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Progressive Collapse of Flat Slab Buildings

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Abstract

Progressive collapse occurs when a local failure triggers successive failures leading to total collapse of the structure. In this project, progressive collapse analysis has been done using a finite element linear static and a non linear static analysis on a 6 storey flat slab building. Though there are dynamic methods also for the analysis but static method has been used owing to its practicality and simplicity in engineering world. Dynamic method is more complicated and involves a number of iteration before it can give any close to accurate result, hence is not in much demand nowadays. The results for the linear static analysis have been compiled in the form of demand capacity ratio at critical section and results for that of the non-linear static analysis have been compiled in the form of support rotation at joints. In both the case the building is not susceptible to progressive collapse both when the central column is removed and the corner column is removed.

Keywords: Progressive collapse, Flat slab building, Dynamic method, linear static analysis, non linear static analysis

1. Introduction

Progressive collapse occurs when a local failure triggers successive failures leading to total collapse of the structure. Progressive collapse starts from an elemental failure which in turn is responsible for partial or complete collapse of any building or structure. Most famous examples of such a failure are the Ronan Point residential apartment tragedy in London in the year 1968, also the terror attack on the World Trade Centre. Due to these incidents many research activities have led to more detailed guidelines on designing and preventing progressive collapses.

There are basically two approaches when dealing with the evaluation and prevention of progressive collapses in a given structure. The first indirect approach consists in ensuring that the structure satisfies prescriptive design rules (such as requirements on structural integrity and ductility or the presence of vertical and horizontal ties). The second approach has two possibilities which are dependent on whether local failure is allowed or not. If there is a possibility of a local failure, then the structure must be verified using the alternate load path method in which a load-bearing element is removed from the structure. If no local failure is allowed, then key elements must be designed to sustain a notional accidental action.

Progressive collapse analysis has been very well described in a paper by Marjanishvili and Agnew (1) wherin a nine-storey building has been taken and analysed for progressive collapse failure. In this paper four methods has been used namely, the linear static, nonlinear static, linear dynamic and finally the non linear dynamic. Each of the methods is deeply investigated and results are evaluated. General Services Administration guidelines have been used throughout the paper with an objective to provide clear concept of the various procedures used and thereby come to the conclusion as to which is the best and the most accurate method of analysis. SAP2000 has been used for the investigation. The conclusion drawn is that the dynamic analysis whether it is linear or non linear gives more accurate result, though a bit complicated but since dynamic procedures inherently incorporate the dynamic amplification factors and also yield more hence accuracy increases for them. Additionally it is also shown that current GSA performance limits for linear analysis procedures are un-conservative, meaning that a structure designed with acceptable linear evaluation criteria may exceed allowable ductility and rotation limits when nonlinear dynamic analysis is performed on the same structure.

Another well written paper is by Qian (2) wherin punching shear in flat slab is discussed in detail.Since RC flat slab structures are unable to develop enough ductility and continuity they are prone to brittle failure like the punching shear failure. This as a result can prove dangerous for the structure as it can also cause the total collapse of the structure. Hence it is important to come out with ways that can help improve the ductility and strength of the structure and also help mitigate progressive collapse failure. In this paper seven flat slab frame building is casted using glass

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fiber reinforced polymer as the reinforcement and then the building is tested. Furthermore, the failure pattern is studied and the differences are noted down. In this paper the test results showed that the above-mentioned strengthening scheme effectively improved the initial stiffness and flexural resistance of the structure. However, they did not succeed in enhancing the post failure resistance of the structure and also its deformation capacity: there was a significant loss in bonding of the GFRP strips from the concrete interface when the structure was in its large displacement stage. This happened even when specially designed fiber anchors were employed.

