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Impact of structural modifications on progressive collapse vulnerability of seismically designed buildings

Mohit Patodiya*, and *P. V.* Ramana

Department of Civil Engineering, MNIT, Jaipur-302017, India

Abstract. This study investigates the progressive collapse resistance of a mid-rise reinforced concrete structure imperilled to critical column loss scenarios. A seven-story RC frame structure, with plan dimensions of 36 meters by 36 meters and uniform 6-meter bays in both orthogonal directions, was modelled using ETABS. The structural model incorporated both material nonlinearity and geometric nonlinearity to capture realistic behaviour under sudden load redistribution accurately. A total of six simulation cases were analysed. The initial three examples consisted of the immediate elimination of a vital column, to be precise, an interior column, a corner column and an edge column that did not undergo any additional structural support. The other three cases were the same column removal situations but with the introduction of X-type steel bracing systems at the outer rim of the first story. These bracing systems were modelled with Fe250 grade I-section steel members, intended to enhance the frame's lateral stiffness and provide alternative load transfer paths in case the core structural element is lost. A nonlinear time-history analysis was used to model the triggering events of a progressive collapse in the real world. Axial stiffness of the target column was rapidly reduced to near zero at 0.1 seconds, thus commencing the collapse mechanism. Parameters of structural response, including joint displacements, rotational deformations, the development of plastic hinges, and Demand-Capacity Ratios (DCRs), were seriously considered to determine collapse behaviour. The analysis results indicate that the provision of steel bracing will considerably enhance the resistance of the structure against progressive collapse. Bracing presence significantly minimised the lateral displacements and minimised the spread of plastic hinges throughout the frame. It was also observed that the DCR values were significantly smaller in braced models, which implies that it have a better stress distribution and increased load carrying capacity.

1 Introduction

The catastrophic breakdown of a structure that occurs in case a relatively small component of the system fails to work is known as a progressive collapse, which triggers a chain of events that ultimately result in the total or partial collapse. Special care should also be taken

* Corresponding author: 2023rce9510@mnit.ac.in

in reinforced concrete (RC) frame structures where the loss of one column, which is considered critical, may cause substantial redistribution of the load, which may well surpass the ability of the other members. These failures may be unpredictable and out of proportion to the original damage and they are of great concern with regards to the strength and stability of structural systems [1]. In recent years, much attention has been paid to the measurement and improvement of the progressive collapse resilience of the RC buildings particularly in the context of the man-made or unintentional hazardous impacts like blasts, vehicle impacts, construction mistakes, etc. Many studies have shown the role of structural configuration, bay sizes and detailing on collapse vulnerability [2]. Steel bracing systems have demonstrated potential as among the many empowering measures in promoting lateral stiffness, redistribution, and the generation of alternative load paths that help to reduce collapse propagation. A study by Kim et al. (2024) showed that the RC frames that had a shorter bay length could sustain a progressive collapse better in scenarios such as sudden removal of columns [3,4]. A pre-test paper by Choi et al. (2024) concerning precast concrete beam-column subassemblies showed that certain connection specificities play a major role in the formation of catenary action, which in turn has an impact on the collapse resistance of the structure [5]. Bracing systems increase structural redundancy, like inverted-V, and offer alternative load paths [6], e.g. eccentric braces. Current studies by Lee et al. (2024) have shown that Inverted-V braced frames showed more ductile characteristics during occurrence of progressive collapse after diverse bracing configurations were conducted. Inverted-V bracing systems and eccentric bracing systems are bracing systems that offer structural redundancy and alternative load paths [7]. Rakhsha et al. (2024) studied six-story five-bay steel frame, with different types of eccentric bracing. Those arrangements, which produced the highest resistance to progressive collapse of the frames, were shown to be significantly enhanced by bracing arrangements [8]. This work is aimed at determining the performance of a mid-rise frame structure made of RC in progressive collapse using the techniques of nonlinear dynamic analysis. ETABS was used to develop a seven story regular bay spacing RC building model and a variety of column removal scenarios, interior, edge, and corner were simulated to initiate one of the collapse mechanisms. Further, the effect of X-type steel bracing, which is installed at the exterior of the first floor, was examined as one of the possible retrofitting measures. The structural response was determined in terms of the important parameters of joint displacements, rotations, formation of plastic hinges, and demand-capacity ratios (DCRs). Such an investigation can help not only to understand the mechanisms of collapse of RC frames but also to recommend practical recommendations on enhancing the resilience of this type of frame by means of specific strengthening measures [9,10].

