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Comparative Study of Progressive Collapse Potential of Steel Moment Resisting Frame and Braced Frame

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Abstract

Progressive collapse is a situation where local failure of a primary structural component leads to the failure of adjoining members, which in turn leads to spread of failure resulting in the collapse of an entire structure or disproportionately large part of it. In this paper, the effectiveness of inverted V type bracings on progressive collapse resistance of steel building is presented. 4-storey moment resisting steel frame building is considered for the study. Progressive collapse analysis is carried out under ten different column and/or bracing removal scenario from the ground floor level by following the U. S. General Services Administration (GSA) guidelines. Linear Static and Linear Dynamic analysis is performed to evaluate progressive collapse potential of 4-storey steel building considered for the study using SAP2000 software. Alternate Path Method (APM) is used to determine the Demand Capacity Ratio (DCR) of selected beam, column and bracing members located in surrounding of removed column. From the analysis results in terms of DCR of beams and columns, it is observed that the addition of bracing members, reduces the risk of progressive collapse.

Keywords: Progressive Collapse, Steel Structure, Braced Frame, Demand Capacity Ratio, Linear Static Analysis, Linear Dynamic Analysis

1. Introduction

Progressive collapse is a chain reaction of failures initiated from local damage to primary structural element. Progressive Collapse is the extent of damage to structures that is disproportionate to the initial event. It is a dynamic failure mechanism in which the loss of one or more local load carrying element propagates through a system causing a widespread collapse progressively. The process evolves due local triggering events like gas explosions, vehicular impacts, blast loadings etc. for which the structure is not designed. The design/protection of structure against progressive collapse becomes a concern after the Ronan Point apartment tower (London, 1968) collapse due to gas explosion. Also after the collapse of World Trade Centre (New York, 2001), many government and private agencies worked on the development of guidelines for progressive collapse resistant structures. The US General Services Administration (GSA) and the Department of Defence's Unified Facility Criteria (UFC) guidelines employ the Alternate Path Method (APM) to ensure the structure's resistance against progressive collapse. As per the APM, the main element of a structure, typically column is damaged or incapable of taking the upcoming load on it. The remaining structural members should be able to span across the lost member.

Moment resisting steel frame is widely used for low rise to medium rise buildings. Steel braced frame is one of the structural system which is very popular in the seismically active regions. There are mainly two kinds of braced frames which includes Concentric Braced Frame (CBF) and Eccentric Braced Frame (EBF). The CBF provide strength and stiffness by inelastic behaviour of brace by yielding both in tension and compression whereas in EBF the energy dissipation is achieved by inelastic behaviour of link beam. The role of bracing in enhancing progressive collapse resistance of steel structures can be evaluated by using APM as suggested by the U.S. General Services Administration (GSA) guidelines.

Many academicians and researchers have carried out numerous studies to evaluate progressive collapse resistance of steel buildings, since the collapse of World Trade Centre. Authors have also conducted studies to investigate influence of different types of bracings on progressive collapse

