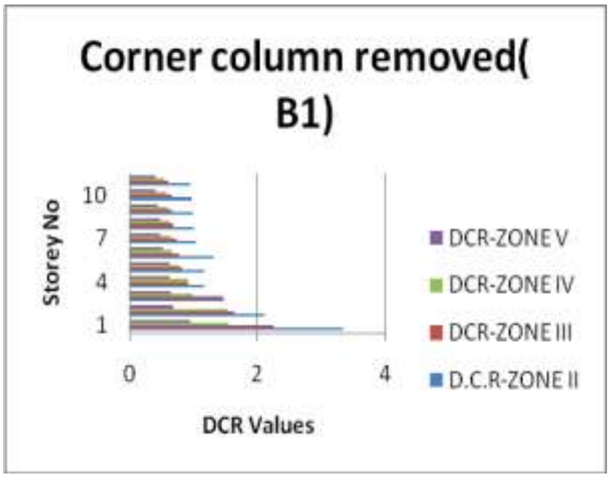

Chart-3: Corner column removal

CONCLUSIONS

1. Seismically Designed building has inherent ability to resist progressive collapse. (From Graph)

2. Nonlinear static analysis reveals that hinge formation starts from the location having maximum demand capacity ratio.

3. To avoid the progressive failure of beams and columns, caused by failure of particular column, adequate reinforcement is required to limit the DCR within the acceptance criteria.

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