Various Approaches for Mitigating Progressive Collapse of Asymmetrical RC Building

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ABSTRACT

The failure of structural members under blast, impact, wind pressure and earthquake is highly dynamic phenomenon. One of the mechanisms of failure during such event is referred to as "Progressive Collapse". In the present study progressive collapse potential of 4-storey and 10-storey asymmetrical concrete framed building is evaluated. Linear static and dynamic analysis is performed by following the General Service Administration and Department of Defense guidelines for evaluating progressive collapse potential. Modeling, analysis and design of the buildings are performed using SAP2000 for five different threat-independent column removal conditions by following the alternate load path method. It is observed that demand capacity ratio (DCR) in beams and columns are exceeding the allowable limit for all the cases. This indicates the building considered for study is having high potential of progressive collapse. To reduce the potential of progressive collapse various approaches for mitigation of the progressive collapse are presented in this paper. Three different approaches like providing bracing at floor level, moderate increase in the size of beam at all the storey level and major increase the size of beam at bottom storey level are studied. Comparison between all the three approaches is presented for building taken into study. Among all the three approaches, bracing at floor level emerges as the most effective and economic approach for mitigating the potential of progressive collapse.

INTRODUCTION

Progressive collapse is defined as "the spread of an initial local failure from element to element resulting in the collapse of an entire structure or a disproportionately large part of it" (Zhongxian and Yanchao, 2008). In other words progressive collapse is a chain reaction failure of building members to an extent disproportionate to the original localized damage (UFC 2009). A progressive collapse is a situation where local failure of a primary structural component leads to the collapse of neighboring members which, in turn, leads to additional collapse.

Hence, the total collapse is disproportionate to the original cause (GSA, 2003).

Progressive collapse of building structures is initiated when one or more vertical load carrying members particularly columns are seriously damaged or collapsed due to accidental loading. Once a column is failed the building's gravity load transfers to neighboring members in the structure. If these members are not properly designed to resist and redistribute the additional load that part of the structure fails. As a result, a substantial part of the structure may collapse, causing greater damage to the structure than the initial impact.

Progressive collapse analysis is a process to determine the potential of progressive collapse of building. Progressive collapse analysis is a threat independent analysis, which is carried out as independent from the cause of the event. Some of the events that will cause the progressive collapse are abnormal loading, internal gas explosion, external blast, vehicular collisions, earthquake, foundation settlement, design and constructional errors or other man-made or natural hazards (Tsai and Lin, 2008).

It is very important to mitigate the susceptibility of progressive collapse of building if it is having high potential of progressive collapse. Mitigation is also referred as structural robustness. Structural robustness is an ability of structure to absorb the effect of an accidental event without suffering damage disproportionate to the event that caused it (Haberland and Starossek, 2009). In the current situation, it is very necessary for engineers to consider progressive collapse mitigation as a basic design criterion. Designing structures subjected to abnormal loading like blast, explosion etc., to have no damage, is generally impractical because the level of risk cannot be ascertained with any accuracy and the threat cannot be clearly quantified.

The probability of progressive collapse P(C) as a result of an abnormal event can be broken down into three parts as: P(E) - probability of occurrence of an abnormal event, P(D/E) - conditional probability of initial damage state of local damage D as a result of the abnormal event E, P(C/D) - conditional probability of the collapse C of the structure as a result of damage state D. Thus the different strategies to limit the probability of a progressive collapse are identified, which aims to reduce the values of the partial probabilities (Haberland and Starossek, 2009), are: Prevent the occurrence of abnormal events, Prevent the occurrence of local significant structural failure in consequence to the occurrence of abnormal events, Prevent the collapse of the structural system in the case of local significant structural failure.

In the present paper 4 storey and 10 storey asymmetric reinforced concrete buildings are analysed to ascertain progressive collapse potential as per GSA and DoD guidelines. To reduce the progressive collapse potential different mitigation strategies are discussed.

BUILDING CONFIGURATION

The typical floor plan of 4-storey and 10-storey asymmetric reinforced concrete framed structure considered for study is shown in the Figure 1. Typical floor-to-floor height of the building is 3.1 m and bottom storey height is 3.4 m. Walls of 115 mm thickness are considered on all the beams. Slab thickness is considered as 150 mm.