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resistance of steel structures. Khandewal et al. [1] analyzed the steel framed building under progressive collapse with special concentric brace frame (SCBF - X type) and Eccentric Brace Frame (EBF) using macro models. The initial imperfection of 1/250 of length of bracing was kept to capture the brace behaviour. They reported less vulnerability of concluded that EBFs compared to SCBF. Also no yielding of brace in SCBF and that of shear link in EBF occurred. Naji and Zadeh [2] carried out Non-linear dynamic analysis of SCBF - X type and EBF by following GSA guidelines using SAP2000 software. The various reduced brace section and different link beam length was adopted in analysis. The capacity curves were generated for every 5% increment of load. The increase in ductility and decrease in progressive collapse potential was observed as the brace section reduced in SCBF and link beam length increase in EBF. Qiao et al. [3] analysed the steel braced frames under progressive collapse considering vierendeel action. The 4-bay, 3-storey steel moment frame with inverted V bracing was analysed in ABAQUS and developed an expression for progressive collapse resistance through vierendeel action for n-story building. Authors proposed the bracing in the top story of the frame to fully utilize the vierendeel action. Mahmoud et al. [4] assess the Progressive Collapse of Steel structures under seismic condition. 5-bay, 5-storey moment frame and moment frame with inverted V bracing in central bay was analysed in SAP2000. Based on the studies, authors found the development of catenary action in perimeter beams due to rigid beam-column connection. The maximum deflection above the removed column was observed in corner column removal case followed by edge column removal. Progressive Collapse analysis of 5 and 15 stories moment frame was carried out by Tavkoli and Alasthi [5]. The various reduced column effective areas considered including 40%, 70% and 100% of actual area of column for non-linear static analysis. For lateral load, triangular and uniform pattern was considered. Robustness Index was calculated to qualify the frame behaviour. The analysis results showed that the uniform load pattern produce larger base shear capacity than triangular pattern. Also as the number of bay and stories increases the progressive collapse resistance increases. The effect of bracing type and topology on progressive collapse resistance of eccentric braced frame was evaluated by Mirjalali et al. [6]. Inverted and combined inverted V, Single and double diagonal eccentric braced frames were analysed in OpensSEES software by using non-linear dynamic analysis. Element removal impact factors were calculated to quantify the effect of removed members on adjacent members. Authors observed that frame with two and three braced bays had more progressive collapse resistance. Also the combined inverted V braced frame had more resistance to progressive collapse than other brace configuration. Liu and Zhu [7] analysed the 6-bays, 8-story moment resisting, X-braced and inverted V braced 2D frames for progressive collapse under column removal scenario using SAP2000. Non-linear static and non-linear dynamic analysis was carried out and Robustness Index of structural members were calculated to qualify their behaviour. Authors concluded that the dynamic response the structure was slowed down due to brace members when column removed from structure. The 4, 7 and 10 story steel building with combined knee and concentric X brace was analysed by Parvari and Bahri [8] under progressive collapse scenario. Non-linear static and non-linear dynamic analysis was carried out to obtain the response of structure against progressive collapse. Authors found the combine knee and x-braced frame was capable to resist the progressive collapse.

In this paper, progressive collapse potential of 4-storey steel building is evaluated. Linear static analysis is performed to evaluate the effectiveness of inverted V-type bracings on progressive collapse resistance under different column and/or bracing removal scenario from ground floor. Alternate load path method is used as suggested by GSA guidelines to determine Demand Capacity Ratio (DCR) of critical members located in surrounding of removed column.

2. GSA Guidelines [12]:

The purpose of GSA guidelines is to reduce the potential for progressive collapse in new and renovated buildings. Alternate Load Path method (APM) is suggested in this guideline. In 2003 edition of GSA guidelines APM was considered as threat independent approach, but in the latest revision of GSA guidelines a threat dependent approach is also specified.

The removal extent of column include the column near the middle of short side, near the middle of long side, corner of building and adjacent to corner of building and column at the location where building changes its shape abruptly for irregular building. Also, removal of columns can be considered from the critical locations as determined by the engineering judgment.

Linear Static, Non-linear Static and Non-linear Dynamic methods should be adopted for analysis of structure affected by progressive collapse. Linear Static analysis can be adopted for buildings up to 10 stories by calculating Demand Capacity Ratios (DCRs). The limiting value of DCR for flexure in beam is 2.0 and for combined axial and moment in column is 1.0. For irregular buildings if DCR of any member is less than 2.0 then Linear Static procedure should not be adopted independent of number of stories. The loadings that need to apply on the part of structure affected by progressive collapse given in GSA guideline is as follows:

For Static analysis: 2 (1.2DL + 0.5LL)…………………..(1)
For Dynamic analysis: (1.2DL + 0.5LL)………………....(2)
Where, DL = Dead Load, LL = Live Load

3 Methodology:

The 4-storey building is analysed and designed using IS:800-2007 [9]. For modelling and analysis SAP2000 software is used. DCR of critical members are calculated as per GSA guidelines.

3.1 Description of Model:

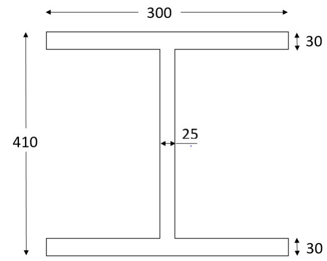
The 4-storey steel building considered for analytical study has 6 bays in longitudinal direction and 3 bays in transverse direction [11]. The uniform spacing of column is 8.25 m in longitudinal direction and 9.75 m in transverse direction. The typical story height is 4.3 m. The plan and elevation of moment frame is shown in Fig. 1 and 2 respectively. For braced frame, the Inverted V type of bracing configurations are considered. The various cases for arrangement of bracing in different bays and stories is given in Table 1. The elevation of braced frames for various cases is shown in Fig. 3 to Fig. 6. The moment resisting frame and braced frames were modelled and analysed in SAP2000 software.

