Comparative study on progressive collapse analysis of RC frame buildings subjected to wind and seismic loads

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Abstract. Progressive collapse occurs when the local failure of the primary structure leads to an eventual collapse of the structure as the adjoining load-bearing elements fail to transfer the load of the lost column. This analysis checks whether the load transfer from adjoining members upon loss of columns. A 10-storey RC structure of square and circular plan geometry were considered in this study. The buildings were modelled and designed for gravity, wind, and earthquake loads as per the guidelines of respective Indian Standards. Further, those models were examined for progressive collapse considering different critical column removal scenarios. The DCR results were calculated for the adjacent beams and adjacent columns to check whether the structure elements reach an alternate equilibrium of the load path or not. Out of both the geometry, the circular plan building was showing better performance than square plan building and it is about 10% to 20% better based upon all the analysis and for different loading conditions.

Keywords: progressive collapse; demand-capacity-ratios; wind and seismic loads; column removal and ETABS.

1. Introduction

Progressive collapse is a dangerous phenomenon with causes disproportionate collapse of the structure upon the loss of any load bearing element like column. The local failure of the structure element causes the partial or even complete collapse of the structural system. So, it is important to design the structure after meeting the requirements of progressive collapse analysis. It is a non-linear happening in which structural elements are tensed past their elastic limit to failure.

The failure of the two towers of World Trade Center buildings (WTC) in 2001 has amplified interest amongst building landlords and administration entities in estimating the progressive collapse potential of prevailing buildings and in designing new buildings to counterattack this type of structural collapse. It was all started after the partial collapse of the Roman Point Building, which is located at Canning town in Newham, East London, United Kingdom. It was a 22-storey precast building. There was a gas explosion on May 16 1968 in the 18th floor and failure of the load-bearing precast concrete panel was failed. Due to the failure of the wall panel in the 18th floor the above wall unable to hold the position due to load, so failed. The impact force caused on the eighteenth floor due to the failure of the above elements caused the additional collapse of the structural elements below resulted in the complete collapse of the corner of the Structure. Due to this collapse, four people were dies and seventeen were injured. A rigorous investigate determination led to develop progressive collapse tactics methods and the first progressive collapse provisions was made by United Kingdom.

On April 19 1995, there was an explosion by truck bomb taken place due to the Local terrorism on Murrah Federal building was situated at the Oklahoma City, United States. In some Studies, Researchers found out that due to the blast only 4% area was damaged but due to the progression of the damage, total 44% area was...
collapsed. In this incident, 167 people died and 759 Injured. So, if that building had been designed in such a way that even after the loss of column, if the remaining elements had successfully resisted the load coming from the above elements, it would have saved lot of the building area and may have saved many people.

On September 11 2001, The World Trade Center (WTC) towers 1 & 2 at Lower Manhattan, New York city, United States has collapsed. It was of 110 floors each has been struck by the two aeroplanes during the September 11 attacks. After the aeroplane crash the building had resisted the heat and transfer of loads for an hour, then the pancake type structure failure occurred which resulted in 2,977 causalities and 25,000 injured. After this attack, many researchers across the world got interested to study about progressive failure of the structure on the loss of some load bearing elements.

The progressive collapse can occur due to different reasons, that may cause due explosives, explosions due to gas, impact due to vehicles, earthquake, human errors in design or in construction phase. There are many chances that the building may loss load bearing element due to the accidental loads, impacts, explosions etc., the loss of property and life will be much lesser. So, it is significant to implicit the progressive collapse resistance to the structures.

Progressive collapse can be defined as an initial local failure that spreads from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large portion of it. Alternate load path method is a method that allows for local failure while also attempting to provide alternate load paths so that the damage is absorbed and major collapse is avoided.

The progressive collapse analysis for the RC frame is done very profoundly and still going on for providing the safety of the building and people in it even after the loss of load-bearing columns. The research was carried out by several researchers for keeping the structure in equilibrium and continuity in load transfer [1-10]. In this study, progressive collapse analysis of the structure for different plan configurations i.e., for square and circular of approximately same slab area, materials, sections and loads has been performed. Both configurations were analysed for progressive collapse, there were compare and concluded.

