iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 9 **Issue:** III **Month of publication:** March 2021

DOI: https://doi.org/10.22214/ijraset.2021.33307

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 9 Issue III Mar 2021- Available at www.ijraset.com

A Simplified Procedure for Determining Critical Column in Progressive Collapse Analysis of RC Structures

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Abstract: The term progressive collapse is defined as the collapse of all or a large part of a structure precipitated by damage or failure of a relatively small part of it. In this paper A 3 storey, 3 bay, 9 slab multistorey framed structure is designed. The building is first analyzed using the software SAP2000 to get moments and the design of beams and columns are then done by using limit state. Loads from slabs, walls are considered but their design is not included. The designed building is analyzed using non- linear time history analysis to find the most critical column loss (i.e the column when removed causes maximum damage in the shortest time). For this nine Column Loss Scenarios are considered with three in each floor using the software SAP2000.
Keywords: Progressive Collapse, Critical Column, SAP2000, RCC Framed Structure, 3-D Modelling

I. INTRODUCTION

The term progressive collapse is defined as the collapse of all or a large part of a structure precipitated by damage or failure of a relatively small part of it. It is sometimes also called a disproportionate collapse, which is defined as a structural collapse disproportionate to the cause of the collapse. ASCE 7-10 defines the progressive collapse as "the spread of an initial local failure from element to element resulting, eventually, in the collapse of an entire structure or a disproportionately large part of it". As the small structural element fails, it initiates a chain reaction that causes other structural elements to fail in a domino effect, creating a larger and more destructive collapse of the structure. Progressive collapse is one of the most devastating types of building failures, most often leading to costly damages, multiple injuries, and possible loss of life.

The failure of vertical members under extreme events, such as blast and impact, is a highly dynamic phenomenon. In such situations sudden column loss represents a more appropriate design scenario, which considers the dynamic influences but is event-independent. Even though such a scenario is not identical, the dynamic effect imparted to column, capture the influence of column failure over a relatively short duration to the response time of the structure, whether the damage is resulting from impact or blast.

General Services Administration (2003) issued Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects. Department of Defence (2009) issued Unified Facilities Criteria for Design of Buildings to Resist Progressive Collapse (UFC 4-023-03). Both these guidelines were the foundation for progressive collapse analysis. They recognized instantaneous/sudden column loss as a suitable event-independent scenario for assessing structural robustness and suggested using it for progressive collapse analysis. Gudmundsson, G.V. and Izzuddin B.A. (2009) showed how progressive collapse can be evaluated using sudden column loss phenomenon as suggested by GSA (2002) & DoD (2009). They compared the ductility demands in multi-storey buildings arising from sudden column loss on one hand, and column damage by blast on the other, by considering a planar sub-frame representing the affected bays to prove that sudden column loss can be used for progressive collapse analysis. Sagirolu, S. and Sasani, M. (2014) compared the different cases of progressive collapse of a 7 storey RC structure due to different column failures to study the resisting mechanism of concrete structures and the effects of initial damage locations using software SAP2000.

Even though Sudden column loss is a suitable method of progressive collapse analysis, there is an uncertainty in selecting the column to be considered for progressive collapse analysis. The objective of this paper is to present the simplified concept of critical column - the column when removed causes maximum damage in the shortest time. If a building analysed for progressive collapse using critical column is safe, it can be inferred that the same building will be safe for all other column loss scenarios.

II. BUILDING SPECIFICATION

In this paper the modelling & analysis of a 3- storey R.C.C. framed building was done using the software SAP2000. Post analysis of the structure, maximum shear forces, bending moments, axial forces were computed by the software. Using the design capability of the software, the area of longitudinal and shear reinforcements was calculated based on IS456:2000. The diameter and number of bars of each structural element are then calculated manually. For simplicity infill walls were not considered and the design was done only for all beams and columns. Design of other structural members such as slabs, foundation and staircase are also not included.

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The specifications of the building designed is as follows:

Number of Storey : 3
Number of Bays : 3
Number of Slabs / Floor : 9
Beams : 400 mm x 600 mm, having Effective Length 4 m.
Columns : 400 mm x 400 mm, having Effective Length 3 m.
Slabs : 0.15 m thick and a floor finish of 0.05 m thickness.
Loads Acting : Dead Load (25 kN/m for Beams & 3.75 kN/m2 for Slabs)
Live Load (15 kN/m for Beams &2 kN/m2 for Slabs)
Floor Finish Load (1.25 kN/m2 for Slabs)
Materials : M25 Concrete, Fe500 Steel.