Primary loading considered on the building for the study are as:
Gravity loading parameters:
Dead load: Self weight of the structural elements
Live load: on roof 1.5 kN/m^2, on floors 3.0 kN/m^2
Floor finish: 1.5 kN/m^2, Wall load: 7.13 kN/m
Seismic loading parameters (IS 1893 Part-I, 2002):
Zone V, Soil type II, Importance factor 1
Material Property:
Grade of concrete f_{ck}: M25
Grade of steel f_y: Fe415

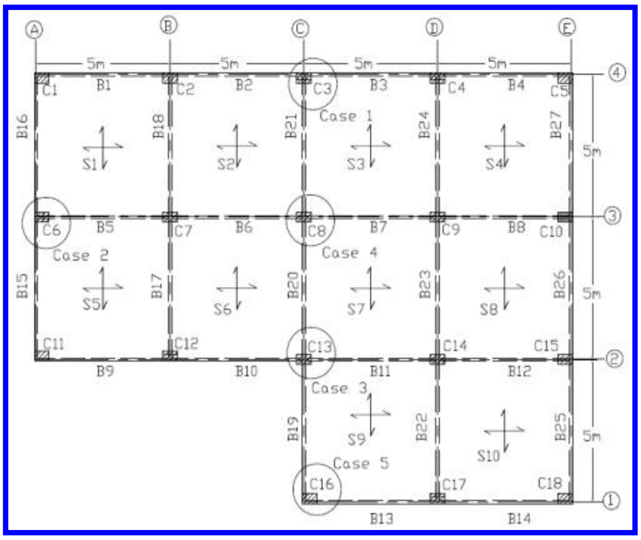


Figure 1. Typical floor plan of the building

The buildings are designed considering appropriate load combinations as specified in IS:1893. The beam size of 300 × 350 mm and column size of 350 × 500 mm are considered for 4-storey RC building. The beam size of 300 × 400 mm and column size of 500 × 700 mm are considered for 10-storey building.

ANALYSIS METHODOLOGY

Progressive collapse analysis of 4-storey and 10-storey asymmetrical concrete framed building is carried out by following the U.S. General Service Administration (GSA), and Department of Defense (DoD) guidelines. These guidelines have suggested three analysis methods: Alternate load path method, Tie force method and Local resistance method. Four analysis procedures are suggested to evaluate the potential of progressive collapse like linear static, linear dynamic, nonlinear static and nonlinear dynamic (Marjanishvili and Agnew, 2006). In this paper linear static and dynamic analysis are performed by following Alternate load path method.

In Alternate load path method original structure is designed for gravity and seismic loading. Subsequently column at ground floor is removed depending on case. The structure is subjected to gravity loading as per guidelines and demand in terms of shear force and bending moment is evaluated from the analysis. Capacity at critical sections is obtained from original design and strength increase factor. If Demand Capacity Ratio (DCR) exceeds permissible values, the element is considered as failed.

Linear Static and Dynamic Analysis. In linear analysis column is removed from the location being considered and analysis is carried out for following vertical load which shall be applied downward on the structure (GSA 2003 and UFC 2009):

As per GSA guidelines

For static analysis: Load = 2(DL + 0.25LL)

For dynamic analysis: Load = DL + 0.25LL

As per DoD guidelines

For static analysis: G = 2(0.9 or 1.2) D + (0.5L or 0.2S)

For dynamic analysis: G = (0.9 or 1.2) D + (0.5L or 0.2S)

Where, G = Gravity Load, D = Dead Load, L = Live Load, S = Snow Load

From the analysis results demand at critical points are obtained and from the designed section the capacity of the member is determined. Check for the Demand Capacity Ratio (DCR) in each structural member is carried out. The DCR of each member of the alternate load path structures is calculated from the following equation.