3.2 Loading on Building: Self weight of structure is included in the Dead Load and calculated based on the density and volume of material. The density of concrete is considered as 23.6 kN/m^3 and density of steel is considered as 76.9 kN/m^3. The thickness of composite concrete slab is considered as 90 mm. Walls are provided on the perimeter beams except roof. The unit weight of wall is considered as 19.7 kN/m^3. The live load is considered as 1.9 kN/m^2 on all typical floors as well as on roof. For seismic loading, the Building is considered in zone III. The building is designed based on the governing load combination and the designed sections of beams, columns and brace members are shown in Table 2. The structural design is performed as per IS 800: 2007 [9] and IS 1893:2016 [10].

Table 1: Arrangement of Inverted V Bracing

Case	Type of Bracing Arrangement		
	Story	Longitudinal direction	Transverse direction
Case 1	All stories	3rd and 4th	Central
Case 2	1st and 2nd Story		
Case 3	1st and 3rd Story		
Case 4	1st and 4th Story		

Table 2: Schedule of Beams, Columns and Braces

Type of Element	Size of Section
Primary Beam (PB1)	ISMB500
Secondary Beam (SB1)	ISMB450
Bracing (All)	2ISA 200×200×10
Built Up Column	 (All dimensions are in mm)

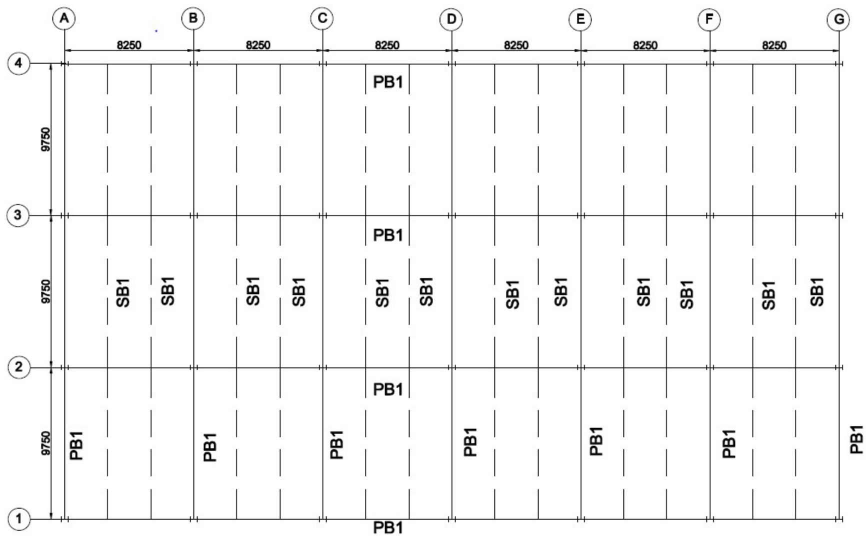
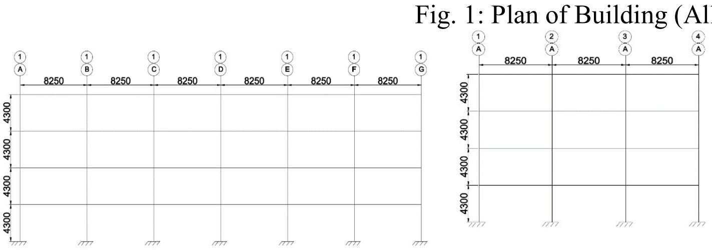
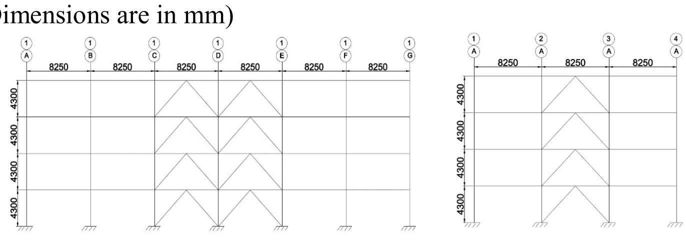


Fig. 1: Plan of Building (All Dimensions are in mm)



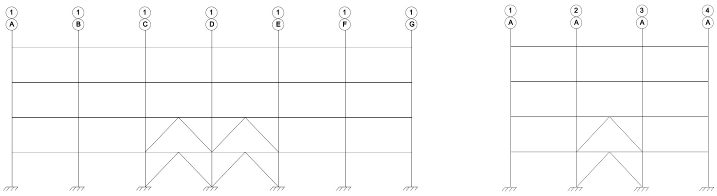
(a) Longitudinal direction (b) Transverse Direction

Fig. 2: Elevation of Moment Frame (All dimensions are in mm)