The Line Sketch of elevation and plan of the building are given Fig 1(a) & (b) respectively.

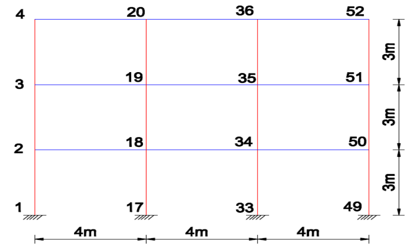

Fig. 1(a) Elevation of building (X-Z Plane)

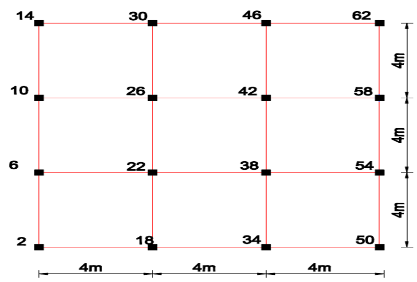

Fig. 1(b) First floor plan of building (X-Y Plane)

III.MODELLING USING SAP2000

A. Modelling

Modelling of R.C structure in SAP2000 is done using the following steps:

1) Open the SAP-2000 SAP program
2) Check the units of the model in the drop-down box in lower right-hand side corner of the SAP-2000 window, click the drop-down box to set units to kN-m
3) Click the File menu > New model command
4) Select 3-D Frame Building >Beam -Slab Building
Enter number of Bays, number of storeys, storey height & bay width
5) Click the Define menu > Material Properties
Select M25 & Fe500.
6) Define section columns and beams using Define > Frame section properties
Both beams and columns are defined with reinforcement to be designed option and providing default reinforcement for columns.
7) Define slab
Slabs are defined as thin shell element using Define > Area section
8) Assign support condition
Drop-down box in the lower right-hand corner of the SAP2000 window, select only bottom single storey level to assign fixed support using assign > Joint/Point>Restrain (Support)

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9) Loading

Define various loads (Dead load, Live load)

a) *Dead Load:* Self-weight multiplier is used 1 to calculate dead load as default.

b) *Live Load:* Self-weight multiplier is kept 0 by default.

10) Load Combination

New load combination is selected as sum of dead load and live load with scale factor 1.5.

11) Assign Loads

a) All beam member is selected and corresponding dead load and live load are assigned by Assign > Frame loads > Distributed.

b) All Slab members are selected and corresponding dead load and live load are assigned by Assign > Area loads > Uninform (shell)

B. Analysis

Analysis of R.C structure in SAP2000 is done using the following steps:

1) Check model for errors in line elements, points, area elements with tolerance factor 0.001m
Analyse>check model command.

2) Static analysis of structure
Analyse>Run analysis command

3) The bending moment diagram, shear force diagram, axial force diagram is as shown in Figure 2.

4) Display> Show Forces/Stresses > Frames

5) Design of Longitudinal and shear reinforcement was done using the software
Design > Concrete Frame design > Start Design/ Check of Structure
Design > Concrete Frame design > Display Design info

The Reinforcement obtained was tabulated as shown in Table I.