Progressive collapse on flat slab is done in paper by Kokot and Negro (3). In this paper structural progressive collapse has been found using a real scale flat slab frame building. 3 loading scenarios are taken in which three different columns are being removed instantaneously and response in each case is calculated. Also to account for dynamic effects example explosion or impacts, dynamic linear and non linear time history analysis is performed next. Result has been compiled in the form of demand resistance ratios at critical cross-sections after which susceptibility of the building to progressive collapse failure is checked according to GSA 2003 guidelines. Further the paper by Keyvani and Sasani (4) gives a detailed analysis of progressive collapse due to accidental collision in a parking garage. In this paper posttensioned parking garage is investigated experimentally and analytically for progressive collapse resistance of the structure. An interior central column was first removed by explosion and then the behaviour of the structure was seen. The structure resisted progressive collapse having a permanent maximum displacement of about 61 mm vertically. And for the analytical analysis, model of the garage is developed using a CSI software and nonlinear dynamic analyses are further done for evaluation. Progressive collapse incorporating masonry walls is studied in the paper by Brunesi and Nascimbene (5). With the increase in research in progressive collapse design and analysis of reinforced concrete framed buildings that was triggered either by accidental or man-made extreme events occurring over the last few decades, in this regard very few studies are there, especially the numerical ones. Moreover the study gets narrower when role of masonry infill walls is also incorporated in the study. Just to note that in the case of first earthquake, infill walls are usually considered as non-structural element and, hence, their resistance is generally not taken into account. However such an assumption during the analysis leads to an ease in both design and assessment of structures, but point to be noted here is that it may also develop some misleading and extra conservative results, because the presence of masonry infill walls will contribute in extra vertical resistance. A paper by Parisi (6) sates that the progressive collapse capacity of gravity-load designed, reinforced concrete (RC) buildings complying with Eurocode 2 is numerically investigated, considering both simultaneous and sequential removal of ground-floor columns. The study focuses on a benchmark RC frame used in previous investigations on single column loss scenarios, using nonlinear fibre-based capacity modelling and incremental dynamic analysis. Progressive collapse capacity was evaluated at multiple structural scales, in terms of axial strains, beam drifts and gravity load resisted by the structure after column loss. Another paper by Weng (7) investigates flat slab analysis using LS-DYNA software. In this paper investigation of the load or stress redistribution is done while subjecting the RC flat slab structure to a central column loss scenario. In order to do this high-fidelity FE models were developed using the software namely LS-DYNA. Furthermore, validation of the numerical model is done with the help of experimental results. It is also noted that the continuous surface cap model (CSCM) incorporated with an erosion criterion keeping in mind both the maximum principal and shear strain will definitely and precisely predict the two way shear failure at all the slab-column connections. In order to investigate the effect of boundary conditions the validated finite element model was developed, amount of integrity reinforcement, and slab thickness on the load redistribution capacity of flat slab structures. Furthermore, multi-story RC flat slab substructures were built to capture the load redistribution behaviour of different floors. Parametric studies indicate that ignoring the constraints from surrounding slabs may underestimate the load redistribution capacity of the flat slab substructures.

Another paper by Azim and Liu (8) describes about progressive collapse on RC structures. Progressive collapse analysis of structures mainly RC structures have gained much momentum in the past ten to twenty years owing to the dangerous impact this phenomenon in general has. In this paper the author has discussed the factors which are responsible or trigger progressive collapse of any structure. It could be any structure be it a beam element or any form of reinforcement such as longitudinal or transverse. By doing some experimental or non-linear analysis using any software these shortcomings are identified and tried to remove so as to render the building safe. Moreover, a detailed database of the above study is prepared and is compared to various literature published. Dynamic behaviour of RC frame structures during a progressive collapse event and numerical modelling methods used for studying progressive collapse are also reviewed. Effects of span-to-depth ratio and longitudinal reinforcement ratio on the resistance increase factor of beam-column substructures are studied as well. Furthermore, an energy absorption index is proposed for evaluating the progressive collapse resistance of RC beam-column and beam-slab substructures. Finally, some conclusion is given for future use. Paper by Izzuddin (9) studies about the multi-storey building with instantaneous column removal. The following paper is based on a novel framework for progressive collapse assessment of multi-storeyed structure, with instantaneous column loss as a design criterion. This offers a pragmatic means for examining robustness of structure at varied levels of idealisation. A crucial characteristic of this new approach is its capacity to accommodate simplified and detailed models of non-linear structural response, with the added advantage of permitting increasing assessment over consecutive levels of structural idealisation. Three (03) main stages are used in the assessment framework proposed, which includes non-linear static response assessment, dynamic assessment, and ductility assessment.

2. Objective

Buildings may be subjected to any form of extreme events such as a natural disaster like earthquake or any kind of accident which may include explosion due to gas cylinders or any kind of vehicular collision, or bomb blasting due to increased terror attacks and sabotages. Due to the above-mentioned events the term ‘progressive collapse’ was coined and studied in detail but not much research has been done on this until now. Also, most of the research done is on framed structure incorporating progressive collapse but the focus in this project is also given on value engineering that is designing a robust structure with optimal economic criteria hence flat slab system has been taken instead of framed structure. Flat slab building has advantage over a normal slab framed structure in terms of economy as building height gets reduced, moreover approximately 10% of vertical member is saved, as a result of which foundation load is also reduced which also helps us in cost cutting of the structure without compromising with the strength of the building.