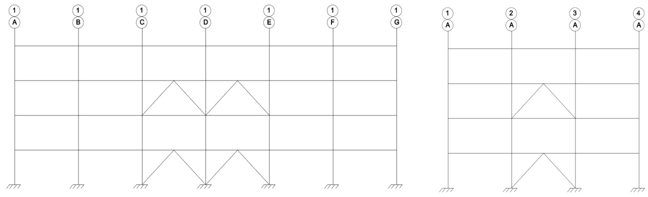


(a) Longitudinal direction (b) Transverse Direction

Fig. 3: Elevation of Braced Frame for Case 1 (All dimensions are in mm)



(a) Longitudinal direction (b)Transverse direction
Fig 4: Elevation of Braced Frame for Case 2



(a) Longitudinal direction (b)Transverse direction
Fig. 5: Elevation of Braced Frame for Case 3

(a) Longitudinal direction (b)Transverse direction
Fig. 6: Elevation of Braced Frame for Case 4

3.3 Linear Static and Linear Dynamic Analysis:

The Linear Static Analysis (LSA) and Linear Dynamic Analysis (LDA) is performed to evaluate the response of 4-storey steel building under progressive collapse. The response is obtained in terms of the Demand Capacity Ratios (DCRs) for both linear static & linear dynamic analysis and displacement time history at joint above removed column for linear dynamic analysis. For progressive collapse analysis, various column and/or brace removal scenario are considered as specified by GSA guidelines. Table 3 shows the various column and/or brace removal scenario considered for the study. The loading on the structure 2 (1.2DL + 0.5LL) for linear static analysis and should be applied to the areas which are affected by progressive collapse as suggested by GSA guidelines. In the remaining area loading (1.2DL + 0.5LL) needs to be applied. Fig. 7 and Fig. 8 shows the hatched portion of the building on which 2 (1.2DL + 0.5LL) is applied. For linear dynamic analysis, apply (1.2DL + 0.5LL) on whole building area. The elevation of all column and/or bracing removal scenario are shown in Fig. 9. Removed column and brace are shown by dotted line and also highlighted by ellipse.

Table 3: Column and/or Brace removal scenario

Scenario	Type of Steel frame	Column and/or Brace Removal Location
Scenario 1	Moment Resisting Frame	MC (from longitudinal bay)
Scenario 2		CC
Scenario 3	Inverted V Braced Frame	MC & B – C1
Scenario 4		MC & B – C2
Scenario 5		MC & B – C3
Scenario 6		MC & B – C4
Scenario 7		CC – C1
Scenario 8		CC – C2
Scenario 9		CC – C3
Scenario 10		CC – C4
Where MC = Middle Column CC = Corner Column B = Bracing	C1 = Case 1 C2 = Case 2 C3 = Case 3 C4 = Case 4	As per Table 1