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

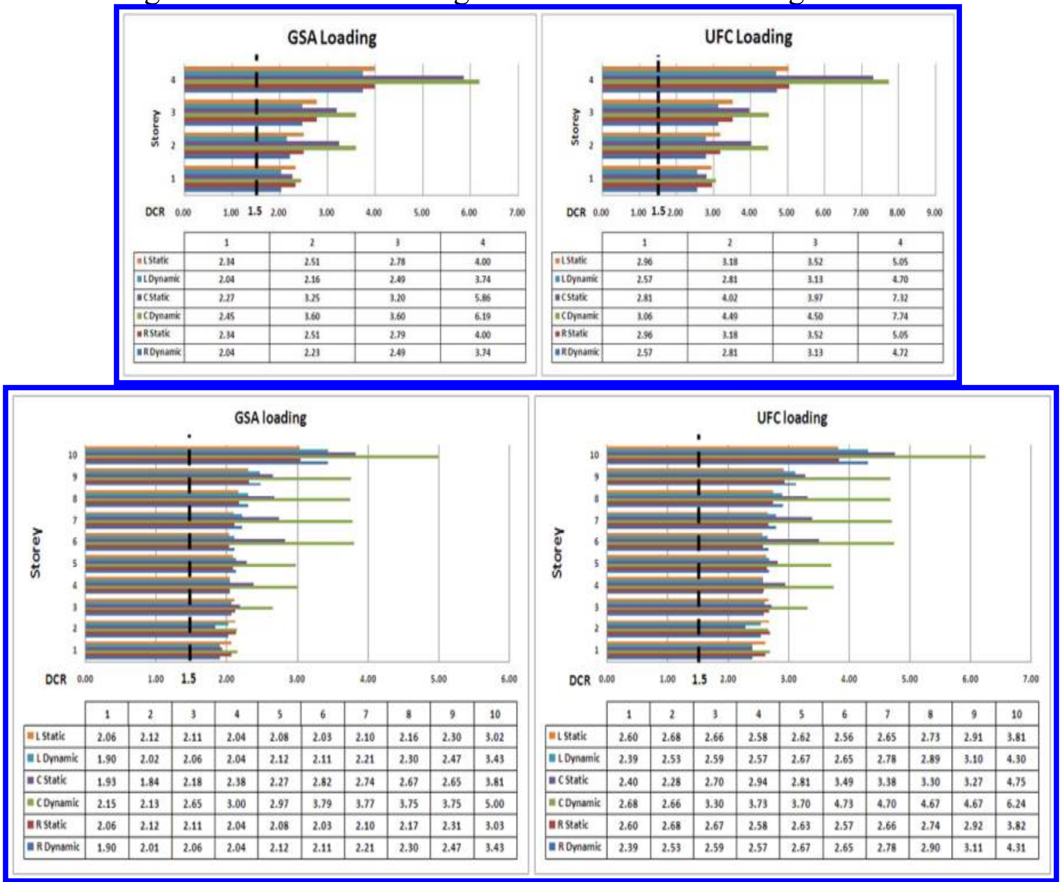
Where,

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

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

If the DCR of a member in flexure exceeds 2 for symmetric configuration and 1.5 for asymmetric configuration, the member is considered as failed. In shear and in axial loading acceptable DCR is 1 for symmetric and asymmetric structures.

Results for linear static and dynamic analysis are obtained for five column removal cases highlighted in Fig.1. From analysis it is observed that case 4 of column removal is having the worst effect on the building structure. Therefore results are presented only for case 4 of column removal. The DCR in flexure in longitudinal frame in case 4 obtained by following static and dynamic analysis considering GSA and UFC loading are shown in Figure 2. The corresponding DCR in column considering axial force and bending moment are shown in Figure 3.