Also after such an analysis several design techniques can be developed which will help find an alternate load paths, so that whenever a column fails the load or the stress gets distributed evenly in the remaining members as a result of which building will withstand extreme conditions of terror attack or accident or any form of natural disaster.

This paper deals with the progressive collapse analysis of buildings which in turn will help in preventing structures from getting damaged due to loss of any member. This will further help in retrofitting of the damaged structure in the most economical way possible.

3. Description of the structure

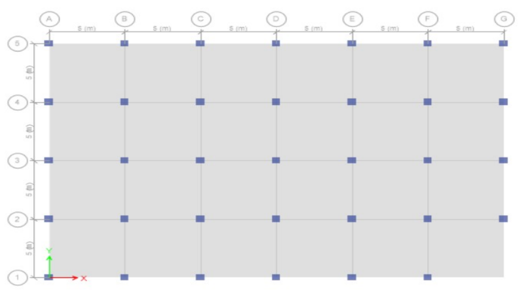

Fig. 1. Plan of the Structure

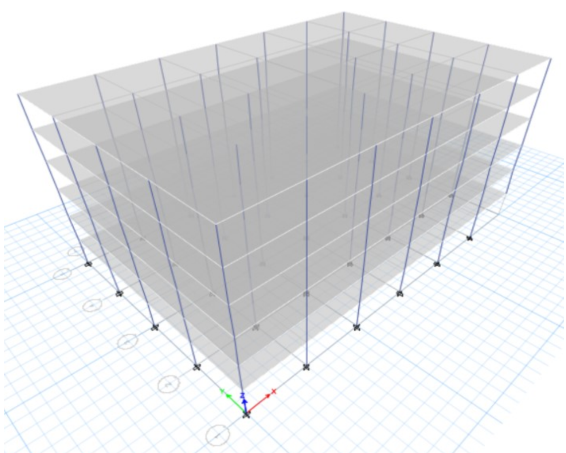

Fig. 2. 3-D View of the Structure

3.1. Structural Data

Table-1. Details of the Structure

Type of Structure	6 Storey RCC building
Zone	IV
Floor to Floor height	3m
Slab thickness	200mm
Live Load	3KN/m^2
Floor finish	1KN/m^2
Column size	550mm x 550mm

3.2. Modelling details

The building in the project consists of 364 joints, 209 frames, 6 shells and 24 edges. Frame section details are as shown along with the reinforcement details. Columns are symmetric and reinforcement is 2% of the gross area in the columns which is well below the maximum limit (10)