2. Progressive collapse analysis

2.1. Structural models

The 3D structural models are designed for gravity loads, wind loads and seismic forces corresponding to seismic Zone III as per IS 456 2000, IS 875 2015 and IS 1893 2016 [11-13]. The description of models and the details of loads considered for analysis are given in Table 1 and Table 2 respectively. The inelastic behaviour of the structural components (beams and columns) was modelled with concentrated plastic hinges in which, the beams possess only moment (modelled as M3 hinges), and the columns have an axial load and a biaxial moment (modelled as P-M2-M3 hinges) as per FEMA 356 (2000) [14]. This local inelastic behaviour of structural components further leads to global non-linear behaviour of entire structural model. Additionally, rigid diaphragms were assigned every story level throughout the structure ignoring the flexibility of the floor. Mander et al. model and Park et al. model was used in characterizing the stress-strain behaviour of concrete and steel rebars (Mander et al. 1988, CSi 2016) as depicted in Fig. 1 [15-16]. Moreover, as per the recommendations of IS 1893 (2016), moments of inertia of beams and columns were reduced to 35% and 70% for beams and columns respectively while performing the non-linear structural analysis. The building configurations considered are depicted in Figs. 1 and 2, were modelled and analysed using a commercial structural software SAP2000 (CSi 2016).

| S. No. | Parameter                        | Data     |
|-------|----------------------------------|----------|
| 1     | Grade of concrete                | M 25     |
| 2     | Poisson’s ratio of concrete      | 0.2      |
| 3     | Unit weight of concrete          | 25 kN/m³ |
| 4     | Modulus of elasticity of concrete| 25 GPa   |
| 5     | Grade of rebar                   | Fe 415   |
| 6     | Modulus of elasticity of rebar   | 200 GPa  |
Table 2. Details of loads considered for analysis

| S. No. | Particulars                                     | Description                                      |
|-------|-------------------------------------------------|--------------------------------------------------|
| 1     | Dead load of beams and columns                  | Self-weight of the structure                     |
| 2     | Live load on slab                               | 3 kN/m²                                          |
| 3     | Dead load on slab including floor finish        | 3.75 kN/m²                                       |
| 4     | Dead load of wall (230 mm thick)                | 14.2 kN/m                                        |
| 5     | Seismic load                                    | IS 1893 (Part 1): 2016                           |
| 6     | Type of structure                               | RC frame structure                               |
| 7     | Importance factor                               | 1                                                |
| 8     | Response reduction factor                       | 3 for OMRF                                       |
| 9     | Soil type                                       | Medium                                           |
| 10    | Zone factor                                     | 0.16 (Zone III)                                  |
| 11    | Wind load                                       | IS 875 (Part 3): 2015                            |

Fig. 1. (a) Mander confined concrete stress-strain model (b) Park stress-strain model

2.2. Column removal scenarios

A. FOR SQUARE PLAN BUILDINGS:
- Removal of corner column, C1.
- Removal of Peripheral Column, C3.
- Removal of Inner Column, C15.

Fig. 2. Column removal scenarios of square plan building
B. FOR CIRCULAR PLAN BUILDINGS:
- Removal of outer peripheral column, C1.
- Removal of middle Column, C3.
- Removal of Inner peripheral Column, C15.

![Column removal scenarios of circular plan building](image)

Fig. 3. Column removal scenarios of circular plan building

2.3. Analysis procedure

There are two methodologies – the guidelines of General Service Administration (GSA) and Department of Defence – Unified Facilities Criteria (UFC) [17-18]. In which, GSA guidelines are followed as the simplicity in calculation for finding out the DCR of the elements. The procedure adopted in this study is:

1. Modelling the 3D structure in the software with required material and sectional properties.
2. Adding the Loads, service and design load combinations to the structure.
3. Ensuring the structural system, pass all the analysis and design checks.
4. Applying GSA guidelines, the checking the structure condition under different column removal scenario and with different analysis.
5. Checking the structural elements around column removal by Demand Capacity Ratio.

2.4. Computation of DCRs

The Demand Capacity Ratio (DCR) of each primary and secondary member of the alternate path structure is calculated from the following equation:

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

where,

- $Q_{UD}$ = Acting force determined in the structural element.
- $Q_{CE}$ = Expected ultimate, un-factored capacity of the structural element.