GSA Loading (4 storey)

	1	2	3	4
L Static	2.34	2.51	2.78	4.00
L Dynamic	2.04	2.16	2.49	3.74
C Static	2.27	3.25	3.20	5.86
C Dynamic	2.45	3.60	3.60	6.19
R Static	2.34	2.51	2.79	4.00
R Dynamic	2.04	2.23	2.49	3.74

UFC Loading (4 storey)

	1	2	3	4
L Static	2.96	3.18	3.52	5.05
L Dynamic	2.57	2.81	3.13	4.70
C Static	2.81	4.02	3.97	7.32
C Dynamic	3.06	4.49	4.50	7.74
R Static	2.96	3.18	3.52	5.05
R Dynamic	2.57	2.81	3.13	4.72

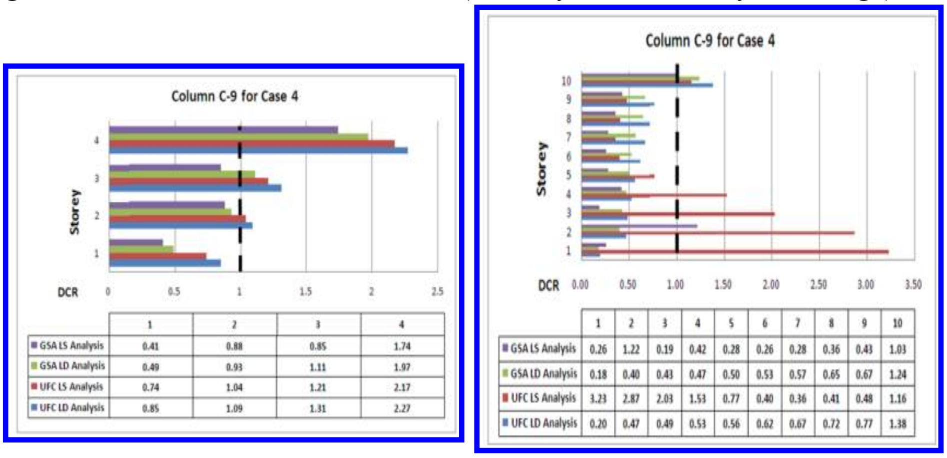
GSA loading (10 storey)

	1	2	3	4	5	6	7	8	9	10
L Static	2.06	2.12	2.11	2.04	2.08	2.03	2.10	2.16	2.30	3.02
L Dynamic	1.90	2.02	2.06	2.04	2.12	2.11	2.21	2.30	2.47	3.43
C Static	1.93	1.84	2.18	2.38	2.27	2.82	2.74	2.67	2.65	3.81
C Dynamic	2.15	2.13	2.65	3.00	2.97	3.79	3.77	3.75	3.75	5.00
R Static	2.06	2.12	2.11	2.04	2.08	2.03	2.10	2.17	2.31	3.03
R Dynamic	1.90	2.01	2.06	2.04	2.12	2.11	2.21	2.30	2.47	3.43

UFC loading (10 storey)

	1	2	3	4	5	6	7	8	9	10
L Static	2.60	2.68	2.66	2.58	2.62	2.56	2.65	2.73	2.91	3.81
L Dynamic	2.39	2.53	2.59	2.57	2.67	2.65	2.78	2.89	3.10	4.30
C Static	2.40	2.28	2.70	2.94	2.81	3.49	3.38	3.30	3.27	4.75
C Dynamic	2.68	2.66	3.30	3.73	3.70	4.73	4.70	4.67	4.67	6.24
R Static	2.60	2.68	2.67	2.58	2.63	2.57	2.66	2.74	2.92	3.82
R Dynamic	2.39	2.53	2.59	2.57	2.67	2.65	2.78	2.90	3.11	4.31

Figure 2. DCR for flexure for Case 4 (4 storey and 10 storey Buildings)



Column C-9 for Case 4 (4 storey)

	1	2	3	4
GSA LS Analysis	0.41	0.88	0.85	1.74
GSA LD Analysis	0.49	0.93	1.11	1.97
UFC LS Analysis	0.74	1.04	1.21	2.17
UFC LD Analysis	0.85	1.09	1.31	2.27

Column C-9 for Case 4 (10 storey)

	1	2	3	4	5	6	7	8	9	10
GSA LS Analysis	0.26	1.22	0.19	0.42	0.28	0.26	0.28	0.36	0.43	1.03
GSA LD Analysis	0.18	0.40	0.43	0.47	0.50	0.53	0.57	0.65	0.67	1.24
UFC LS Analysis	3.23	2.87	2.03	1.53	0.77	0.40	0.36	0.41	0.48	1.16
UFC LD Analysis	0.20	0.47	0.49	0.53	0.56	0.62	0.67	0.72	0.77	1.38