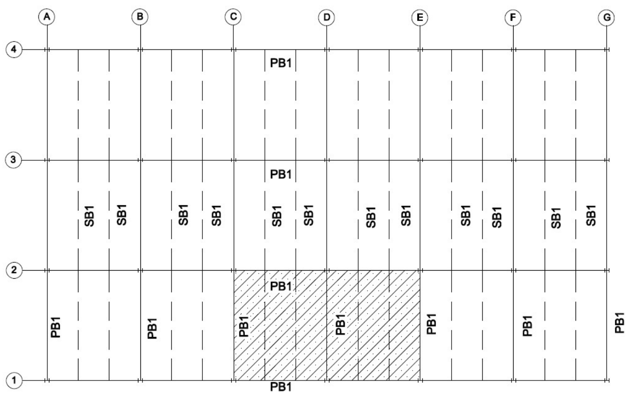


Fig. 7: GSA loading in plan for middle column removal

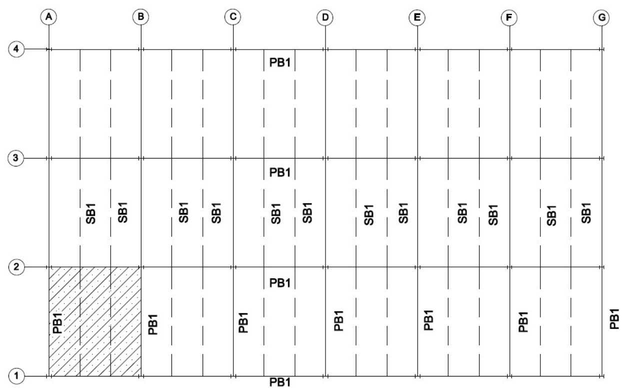


Fig. 8: GSA loading in plan for corner column removal

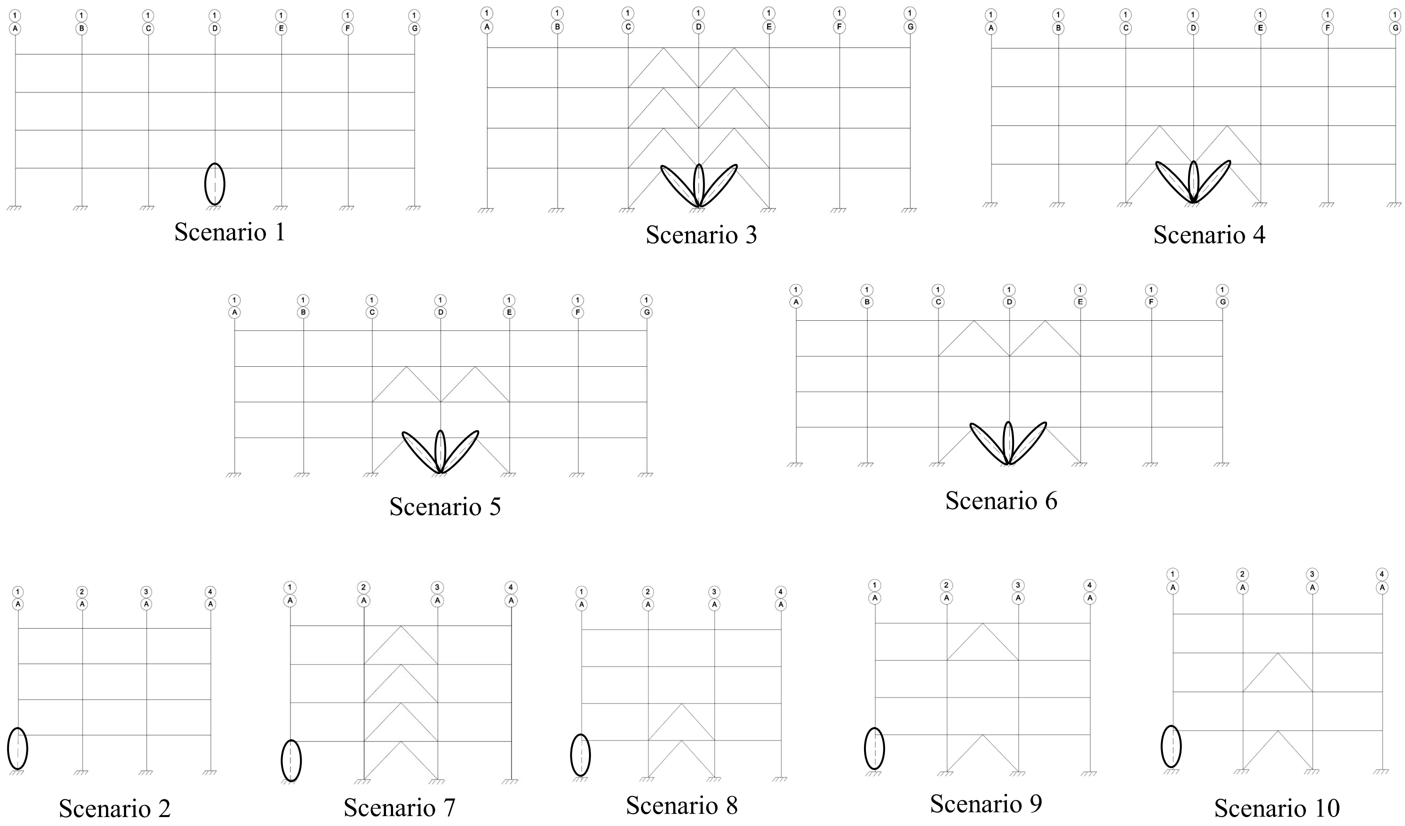


Fig. 9: Column and/or Brace removal scenario

4. Calculation of Demand Capacity Ratio (DCR):

In the present study, the structural response is evaluated by calculating the Demand Capacity Ratio of all the critical structural members. GSA guidelines provides a calculation for DCR for various structural elements like beams, columns and bracings. For Beams, the DCR is calculated for flexure. In column the DCR is calculated by considering the axial load and bending moment.

DCR for Flexure in Beam:

The plastic moment capacity of the section is required to calculate the DCR for flexure in beam.