2 Methodology

The progressive collapse resistance of a mid-rise reinforced concrete (RC) frame structure was evaluated using a detailed numerical simulation approach. The process included structural modelling, definition of material and geometric nonlinearity, simulation of the column removal conditions, dynamic analysis application, and the assessment of the important response parameters [11].

2.1 Structural models

The structural model that has been taken into consideration in the analysis is a 36x 36 meter RC frame school building whose bay dimensions are equal, which are 6 meters in two orthogonal directions. The building is made up of 7 storeys with a uniform height of 3.5 meters of storey height as in Figure 1(a). In both case of steel reinforcement and concrete,

nonlinear material characteristics were taken into account. The concrete was simulated with the grade of M30, and the steel reinforcement of Fe415 grade. Geometric nonlinearity (P-Delta effects) was also allowed to emphasize second-order behaviour in the presence of redistribution of the load. FEMA 356 provided that beams and columns have nonlinear hinges, and that flexural failure modes are reflected in moment-curvature relationships. All the models have the same cross-sectional dimensions and reinforcement details to make a fair comparison [12]. It was presumed to be either a residential or office structure, and the common dead and live loads were attributed according to IS 875 (Part 1 and 2). The design of the frame was in line with the IS 456:2000, and detailing would be in line with ductile detailing requirements of IS 13920:2016.

2.2 Bracing system modelling

To examine the effect of structural enhancement, X-type concentric steel bracing was modelled at the outer periphery of the first story. The bracings were defined using Fe250 grade steel I-section members. Bracings were connected diagonally across the bays and intended to act as alternative load paths in the event of column loss. No dampers or nonlinear devices were used in the bracing system for simplification.

2.3 Progressive collapse scenarios

To assess the progressive collapse strength under various column elimination circumstances, six distinct structural instances are examined:

- Case 1(CWB): Suddenly removing one of the columns in the corners (no bracing)
- Case 2(EWB): Sudden removal of an edge column (no bracing)
- Case 3(IWB): Sudden removal of an intermediate column (no bracing)
- Case 4(CB): Sudden removal of a corner column with steel bracing provided along the outer periphery at the first story
- Case 5(EB): Sudden removal of an edge column with steel bracing at the outer periphery of the first story
- Case 6(IB): Sudden removal of an intermediate column with steel bracing at the outer periphery of the first story.

All the cases are after the column loss.

2.4 Analysis procedure

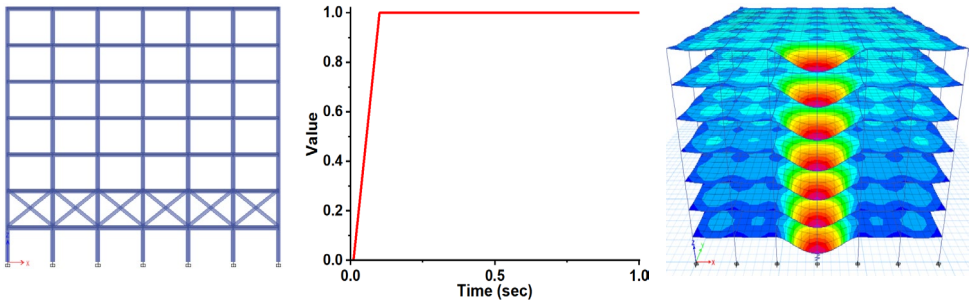
The progressive collapse simulation is carried out using nonlinear time-history (dynamic) analysis using direct integration methods [14]. A total simulation time of 1 second was used with sufficiently small time steps to ensure numerical. The column loss time step of 0.01s was chosen by performing a convergence analysis using the Newmark-beta integration method, which guaranteed numerical stability by keeping the Courant-Friedrichs-Lewy (CFL) condition below the critical threshold. Rayleigh damping at 5% critical damping for the first two modes was evaluated through modal analysis, which confirmed that energy dissipation was compatible with experimental results from similar RC frame studies. This technique minimized erroneous oscillations and gave proper capturing of the dynamic response upon removal. These are the details that will be given in the revised text to provide clarity. The key steps include:

1) Model Set-up: 3D RC frame (7 stories, 3.5m high, 3x6 bays).
2) Determine materials: Concrete M30, Steel Fe415 Assign sections, dead/live loads (IS 456:2000)

3) Assign Nonlinear: Plastic hinges (FEMA 356: moment-curvature for flexure), Geometric nonlinearity (P-Δ)
4) An element of a link is inserted where the column that is to be removed is.
5) Initially, the axial stiffness of the link is set equal to the vertical reaction force of the corresponding column, ensuring equilibrium in the model before removal.
6) A sudden force is applied at t = 0.1 seconds, as displayed in Figure 1(b). By reducing the link's axial stiffness to zero, the abrupt removal of the column is accurately simulated.
7) This dynamic stiffness degradation mimics real-world collapse triggers such as blast or impact. Deflected shape of the building shown in Figure 1(c).

The dynamic response was computed in terms of:

- Joint displacements at critical nodes
- Rotational responses of beams and columns
- Plastic hinge development and location tracking
- Demand-Capacity Ratios (DCRs) to assess overloading and failure potential



(a) (b) (c)

Fig. 1. (a) Elevation view with bracing, (b) Time history function, and (c) Deflected shape of building

3 Results and discussion

3.1 Maximum joint displacement

The maximum vertical displacement at the junction above the deleted column is shown in Table 1. Bracing considerably lowers displacement in corner and edge columns, as evidenced by the data, which demonstrate reductions of -72.457 to -20.396 and -63.658 to -26.729, respectively. This indicates improved structural stiffness and resistance to collapse at the periphery [15]. However, the intermediate column showed no change in displacement, suggesting that bracing had minimal effect due to the column's central location and existing structural support, shown in Figure 2.

Table 1. Maximum joint displacement.

Cases	Displacement without bracing (mm)	Displacement with bracing (mm)
corner column	-72.457	-20.396
Edge column	-63.658	-26.729
Intermediate column	-58.058	-58.058

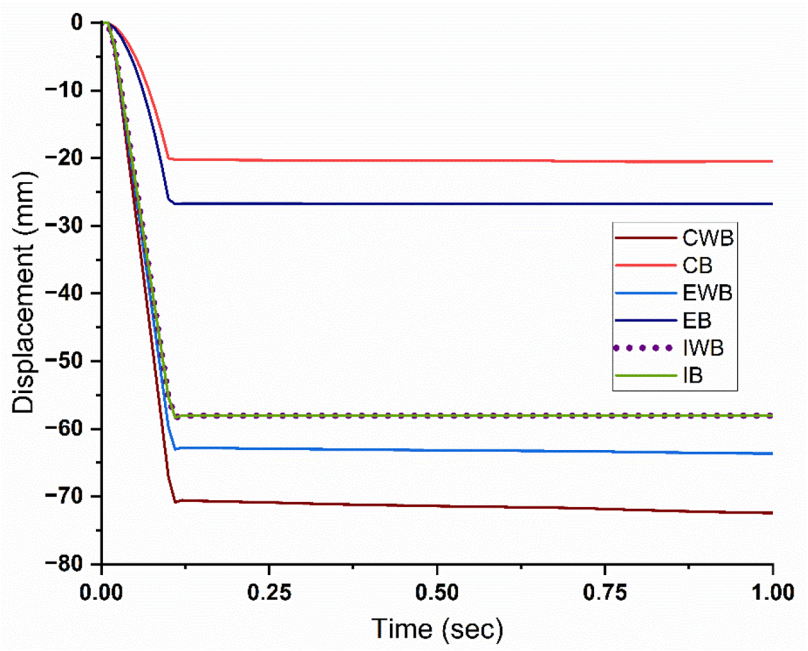


Fig. 2. Maximum displacement at the removed column's top junction.