DCR limits as per GSA guidelines:
- $DCR \leq 2.0$ for typical structural configuration
- $DCR \leq 1.5$ for atypical structural configuration

$Q_{CE}$ calculation:

For Columns:

$$Pu = 0.4*F_{ck}*A_c + 0.67*F_y*A_{sc}$$

For Beams:

$$Mu = 0.87*F_y*A_{st}*d*(1-(A_{st}*F_y)/(b*d*F_{ck}))$$

$Q_{UD}$ is obtained from analysis performed on the model in ETABS.

3. Results and discussions:

| Table 3. DCR values of the buildings subjected to wind with LSA, NLSA and LDA |
|---------------------------------------------------------------|------------------|
| LINEAR STATIC ANALYSIS -RC STRUCTURE OF SQUARE PLAN BUILDING – WIND LOAD |
| CORNER COLUMN REMOVAL DCR | PERIPHERAL COLUMN REMOVAL DCR | MIDDLE COLUMN REMOVAL DCR |
|---------------------------|-------------------------------|---------------------------|
| Removed Column is C1      | Removed Column is C3          | Removed Column is C15     |
| C2 = 0.707185             | C2 = 0.69050                  | C9 = 0.883717             |
| C7 = 0.707185             | C4 = 0.714513                 | C14 = 0.883717            |
| C8 = 0.757477             | C9 = 0.879371                 | C16 = 0.921335            |
| B1 = 0.736318             | B2 = 0.816576                 | C21 = 0.921335            |
| B6 = 0.736318             | B3 = 0.819936                 | B19 = 0.810196            |
|                           | B8 = 0.632424                 | B24 = 0.810196            |
|                           |                               | B25 = 0.804182            |
|                           |                               | B30 = 0.804182            |

**LINEAR STATIC ANALYSIS – RC STRUCTURE OF CIRCULAR PLAN BUILDING – WIND LOAD**

| OUTER PERIPHERAL COLUMN REMOVAL DCR | MIDDLE COLUMN REMOVAL DCR | INNER PERIPHERAL COLUMN REMOVAL DCR |
|-------------------------------------|----------------------------|-------------------------------------|
| Removed Column is C2               | Removed Column is C5       | Removed Column is C12              |
| C1 = 0.488316                       | C2 = 0.534642               | C5 = 0.715533                       |
| C5 = 0.985677                       | C4 = 0.755479               | C10 = 0.575138                      |
| C7 = 0.518084                       | C9 = 0.796775               | C14 = 0.593177                      |
| B1 = 0.44175                        | C12 = 0.571264              | B13 = 0.16107                       |
| B4 = 0.651508                       | B4 = 0.391322               | B17 = 0.540019                      |
| B6 = 0.439254                       | B8 = 0.38780                | B23 = 0.528023                      |
|                                   | B11 = 0.376886              | B13 = 0.400235                      |
|                                   | B15 = 0.907815              | B25 = 0.821405                      |

**NON-LINEAR STATIC ANALYSIS – RC STRUCTURE OF SQUARE PLAN BUILDING – WIND LOAD**

| CORNER COLUMN REMOVAL DCR | PERIPHERAL COLUMN REMOVAL DCR | MIDDLE COLUMN REMOVAL DCR |
|---------------------------|-------------------------------|---------------------------|
| Removed Column is C1      | Removed Column is C3          | Removed Column is C15     |
| C2 = 0.845264             | C2 = 0.821641                 | C9 = 0.910463             |
| C7 = 0.845264             | C4 = 0.848921                 | C14 = 0.910463            |
| C8 = 0.886241             | C9 = 1.026436                 | C16 = 0.949144            |
| B1 = 0.907815             | B2 = 0.952037                 | C21 = 0.949144            |
| B6 = 0.907815             | B3 = 0.956005                 | B19 = 0.82750             |
|                           | B8 = 0.773925                 | B24 = 0.82750             |
|                           | B11 = 0.376886                | B25 = 0.821405            |
|                           | B13 = 0.400235                | B30 = 0.821405            |