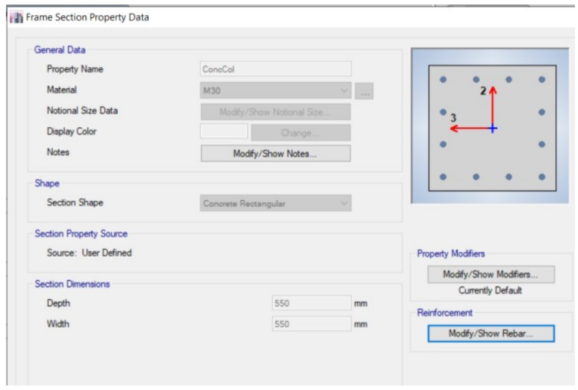

Fig. 3. Column Details of the Structure

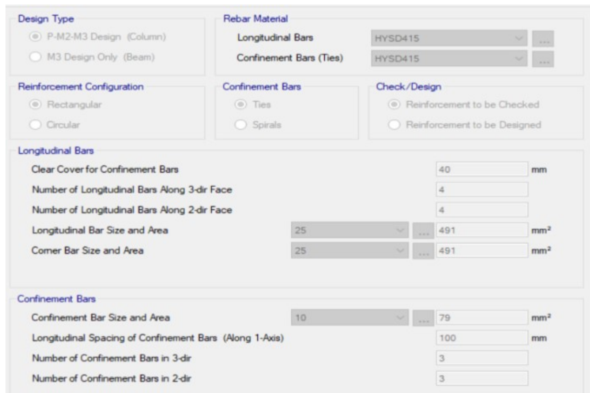

Fig. 4. Reinforcement Details of the Structure

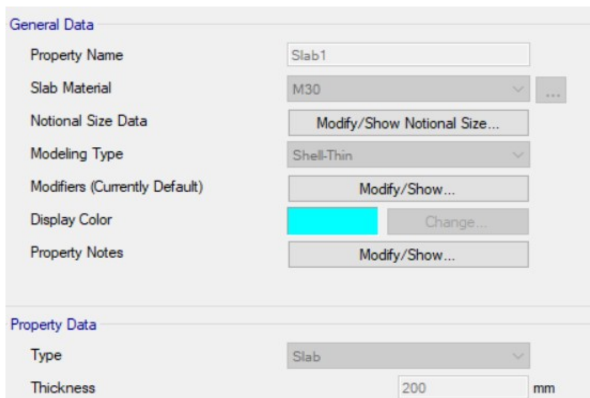

Fig.5. Slab Details of the Structure

3.3. Material Properties

Table-2. Material Properties of the Structure

Grade of concrete	M30
Rebar	HYSD415
Diameter of the reinforcement (φ)	25mm
Modulus of elasticity	2x10^5 MPa

4. Methodology

This section deals with the description of the different methods of analysis specifically used in this project. Following are the methods used:

- Linear static analysis
- Non-linear static analysis
- Non-linear dynamic analysis

4.1. Linear Static Analysis

Progressive collapse is a phenomenon incorporating dynamic and non linear properties. The effect of nonlinear dynamic characteristic on the phenomenon namely progressive collapse resistance is accurately studied and therefore calculated by the nonlinear dynamic (ND) method. This method owing to its complexity is not much used. In engineering and practical practice, however, the simplified and easy-to-use procedure is adopted which is namely the linear static (LS) method. In this process a dynamic amplification factor (DAF) is used to correct the linear static resistance demand to approximate the true non linear dynamic resistance demand (11)
GSA 2013 makes it compulsory to follow the following loading combinations for the progressive collapse analysis of a RC structure by means Linear Static Analysis:
Load = 2 x (DL + 0.25LL)
In the above equation DL is the dead load which gets generated automatically while modelling the structure is done. And LL is the live load imposed on the structure.

4.1.1. Central column removal case

Following graph shows the magnitude of the point displacement and drift under various load cases in the negative Z direction that is downwards.

Table-3. Demand Capacity Ratio of the Structure

Number of storey	**Moment of 1st row 3rd column (KN-m)**	**Demand capacity Ratio (in percentage)**
6	T= 47.445 B= -30.15	T= 14.83 B= 9.422
5	T= 20.22 B= -24.05	T= 6.318 B= 7.515
4	T= 25.43 B= -25.44	T= 7.947 B= 7.950
3	T= 23.73 B= -24.45	T= 7.415 B= 7.640
2	T= 24.20 B= -29.76	T= 7.562 B= 9.300
1	T= 17.25 B= -12.45	T= 5.390 B= 3.890