$M_p = Z_p f_y$

$$\text{DCR (Flexure)} = \frac{M_{actual}}{M_p} \leq 2.0 \quad (3)$$

Where M_p = Plastic Moment capacity of beam section

Z_p = Plastic Section Modulus

f_y = Yield Stress of steel material

M_{actual} = Actual moment acting on beam

DCR for Column:

When any column is removed from the structure than the loads and moments action on it becomes unbalanced. So it is redistributed to the adjacent structural members. The DCR for column can calculates as per following interaction formula.

$$\text{DCR (Column)} = \frac{M}{1.18 Z_p f_{ye}} + \frac{P}{P_{ye}} \leq 1 \ldots\ldots\ldots.(4)$$

Where P = Axial force acting on column

Py = Yield strength of axially loaded column = $A_s f_y$

A_s = Effective c/s area of column

M_{pc} = Maximum moment acting on the column

M_p = Plastic moment capacity of column section

5. Results and Discussion:

Progressive Collapse potential of moment resisting frame and inverted V braced frame is evaluated for 10 different column and/or brace removal scenario as suggested by GSA guidelines and DCRs are calculated. The DCR for flexure in case of beam and DCR for column is calculated according to equation (3) and (4), respectively. This DCR values in different stories for each case is represented in the form of bar chart. The DCR for scenario 3 to scenario 6 for both flexure in beam and for column satisfying the acceptance criteria. Therefore, results of DCR shown for scenario 1, scenario 2 and scenario 7 to 10.

5.1. DCR for Flexure for Beam:

DCR for flexure in case of beam is shown in Fig. 10 (a) to Fig. 10 (j). DCR is calculated for the beams located around the area of removed column. For middle column removal, the DCR is calculated for beams located between gridline C1-E1 for all 4 stories and for corner column.

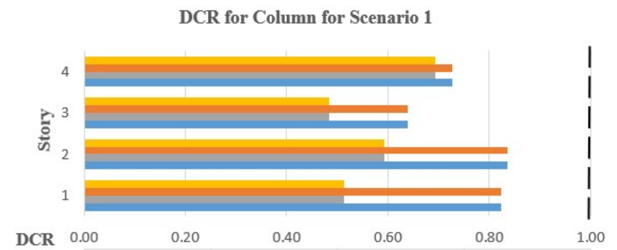
Fig. 10: DCR for Flexure for Beam for all member removal scenario

removal, DCR is calculated for beams located between gridline A1-B1 (in longitudinal direction) and A1-A2 (in transverse direction) for all 4 stories. C1 is the intersection point of gridline C and gridline 1. DCR for the beams which are not shown in the graph are satisfying the acceptance criteria.

The beam section of moment resisting frame are not capable to resist progressive collapse for both middle and corner column removal scenario, as their DCR values exceeding the permissible limit of 2. The inverted V bracing enhance the progressive collapse potential of beams in scenario 3 to scenario 6. However, this bracing configuration is not effective for the beams around corner column removal area. So, it is essential to provide the bracings in the corner bay in longitudinal and transverse direction to increase the progressive collapse resistance of structure under corner column removal scenario.

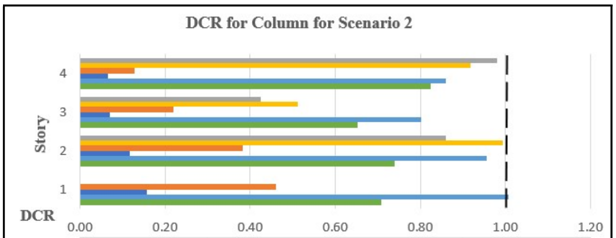
5.2 DCR for Column:

The DCR for column is presented in Fig. 11 (a) to Fig. 11 (f). For middle column removal scenario, the DCR is calculated for columns located in the Gridline C1 and E1, while for corner column removal scenario, the DCR is calculated for columns located in gridline A1, A2 and B1. Notation C1 indicates the column located at the intersection of gridline C and gridline 1. Same way other notations can interpret as location of columns at intersection of respective gridlines.