**NON-LINEAR STATIC ANALYSIS – RC STRUCTURE OF CIRCULAR PLAN BUILDING – WIND LOAD**

| OUTER PERIPHERAL COLUMN REMOVAL DCR | MIDDLE COLUMN REMOVAL DCR | INNER PERIPHERAL COLUMN REMOVAL DCR |
|-------------------------------------|----------------------------|-------------------------------------|
| Removed Column is C2               | Removed Column is C5       | Removed Column is C12              |
| C1 = 0.707784                       | C2 = 0.709452               | C5 = 0.715533                       |
| C5 = 1.239369                       | C4 = 0.972065               | C12 = 0.731362                      |
| C7 = 0.706969                       | C9 = 0.958603               | C5 = 0.732989                       |
| B1 = 0.652457                       | C12 = 0.701207              | B13 = 0.3178                         |
| B4 = 0.90599                        | B4 = 0.531317               | B17 = 0.638735                      |
| B6 = 0.679709                       | B8 = 0.475092               | B23 = 0.679007                      |
|                                   | B11 = 0.477698              | B25 = 0.821405                      |
|                                   | B13 = 0.48046               | B30 = 0.821405                      |

**LINEAR DYNAMIC ANALYSIS – RC STRUCTURE OF SQUARE PLAN BUILDING – WIND LOAD**

| CORNER COLUMN REMOVAL DCR | PERIPHERAL COLUMN REMOVAL DCR | MIDDLE COLUMN REMOVAL DCR |
|---------------------------|-------------------------------|---------------------------|
| Removed Column is C1      | Removed Column is C3          | Removed Column is C15     |
C2 = 0.943884  C2 = 0.927118  C9 = 1.14930
C7 = 0.943884  C4 = 0.998251  C14 = 1.14930
C8 = 0.937273  C9 = 1.158549  C16 = 1.187444
B1 = 1.054819  B2 = 1.206898  C21 = 1.187444
B6 = 1.054819  B3 = 1.202952  B19 = 1.040616
B8 = 0.944765  B24 = 1.040616
B25 = 1.044106
B30 = 1.044106

| OUTER PERIPHERAL COLUMN REMOVAL DCR | MIDDLE COLUMN REMOVAL DCR | INNER PERIPHERAL COLUMN REMOVAL DCR |
|------------------------------------|--------------------------|------------------------------------|
| Removed Column is C2               | Removed Column is C5     | Removed Column is C12              |
| C1 = 0.707905                      | C2 = 0.709518            | C5 = 0.862088                       |
| C5 = 1.23952                       | C4 = 0.972082            | C10 = 0.731193                      |
| C7 = 0.707055                      | C9 = 0.958677            | C14 = 0.73265                       |
| B1 = 0.653759                      | C12 = 0.701084           | B13 = 0.321039                      |
| B4 = 0.901304                      | B4 = 0.528004            | B17 = 0.653589                      |
| B6 = 0.680323                      | B8 = 0.471848            | B23 = 0.690279                      |
| B11 = 0.476276                     | B13 = 0.480384           |                                    |

The demand capacity ratios obtained from the calculation of the output results from ETABS had been satisfied GSA guidelines i.e., the DCR values obtained are below 2, as presented in Table 3. The comparison of both the different plan configuration i.e., square and circular gives the better results in the circular plan building as it is more symmetry.

From the observation, it can be concluded that the circular building elements subjected to 30 to 40 percent less to stresses when compared to the square plan building. In observing the DCR value, it can also be concluded that the stress cause upon removal of external column leads to development to more stresses and further leads to failure of the structure and the damage will progress. In square plan building the removal of corner column has more development of internal stresses, the middle column and when comes to least stress developing elements upon the column loss is the middle column removal in square building and inner peripheral column in case of circular plan buildings, as depicted in Fig. 4 and Fig. 5.