Figure 3. DCR for column for Case 4 (4 storey and 10 storey Buildings)

METHODS TO MITIGATE PROGRESSIVE COLLAPSE

For an important building having high potential for progressive collapse, it is necessary to reduce the potential of progressive collapse. If DCR for beam and column members exceed the permissible value specified by guidelines, then it is said that building is having high potential for progressive collapse. In order to minimize the potential for progressive collapse necessary structural changes are required. Significant structural changes like greatly increased member sizes, the addition of reinforcement and devloping structural actions which provide resistance like vierendeel, catenory, suspension and arch action, enhance the type of connection to moment resistance connections etc. are required based on type and configuration of building.

In this paper, three different alternatives are implemented to minimize the potential of progressive collapse of 4-storey and 10-storey Asymmetric reinforced concrete building. These three alternatives are as follows:

Alternative 1: Provision of bracing at top storey level.
Alternative 2: Moderate increase in the size of frame members across all storey level.
Alternative 3: Significant increase in the size of frame members at bottom two storey level.

From the analysis results it is observed that linear static analysis considering UFC loading give higher DCR compared to static and dynamic analysis as per GSA loading. Further case 4 column removal is governing among all cases as shown in Fig. 2. Therefore effects of mitigation strategies are studied for case 4 column removal and static analysis considering UFC loading. The original and proposed sizes of structural members for 4-storey and 10-storey buildings are shown in Table 1 and Table 2. Typical elevations of 4-storey and 10-storey buildings with three alternatives are shown in Figure 4 and 5 respectively.

Table 1. Member sizes for 4-strorey building for various alternatives

Member	Original Size (mm)	Alternative-1 (mm)	Alternative-2 (mm)	Alternative-3 (mm)
Beam	300×350	300×350	300×650	350×900
Column	350×500	350×500	400×550	400×550
Bracing	----	150×200	----	----

Table 2. Member sizes for 10-stroey building for various alternatives

Member	Original Size (mm)	Alternative-1 (mm)	Alternative-2 (mm)	Alternative-3 (mm)
Beam	300×400	300×400	350×750	350×950
Column	500×700	500×700	600×750	600×750
Bracing	----	400×400	----	----