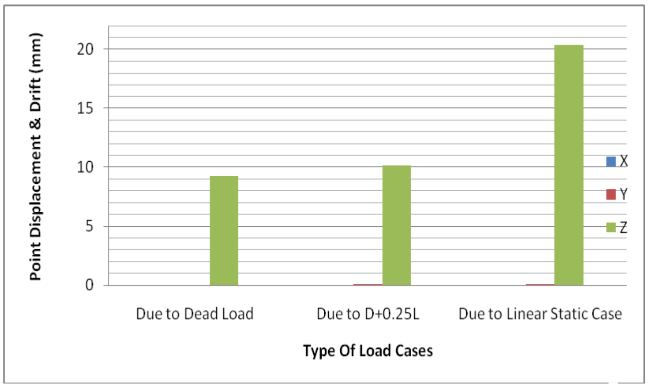

Fig. 6. Point Displacement and Drift vs. Type of Load Cases

4.1.2. Corner column removal case

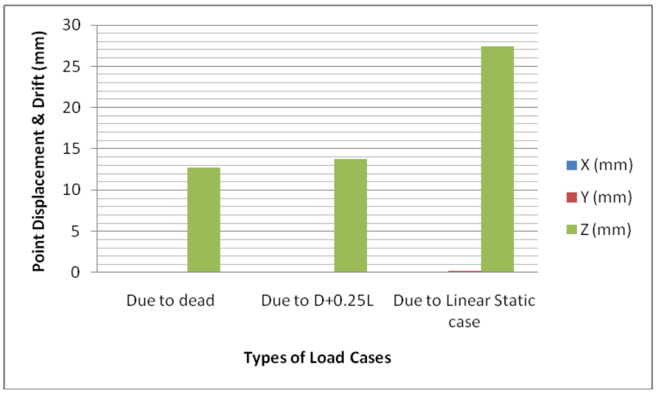

Fig. 7. Point Displacement and Drift vs. Type of Load Cases

Table-4. Demand Capacity Ratio of the Structure

Number of storey	**Moment of 1st row 6th column (KN-m)**	**Demand capacity Ratio (in percentage)**
6	T= 96.46 B= -51.52	T= 44.79 B= 26.71
5	T= 40.79 B= -48.84	T= 18.94 B= 22.67
4	T= 51.79 B= -51.81	T= 24.05 B= 24.06
3	T= 48.36 B= -49.65	T= 22.46 B= 23.27
2	T= 49.74 B= -60.36	T= 23.09 B= 28.03
1	T= 36.14 B= -24.64	T= 16.78 B= 11.44

4.2. Non-Linear Static Analysis

In this procedure also there is an increase in vertical loads by a factor of 2 but unlike the above mentioned linear static case the load in this case is amplified stepwise. And amplification is paused only when the maximum load is attained or when the building or the structure begins to collapse. This is basically known as vertical pushover analysis. Hence we can say that vertical pushover is controlled by loads, and also in this case the behaviour of the structure is studied under amplified service loads. Amplified service loads is nothing but service loads increased by a factor of 2.

Following is the procedure-Building an ETAB model then defining and assigning all the required non linear hinges. After which static loading condition as mentioned earlier in the static case is applied. Finally non linear analysis is run following a specific procedure (12)

4.3. Types of Non-Linearity

Geometric nonlinearities arise because of large strains, huge displacements, large rotations etc. Contact non-linearity also comes under geometric nonlinearity due to the area of contact which is nothing but a function of deformation. One more type of geometric non-linearity is the P-Delta effect, which incorporates the equilibrium compatibility interaction of any structural arrangement loaded about its deflected configuration. One of the many important concerns is the application of gravity load on laterally shifted or displaced or drifted multi-story building. The above condition henceforth magnifies story drift and some specific mechanical characteristics while decreasing the deformation potential or capacity.

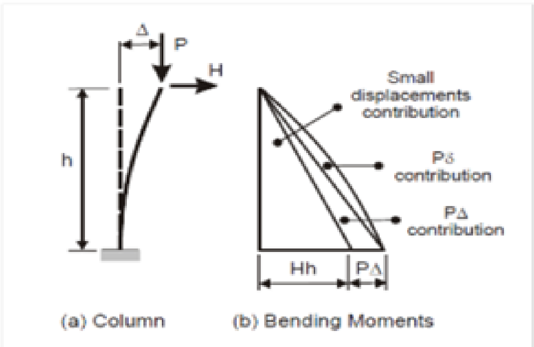

Fig. 8. P-Delta Effect

Material nonlinearities arise when the stress-strain or force-displacement rule is not linear, or when the substance or material properties alter with the applied loads.

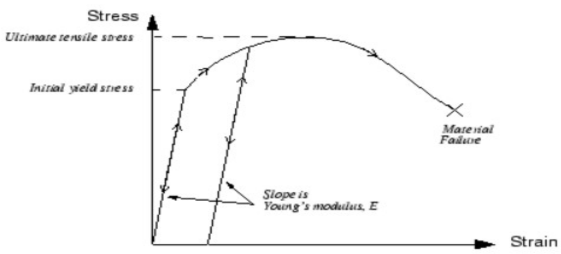

Fig. 9. Material Non-linearity

4.2.1. Central column removal case

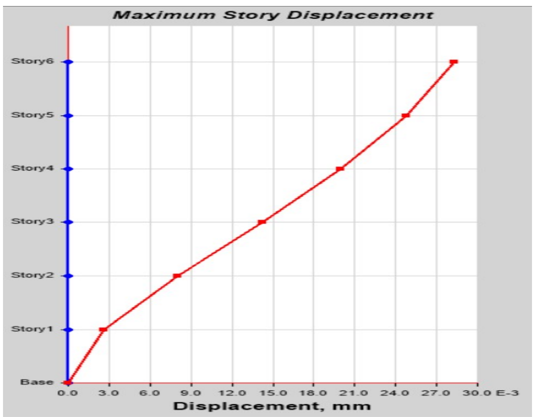

Fig. 10. Storey response graph

Table-4. Support Rotation for various stories of the Structure

Story	Load Case/Combo	RZ Rad	X m	Z m
Story6	NLScn	-3.71E-11	15	18
Story5	NLScn	-3.76E-11	15	15
Story4	NLScn	-3.70E-11	15	12
Story3	NLScn	-3.35E-01	15	9
Story2	NLScn	-2.56E-11	15	6
Story1	NLScn	-1.32E-11	15	3