![Fig. 4. DCR Graphs of Square building with wind loading](image-url)
Fig. 5. DCR Graphs of Circular building with wind loading

Table 4. DCR values of the buildings subjected to seismic with LSA, NLSA, LDA & NLDA

| CORNER COLUMN REMOVAL DCR | PERIPHERAL COLUMN REMOVAL DCR | MIDDLE COLUMN REMOVAL DCR |
|----------------------------|--------------------------------|----------------------------|
| Removed Column is C1       | Removed Column is C3           | Removed Column is C15      |
| C2 = 0.71276               | C2 = 0.70006                   | C9 = 0.93788               |
| C7 = 0.71276               | C4 = 0.72745                   | C14 = 0.93788              |
| C8 = 0.77558               | C9 = 0.94543                   | C16 = 0.96088              |
| B1 = 0.83378               | B2 = 1.03319                   | C21 = 0.96088              |
| B6 = 0.83378               | B3 = 1.01116                   | B24 = 0.91832              |
|                            | B8 = 0.68635                   | B25 = 0.94156              |
|                            |                                | B30 = 1.37218              |

| OUTER PERIPHERAL COLUMN REMOVAL DCR | MIDDLE COLUMN REMOVAL DCR | INNER PERIPHERAL COLUMN REMOVAL DCR |
|-------------------------------------|---------------------------|-------------------------------------|
| Removed Column is C2                | Removed Column is C5      | Removed Column is C12               |
| C1 = 0.457553                       | C2 = 0.489051             | C5 = 0.545759                       |
| C5 = 0.784699                       | C4 = 0.616149             | C10 = 0.458968                      |
| C7 = 0.461616                       | C9 = 0.607928             | C14 = 0.469384                      |
| B1 = 0.367008                       | C12 = 0.448141            | B13 = 0.21785                       |
| B4 = 0.753054                       | B4 = 0.464812             | B17 = 0.437716                      |
| B6 = 0.409252                       | B8 = 0.454443             | B23 = 0.409121                      |
|                                   | B11 = 0.347459            |                                    |
|                                   | B13 = 0.336908            |                                    |

| CORNER COLUMN REMOVAL DCR | PERIPHERAL COLUMN REMOVAL DCR | MIDDLE COLUMN REMOVAL DCR |
|----------------------------|--------------------------------|----------------------------|
| Removed Column is C1       | Removed Column is C3           | Removed Column is C15      |
| C7 = 0.6420099             | C2 = 0.630305                  | C9 = 0.779207               |
| C2 = 0.6420099             | C4 = 0.67812                   | C14 = 0.779207              |
| C8 = 0.636941              | C9 = 0.785654                  | C16 = 0.80521               |
| B1 = 0.610135              | B2 = 0.737939                  | C21 = 0.80521               |
| B6 = 0.610135              | B3 = 0.727301                  | B19 = 0.637694              |
|                            | B8 = 0.526470                  | B24 = 0.637218              |
### NON-LINEAR STATIC ANALYSIS – RC STRUCTURE OF CIRCULAR PLAN BUILDING WITH SEISMIC

| OUTER PERIPHERAL COLUMN REMOVAL DCR | MIDDLE COLUMN REMOVAL DCR | INNER PERIPHERAL COLUMN REMOVAL DCR |
|------------------------------------|---------------------------|-------------------------------------|
| Removed Column is C2               | Removed Column is C5      | Removed Column is C12               |
| C1 = 0.457474                      | C2 = 0.488761             | C10 = 0.54569                       |
| C5 = 0.784602                      | C4 = 0.616138             | C12 = 0.459074                      |
| C7 = 0.461558                      | C9 = 0.60788              | C5 = 0.469601                       |
| B1 = 0.366299                      | C12 = 0.448219            | B13 = 0.215725                      |
| B4 = 0.756968                      | B4 = 0.46768              | B17 = 0.426195                      |
| B6 = 0.40891                       | B8 = 0.457236             | B23 = 0.402333                      |
|                                    | B11 = 0.34843             | B13 = 0.336835                      |