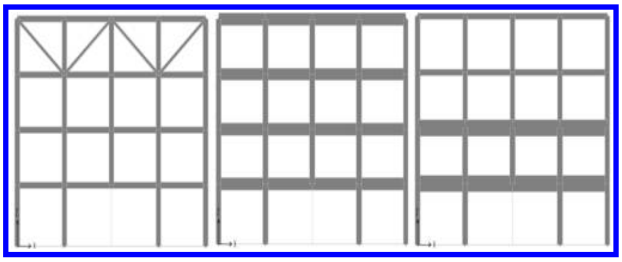


Figure 4. Various mitigation alternatives for 4-storey building

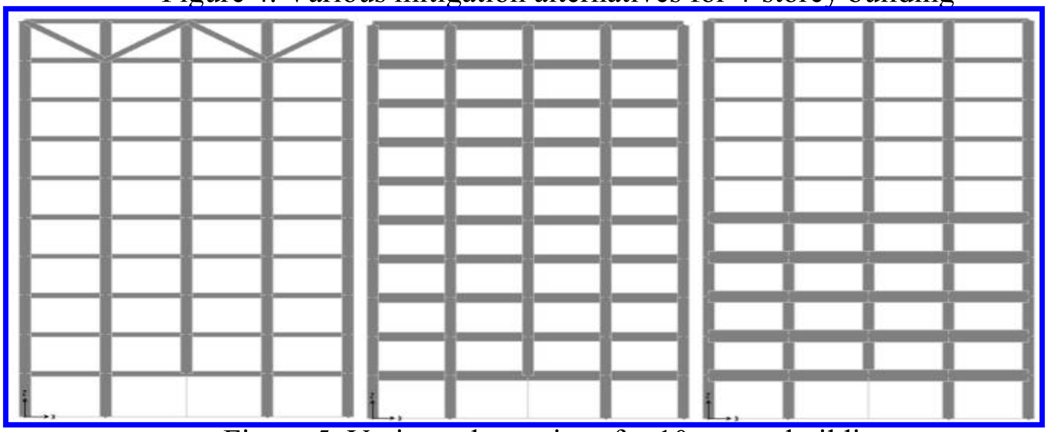


Figure 5. Various alternatives for 10-storey building

ANALYSIS RESULTS

The DCR is calculated at critical locations for UFC linear Static load case i.e. 2(1.2DL + 0.5LL) for column removal case 4, which is having maximum effect on the building. For case 4 one internal column C-8 is removed from the building and The Demand Capacity Ratio (DCR) is calculated at each storey by removing the column from ground storey. DCR for flexure is calculated at three points left, center and right side of the column removal position.

Results of DCR for flexure for case 4 following UFC linear static analysis i.e 2(1.2DL + 0.5LL) before and after mitigation for 4-storey building is presented in Figure 6. Figure 7 shows the DCR calculated for 10-storey building before and after mitigation. DCR is calculated for one proximity column C-9 which is subjected to maximum redisributed forces when column C-8 is removed from the ground storey. Figure 8 shows the DCR values for column for 4-storey building before and after mitigation. Similiarly DCR is calculated before mitigation and after considering all the three alternatives of mitigation for 10-storey building as shown in Figure 9.

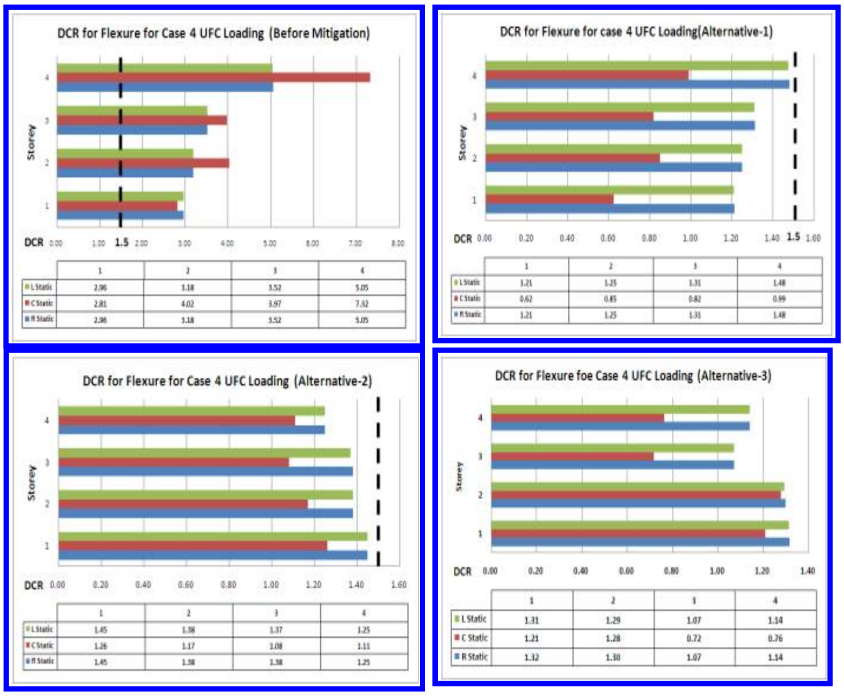


Figure 6. DCR for Flexure for case 4 of 4-storey building with various alternatives