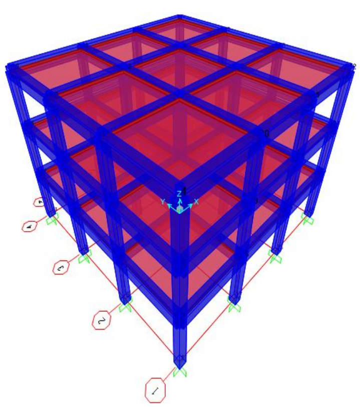

Fig. 2(a) 3D Frame

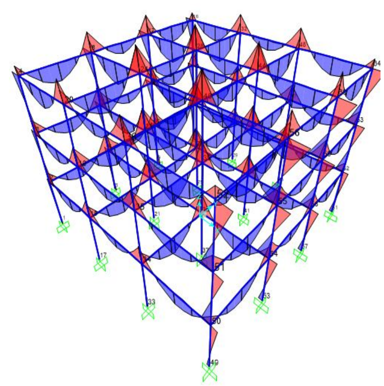

Fig. 2(b) Bending Moment Diagram

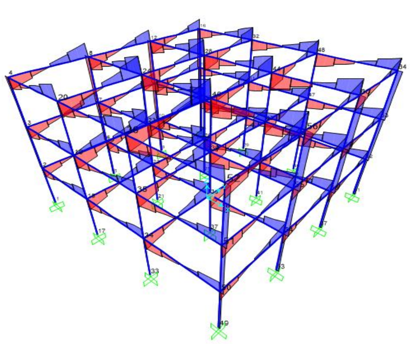

Fig. 2(c) Shear Force Diagram

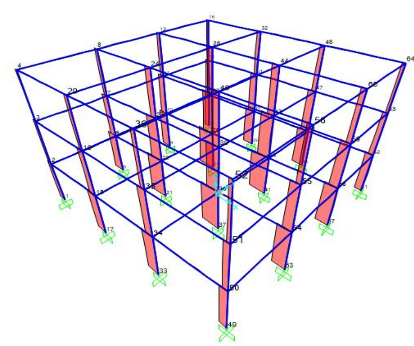

Fig. 2(d) Axial Force Diagram

Table I
Reinforcement of Beams & Columns

Beam (B) Or Column (C)	Area of Longitudinal Reinforcement Obtained (mm^2)		Area of Longitudinal Reinforcement Provided (mm^2)		Provided Shear Reinforcement
	Top	Bottom	Top	Bottom	
B_1	576	576	T16 - 3Nos	T16 - 3Nos	2 Legged T8 Stirrups @ 150mm c/c
B_2	624	576	T16 - 4 Nos	T16 - 3Nos	2 Legged T8 Stirrups @ 150 mm c/c
B_3	584	576	T16 - 3 Nos	T16 - 3Nos	2 Legged T8 Stirrups @ 150 mm c/c
B_4	604	576	T14 - 4 Nos	T16 - 3Nos	2 Legged T8 Stirrups @ 150 mm c/c
C_1	4151		T25 - 4 Nos & T12 – 4 Nos		Lateral Ties T8 @ 100 mm c/c
C_2	1280		T16 - 8 Nos		Lateral Ties T8 @ 100 mm c/c

For the building designed B1 represents all the edge beams (36 Nos) of the building, B2, B3, B4 (each 12 Nos) represents all interior columns of ground floor, first floor, second floor respectively. C1 represents the four interior columns on the ground floor (21-22, 25-26, 37-38 ,41-42), while C2 represents all the other columns. Since the software performs all the necessary checks while designing, the provided reinforcement is sufficient and the structure as a whole is safe.

IV. DETERMINATION OF CRITICAL COLUMN

Progressive collapse is simulated using SAP2000 by removing certain columns, to study the effect on the structure. Dynamic effects of progressive collapse are evaluated by performing time-history analysis. For this the designed building is first modelled using SAP2000. Analysis is done for all the possible column removal scenarios individually to find the critical column.

A. *Column Removal Scenarios*

The nine column removal scenarios can be grouped into three types- corner columns, edge columns and interior columns. Each of these scenarios exist for each floors making a total of nine.
The corner columns considered in the analysis are 1-2, 2-3 and 3-4.
The edge columns considered in the analysis are 5-6, 6-7 and 7-8.
The interior columns considered in the analysis are 21-22, 22-23 and 23-24.

B. *Analysis of Column Loss Scenarios*

The first step of analysis is to create the model (Model A) which contains the entire structure, including the column to be removed. This structure was analysed to obtain the internal axial forces on the column which is to be removed. Another model (Model B) is then modelled with the column removed. The column end forces, obtained during the analysis of Model A was applied at the joint of removed column to simulate its presence. The equivalent column load was applied together with the dead load in a nonlinear-static load case. The removal of the column was simulated by running a time-history analysis in which these equivalent column loads were reduced to zero over a short period of time (say 10 sec) [Figure 3]. This was done by applying a ramp time function in which loads opposite to those of the equivalent column loads were scaled from zero to the full value. The time-history load case, in which the column was removed using a time function, starts at the end of the nonlinear-static load case. In time history analysis, the displacement-velocity-acceleration relationships were defined by the step-by-step integration method.