4.2.2. Corner column removal case

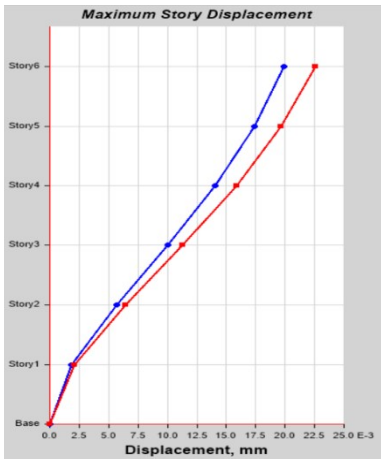

Fig. 11. Storey response graph

Table-5. Support Rotation for various stories of the Structure

Story	Load Case/Combo	RZ rad	X m	Z M
Story6	NLScn	-5.30E-05	15	18
Story5	NLScn	-4.50E-05	15	15
Story4	NLScn	-3.50E-05	15	12
Story3	NLScn	-2.50E-05	15	9
Story2	NLScn	-1.50E-05	15	6
Story1	NLScn	-6.00E-06	15	3

5. Summary of the analysis

Displacements generated above in the linear static cases is just the double of that generated in the D+0.25L cases, hence we can say that the values are up to the mark. Further the values of displacements are minor so the building is not susceptible to progressive collapse failure.

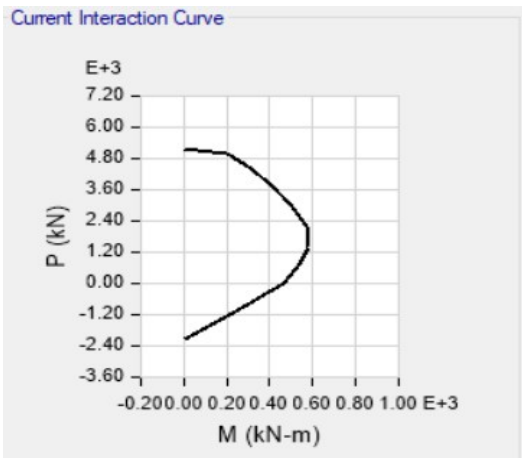

Fig. 12. Interaction Curve

Moment values from the interaction data are taken keeping in mind the optimal axial force as well as moment hence for the central column removal case 319.99 KN-m is taken as the moment whereas for the corner column removal case 215.37 KN-m is taken as the desired value. The graph just shows the general pattern of the interaction curve, however data is given in the table.In Linear analysis cases Demand Capacity ratio is to be checked which should be less than 200% in case of concrete structures according to the GSA guidelines. And as seen from the table above in no case is the DCR value greater than 200% hence the building is not susceptible to progressive collapse failure (12)

In the Non-Linear cases support rotations are to be checked as given above in the tables for both the cases that is when the central column is removed or when the corner column is removed and in none of the case the support rotation exceeds 6^0, which is the limiting value for support rotation given by the GSA guidelines for concrete structures. In the above graph it is very well depicted that the storey displacement is well below the limit as prescribed in IS 1893 (13). Storey Drift in any storey shall not exceed 0.4% of the storey height under the action of base shear with no load factor.

6. Conclusions and Discussions

In this project, progressive collapse analysis has been done using a finite element linear static and a non linear static analysis on a 6 storey building. Though there are dynamic methods also for the analysis but static method has been used owing to its practicality and simplicity in engineering world. The results for the linear static analysis have been compiled in the form of demand capacity ratio at critical section and results for that of the non linear static analysis have been compiled in the form of support rotation at joints. In both the case the building is not susceptible to progressive collapse both when the central column is removed and the corner column is removed.

Since in no case in the linear static analysis the DCR is more than 200%, hence we can say the building is safe. The maximum DCR in the above mentioned method is 44.79% which is way less than 200%. Also in the non linear static analysis in no case the support rotation exceeds the limited value of 6 degree hence this method also renders the building safe.

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