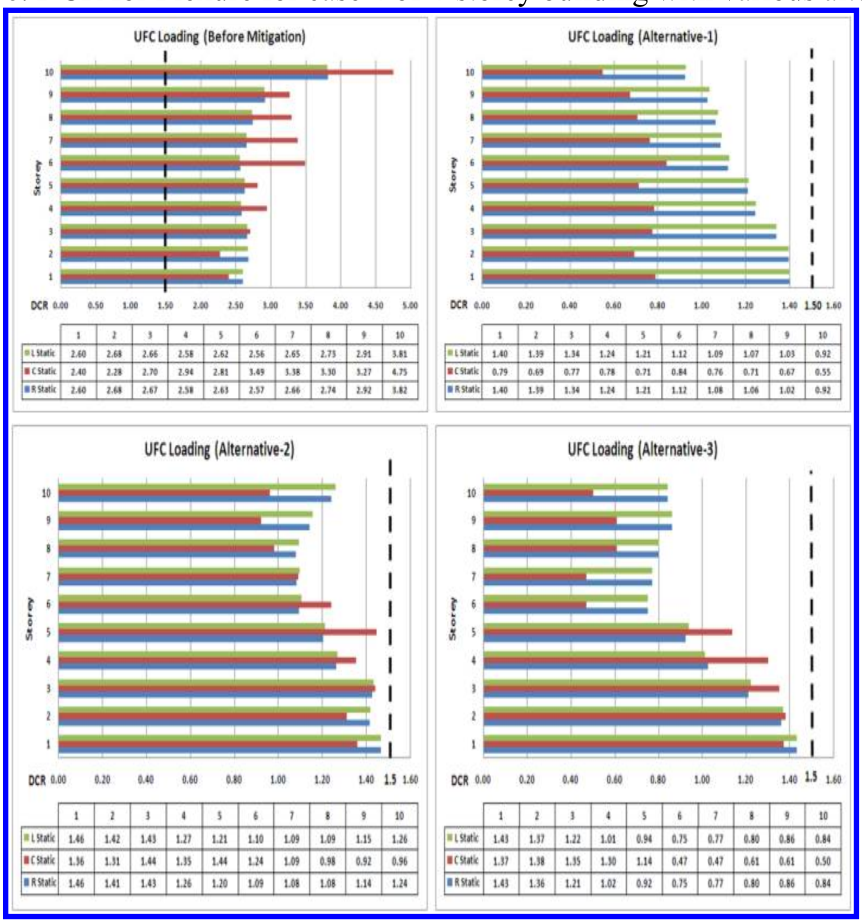


Figure 7. DCR for Flexure for case 4 of 10-storey building with various alternatives

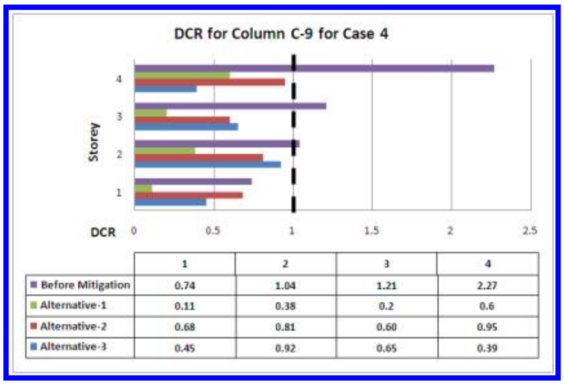


Figure 8 DCR for column C-9 for Case 4 before and after mitigation for 4-storey building

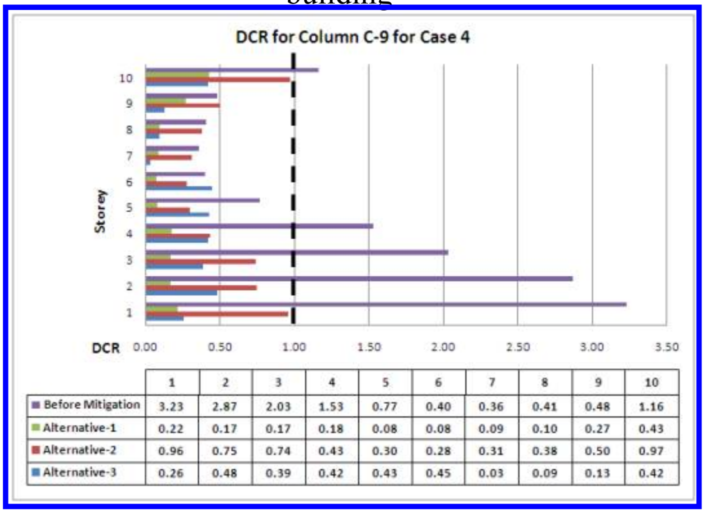


Figure 9 DCR for column C-9 for Case 4 before and after mitigation for 10-storey building

Displacement is observed under the column removal point, when column is removed from ground storey. Comparison of displacement under the column removal point before and after mitigation for 4-storey and 10-storey building is presented in Figure 10.