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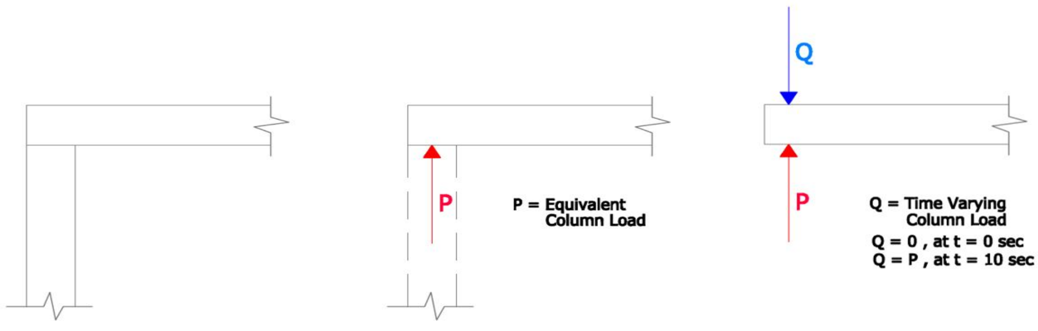

Fig. 3 Time dependent column removal: (a) before column removal (b) column removed & equivalent column load provided (c) column removal in 10 sec

C. Analysis Results

The result of the time history analysis is tabulated in Table II.

Table II
Vertical Displacement and Time of Various Column Removal Scenarios

Floor	Column Removed	Equivalent Column Load (KN)	Maximum Joint Vertical displacement (mm)	Time (sec)
Ground floor	1-2	1003.489	0.4064	7.6
	5-6	1700.774	0.16	4.3
	21-22	1021.209	7.835	2.7
1st floor	2-3	1027.04	10.71	4.3
	6-7	1147.369	16.41	7.4
	22-23	2659.157	13.05	7.6
2nd floor	3-4	330.938	0.0345	2.5
	7-8	799.054	0.0254	1.3
	23-24	900.868	0.016	2.7

Out of this the maximum vertical deflection is for 21-22 for ground floor, 6-7 for first floor and 3-4 for second floor. However critical column is selected as the one with maximum vertical deflection in the shortest time. Hence the column 21-22 is selected as critical column. (i.e. ground floor interior column)

The deformed shapes of the building subjected to column removal in three floors are shown in Figure 4. The deformed shapes of the column removed building confirms that most damage occurs when the ground floor interior column is removed as the removal of this column affects all the three floors above it. This damage is less compared to the column loss scenarios in the first and second floor as the severity is confined to upper floors. The same is found to be applicable for edge and corner columns.

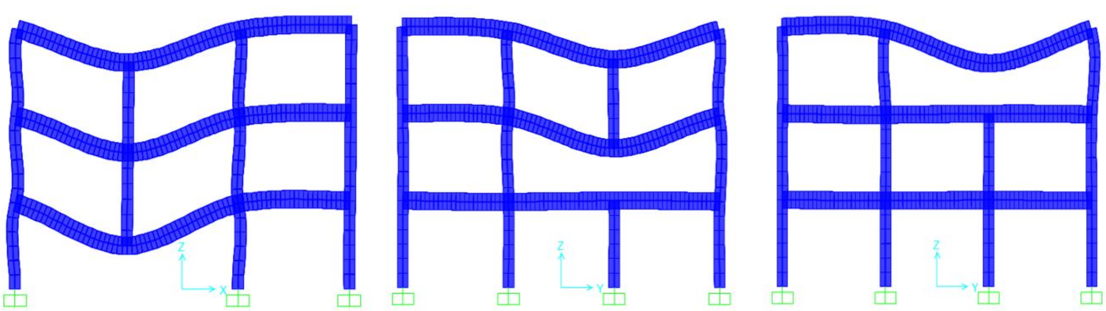

Fig. 4 Deformed shape of building for various column removal scenarios

Moreover, it is found that even though the vertical deflection of the some of the column (say A) may be higher for a particular floor, but it may not be as critical as some other column (say B) in that particular floor. This may be accounted by the time delay caused by sharing of loads by all possible alternate load paths. Since column B have limited alternate paths it may have higher vertical deflection in the shortest time. That is the damage may be less but the severity will be more as it happens faster. But when a column A fails it distributes the loads and gain some more time. But when all the alternate paths fail the damage will be very high but the time delay might have paved way for evacuation of the building or controlling the damage from spreading. Hence it is better to consider the column whose loss creates maximum deflection in shortest time as critical column.

V. CONCLUSIONS

In this paper a 3 storey, 3 bay building frame having beams of size 400 x 600 mm and length 4 m and columns of size 400 x 400 mm and length 3 m was modelled using SAP2000. The plan and elevation of the building is as shown in Figure 1. The reinforcement was found manually from the area of steel obtained from analysis. The beams were named B1 for all edge beams, B2, B3&B4 for interior beams of ground, first & second floor respectively. The columns were named C1 which consist of the four interior columns of ground floor & C2 for all the other columns. The reinforcement provided for each beams & columns are tabulated in Table 1.