3.2 Plastic Hinge Formation

The inclusion of bracing was found to improve the structural performance of corner and edge columns significantly. In both cases, hinge formation was decreased from 28 and 35 hinges to 11 and 14, as displayed in Table 2. and Figure 3(a), and joint rotation was reduced from 0.002163 and 0.002245 to 0.0005 and 0.00022, respectively. Indicating a substantial enhancement in structural rigidity and damage resistance shown in Figure 3(b). In contrast, the intermediate column showed no change in hinge formation and only a slight reduction in joint rotation from 0.00096 to 0.000933, as displayed in Table 3. Figure 4 illustrates the deformed shape and hinge formation of the building in the software.

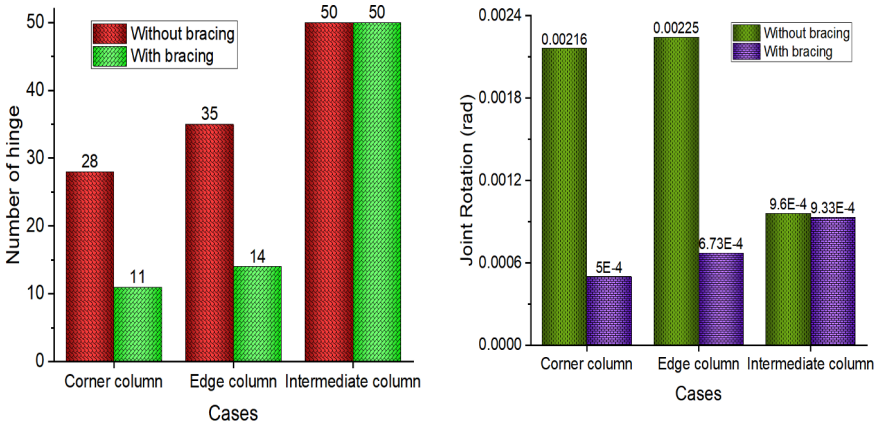


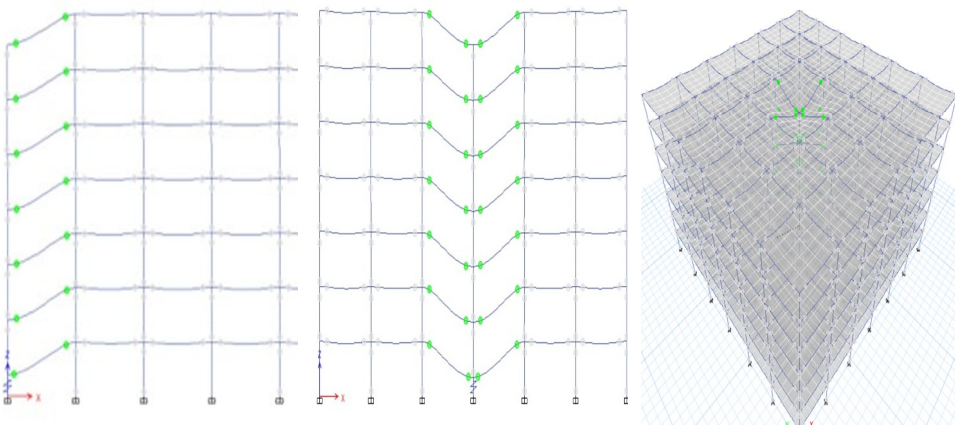
Fig. 3. (a) Number of hinge formations and (b) Joint rotation in the surrounding beam for corner, edge, and intermediate column removed cases.

Table 2. Total number of plastic hinge forms.