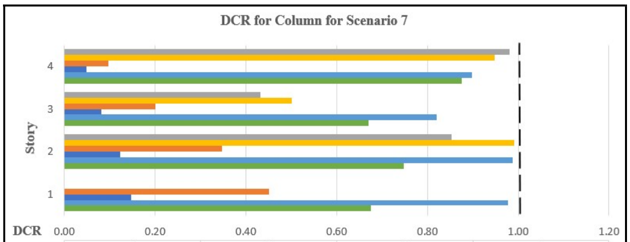
	1	2	3	4
E1 - LDA	0.51	0.59	0.48	0.69
C1 - LSA	0.82	0.84	0.64	0.73
C1 - LDA	0.51	0.59	0.48	0.69
E1 - LSA	0.82	0.84	0.64	0.73

(a)



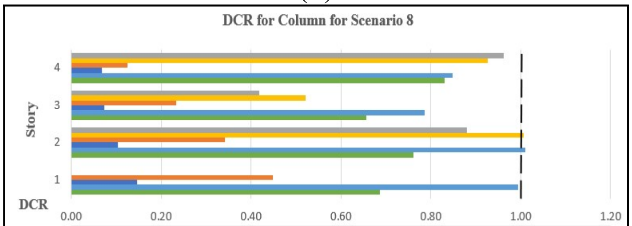
	1	2	3	4
A1 - LSA	0	0.86	0.43	0.98
A1 - LDA	0	0.99	0.51	0.92
A2 - LSA	0.46	0.38	0.22	0.13
A2 - LDA	0.16	0.12	0.07	0.07
B1 - LSA	1.01	0.96	0.80	0.86
B2 - LDA	0.71	0.74	0.65	0.82

(b)



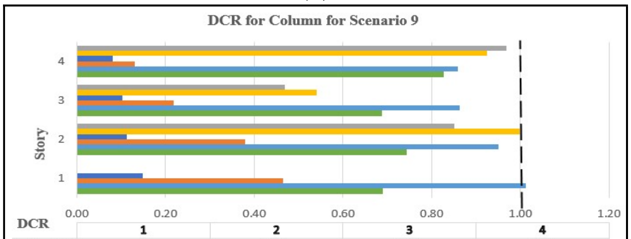
	1	2	3	4
A1 - LSA	0	0.85	0.43	0.98
A1 - LDA	0	0.99	0.50	0.95
A2 - LSA	0.45	0.35	0.20	0.10
A2 - LDA	0.15	0.12	0.08	0.05
B1 - LSA	0.98	0.99	0.82	0.90
B1 - LDA	0.67	0.75	0.67	0.88

(c)



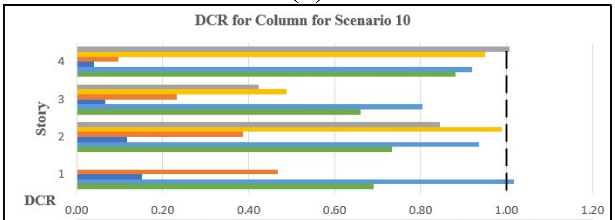
	1	2	3	4
A1 - LSA	0	0.88	0.42	0.96
A1 - LDA	0	1.01	0.52	0.93
A2 - LSA	0.45	0.34	0.23	0.12
A2 - LDA	0.15	0.10	0.07	0.07
B1 - LSA	0.99	1.01	0.79	0.85
B1 - LDA	0.69	0.76	0.66	0.83

(d)



	1	2	3	4
A1 - LSA	0	0.85	0.47	0.97
A1 - LDA	0	1.00	0.54	0.92
A2 - LDA	0.15	0.11	0.10	0.08
A2 - LSA	0.46	0.38	0.22	0.13
B1 - LSA	1.01	0.95	0.86	0.86
B1 - LDA	0.69	0.74	0.69	0.83