Critical Column was determined from the designed building by conducting a time history analysis for each column removal scenarios using SAP2000. Nine column removal scenarios are investigated. It was found that the interior column of the ground floor reached a maximum vertical displacement of 7.835 mm in 2.7 sec (analysis was done for 10 sec). Since no other column had more than this displacement in 2.7 sec it was selected as critical column. The maximum vertical displacement and its corresponding time for various scenarios is tabulated in Table 2. This method of determining critical column can hence be extended to any building. Hence the building analysed based on this critical column will be safe for all the other column scenarios. This simplified procedure can be extended to any RC structure to find the critical column for progressive collapse analysis.

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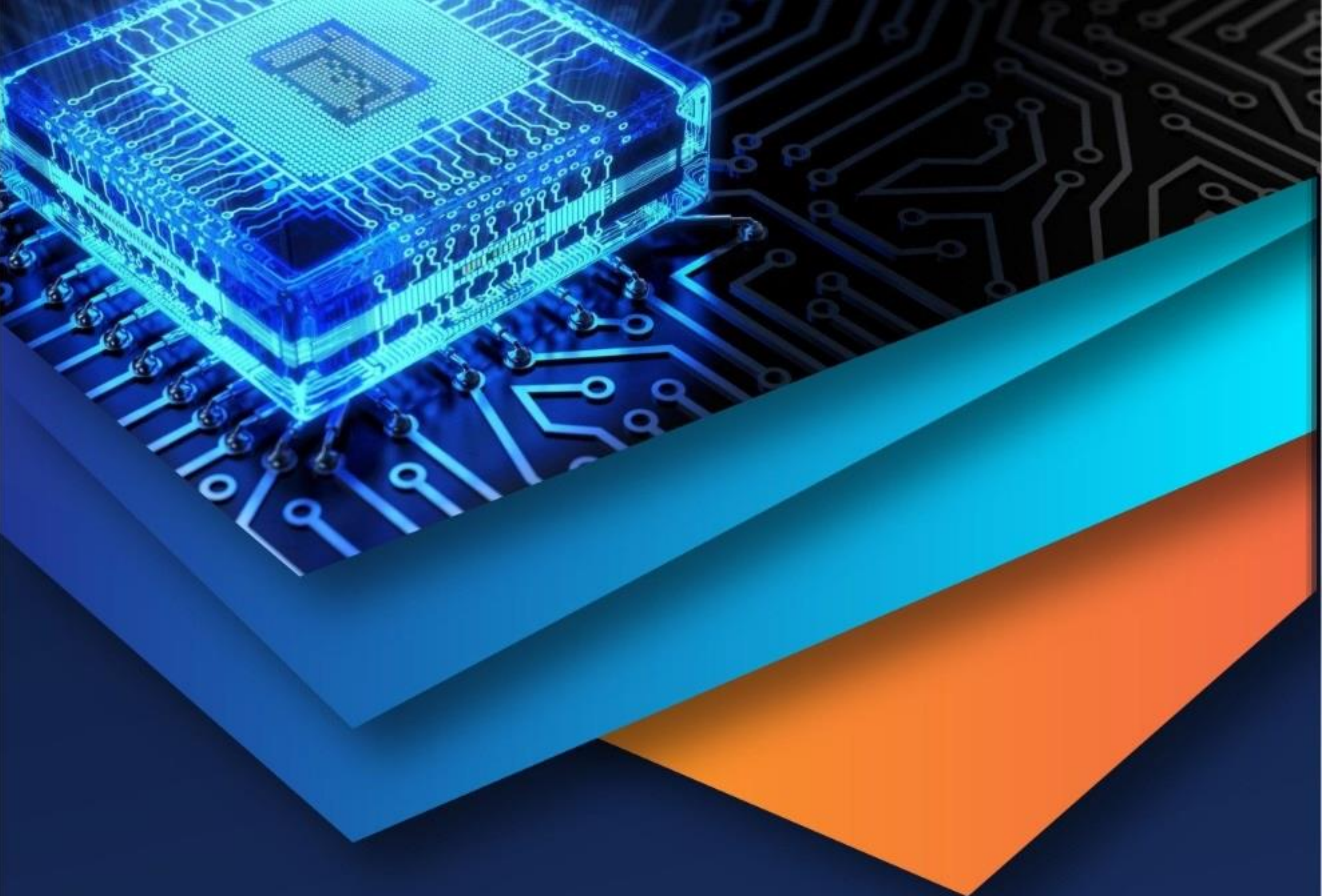

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