### LINEAR DYNAMIC ANALYSIS - RC STRUCTURE OF SQUARE PLAN BUILDING WITH SEISMIC

| CORNER COLUMN REMOVAL DCR          | PERIPHERAL COLUMN REMOVAL DCR | MIDDLE COLUMN REMOVAL DCR                |
|------------------------------------|-----------------------------|-----------------------------------------|
| Removed Column is C1               | Removed Column is C3        | Removed Column is C15                    |
| C2 = 0.717964                      | C2 = 0.697461               | C9 = 0.966389                           |
| C7 = 0.717964                      | C4 = 0.725158               | C14 = 0.966389                          |
| C8 = 0.780681                      | C9 = 0.986758               | C16 = 0.983645                          |
| B1 = 0.516291                      | B2 = 0.641645               | C21 = 0.983645                          |
| B6 = 0.532649                      | B3 = 0.630656               | B19 = 0.796466                          |
|                                    | B8 = 0.421344               | B24 = 0.530256                          |
|                                    |                             | B25 = 0.52716                           |
|                                    |                             | B30 = 0.769867                          |

### LINEAR DYNAMIC ANALYSIS – RC STRUCTURE OF CIRCULAR PLAN BUILDING WITH SEISMIC

| OUTER PERIPHERAL COLUMN REMOVAL DCR | MIDDLE COLUMN REMOVAL DCR | INNER PERIPHERAL COLUMN REMOVAL DCR |
|------------------------------------|---------------------------|-------------------------------------|
| Removed Column is C2               | Removed Column is C5      | Removed Column is C12               |
| C1 = 0.68633                       | C2 = 0.73321               | C5 = 0.81864                         |
| C5 = 1.17705                       | C4 = 0.86511               | C10 = 0.68845                        |
| C7 = 0.69242                       | C9 = 0.96907               | C14 = 0.70408                        |
| B1 = 0.53051                       | C12 = 0.67221              | B13 = 0.32692                        |
| B4 = 1.12958                       | B4 = 0.69722               | B17 = 0.65637                        |
| B6 = 0.61388                       | B8 = 0.65319               | B23 = 0.61368                        |
|                                    | B11 = 0.54391              | B13 = 0.50536                        |

### NON-LINEAR DYNAMIC ANALYSIS – RC STRUCTURE OF SQUARE PLAN BUILDING - SEISMIC

| CORNER COLUMN REMOVAL DCR          | PERIPHERAL COLUMN REMOVAL DCR | MIDDLE COLUMN REMOVAL DCR                |
|------------------------------------|-----------------------------|-----------------------------------------|
| Removed Column is C1               | Removed Column is C3        | Removed Column is C15                    |
| C2 = 0.72726                       | C2 = 0.71391                | C9 = 0.95380                           |
| C7 = 0.72726                       | C4 = 0.74125                | C14 = 0.95380                          |
| C8 = 0.79263                       | C9 = 0.96169                | C16 = 0.97736                          |
| B1 = 0.87066                       | B2 = 1.07811                | C21 = 0.97736                          |
| B6 = 0.87066                       | B3 = 1.05569                | B19 = 1.46293                          |
|                                    | B8 = 0.72671                | B24 = 0.97387                          |
|                                    | B25 = 0.96809               | B30 = 1.41178                          |
In case of the building designed for earthquake loading, the earthquake resistant building performs better than the building which are not designed for earthquake, as presented in Table 4. This indicates that the design of earthquake structures indirectly has ability to resist progressive collapse. The buildings performance is same as the initial case even with earthquake loading as depicted in Fig. 6.
Fig. 6. DCR Graphs of building with EQ loading

4. Conclusions:
From the results presented above, it can be concluded:

1. All the demand capacity ratios values are below 2, which indicates the structure is satisfying the GSA guidelines i.e., good structural stability after different column removal scenarios.
2. From the outcome of this project, we can conclude that the building of circular plan will performing 10% to 20% better than the square plan building when subjected to progressive collapse.
3. The stress cause upon removal of external column leads to development to more stresses due to distance between the neighbouring columns and intensity of the loads on the neighbouring elements which further leads to failure of the structure and the damage will develop gradually.
4. In the Square planned buildings, the stress caused upon loss of internal column is more, when compared to loss of corner or peripheral column. Then corner column and later peripheral column removal.
5. In Circular plan Columns, the loss of the outer peripheral column produces more stress proceeding to middle column loss and then internal column loss.
6. Seismically designed building will have more resistance to progressive collapse than the non-seismic design building, as the earthquake design itself implicit the resistance to progressive collapse.
7. The symmetry of the building also contributes to the structure stability, with the symmetry of the material, sectional and as well as the plan.

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