Cases	Hinge form without bracing	Hinge form with bracing
corner column	28	11
Edge column	35	14
Intermediate column	50	50

Table 3. Maximum Joint Rotation in the surrounding beam element.

Cases	Joint Rotation without bracing (rad)	Joint Rotation with bracing (rad)
Corner column	0.002163	0.0005
Edge column	0.002245	0.000673
Intermediate column	0.00096	0.000933



(a) (b) (c)

Fig. 4. Plastic hinge formation in (a) Corner, (b) Edge, and (c) Intermediate column elimination condition.

3.3 Demand-Capacity Ratio (DCR)

The DCR results indicate that bracing is highly effective in improving structural performance at the perimeter columns. For both the corner and edge columns, DCR values dropped from 0.217 and 0.255, respectively, to 0.141 and 0.166 after bracing was introduced, reflecting a complete mitigation of demand beyond capacity in these locations. In contrast, the intermediate column decreased in DCR from 0.187 to 0.180, as shown in Table 4. and Figure 5, suggesting that while bracing relieved the outer columns, it may have redirected internal forces, increasing the demand on central members [15].

Table 4. Maximum Demand-Capacity Ratio in the surrounding frame hinges for immediate occupancy.

Cases	DCR without bracing	DCR with bracing
Corner column	0.217	0.141
Edge column	0.255	0.166
Intermediate column	0.187	0.18044

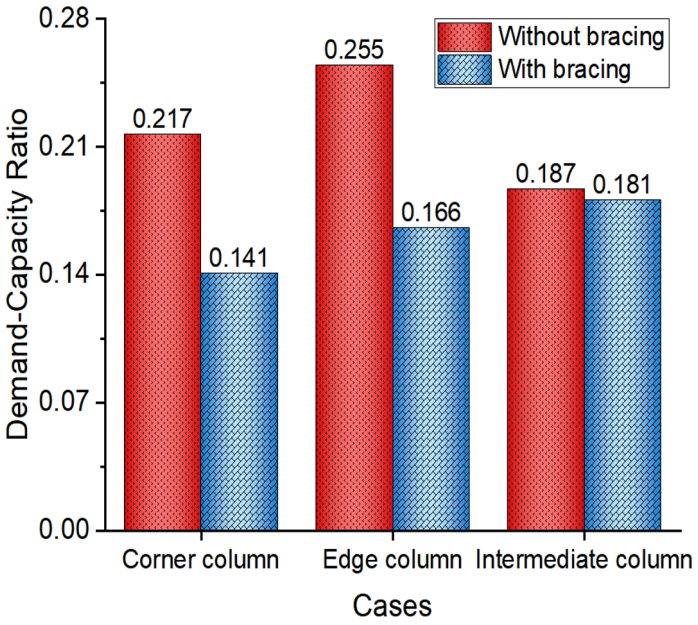


Fig. 5. Maximum Demand-Capacity Ratio in the surrounding frame hinges for immediate occupancy, corner, edge, and intermediate column removed cases.

4 Conclusion

This research paper tested a seven-story reinforced concrete (RC) structure that had a 6-meter bay separation and its structural strength to progressive collapses in various critical column avoidances. The main study findings are as follows that were determined through nonlinear dynamic analysis in ETABS:

- There was also increased vulnerability around the perimeter of the building as the corner and edge columns were taken away since numerous larger displacements and damage would be caused than having a middle column removed.
- Effects of first-story peripheral steel bracing the addition of the first-story peripheral steel bracing enhanced the structure response considerably in all the situations. Bracing decreased joint displacement, minimised hinge formation, and decreased Demand-Capacity Ratios (DCRs), and found this proved to be effective in upgrading alternate load paths.

- The use of braced configurations demonstrated the improvement of energy redistribution and retardation or prevention of propagation of collapse giving evidence to the idea of specific structural improvements to eliminate collapse.
- The paper highlights the need to take into account both structural geometry and retrofit in the progressive collapse-resistant design. The punch drunk Approach It is important to note that incorporation of strategically placed steel bracing, even at a single story can greatly increase the strength of RC frame particularly in unexpected local failures.

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