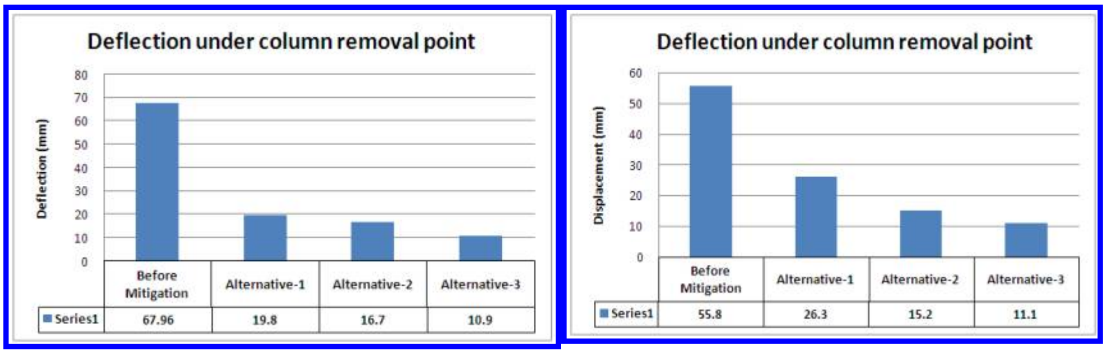


Figure 10. Displacement under column removal point for 4-storey and 10-storey building

All the three mitigation strategy reduce the DCR within permissible limit. Also the vertical displacement under column removal point is greatly reduced. This indicates effectiveness of all the three mitigation strategies. For comparison purpose additional concrete (in m^3) and additional cost (in Rs) incurred for all the three approaches of mitigation is also calculated considering current market rates. This comparison of additional concrete and cost is shown in Table 3 and Table 4 for 4-storey and 10-storey building respectively for all the three mitigation approach adopted in this study.

Table 3. Comparison of additional quantity and cost for 4-storey building

Item	Alternative-1	Alternative-2	Alternative-3
Concrete (m^3)	4.77	58.88	61.97
Cost (Rs)	19,080/-	2,35,520/-	2,47,880/-

Table 4. Comparison of additional quantity and cost for 10-storey building

Item	Alternative-1	Alternative-2	Alternative-3
Concrete (m^3)	25.41	248.72	171.88
Cost (Rs)	1,01,640/-	9,94,880/-	6,87,520/-

From the comparison of additional concrete and cost, it is observed that provision of bracing at the top storey level is more economical way to reduce the potential of progressive collapse. It can also be reduce by increasing member sizes but it would result in higher cost compared to bracing.

CONCLUDING REMARKS

In this study, linear static and dynamic analysis of 4-storey and 10-storey asymmetric RC building is carried out by following GSA and DoD guidelines. Progressive collapse potential of building is found out by considering five different threat-independent column removal cases. Out of all the five cases of column removal as suggested by guidelines, case 4 i.e. internal column removal creates worst effect on the building structure.

From the results, it is observed that DCR in flexure in beam exceeds permissible limit of 1.5 in all storey of building for all the five cases. The DCR values in beams indicate that building considered for the study is having very low potential to resist the progressive collapse. Therefore, three different alternatives are explored to mitigate the progressive collapse. When mitigation strategy is adopted, DCR value is reduced within permissible limit. Displacement obtained under column removal point after mitigation is about 70-80% lower than that of before mitigation.

From all the three mitigation strategies presented, provision of bracing in the building is most economical solution to reduce the potential of progressive collapse. The provision of bracing in top storey is more effective for reducing potential of progressive collapse for the building considered in this study, but it may depends on geometry of building. Potential of progressive collapse can be reduced effectively by combining two or more mitigation approaches in the buildings.

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