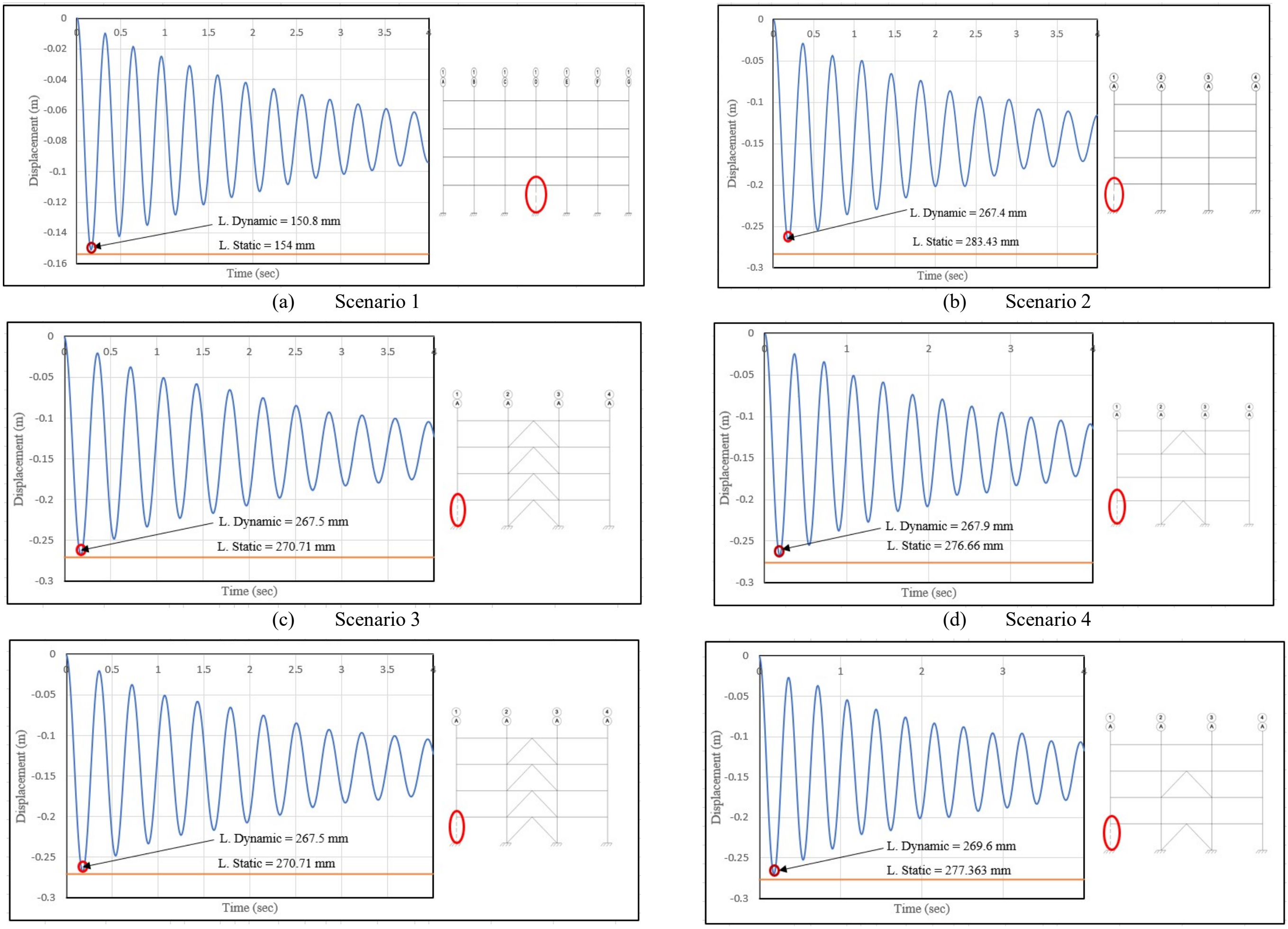
(e)



	1	2	3	4
A1 - LSA	0	0.84	0.42	1.01
A1 - LDA	0	0.99	0.49	0.95
A2 - LSA	0.47	0.39	0.23	0.10
A2 - LDA	0.15	0.12	0.07	0.04
B1 - LSA	1.02	0.94	0.80	0.92
B1 - LDA	0.69	0.73	0.66	0.88

(f)

Fig. 11: DCR for Column for all member removal scenario



(a) Scenario 1 (b) Scenario 2

(c) Scenario 3 (d) Scenario 4

(e) Scenario 5 (f) Scenario 6

Fig. 13: Comparison of maximum displacement as per LSA and LDA

Table 4: Maximum displacement of joint above removed column for scenario 3 to scenario 6

Member removal scenario	Displacement of joint above removed column	
	Linear Static Analysis	Linear Dynamic Analysis
Scenario 3	13.11 mm	0.00633
Scenario 4	25.74 mm	0.01516 mm
Scenario 5	27.926 mm	0.01759
Scenario 6	29.828 mm	0.01859

The DCR of most of the columns for various column and/or bracing removal scenario is less than 1, which is well within the permissible limit specified by the guidelines. So, it is evident that column section of the steel building considered for the study is having high potential to resist the progressive collapse

5.4 Displacement time history from Linear Dynamic Analysis:

The progressive collapse due to failure of vertical load bearing element is highly dynamic phenomenon. Dynamic analysis gives more accurate results compared to static analysis, because it includes the dynamic amplification factors, inertia and damping forces. Linear dynamic analysis can be carried out using time-history analysis. Linear dynamic analysis is performed on 4-story steel moment resisting frame and braced frame to capture the displacement time history of joint exactly above the removed column. Fig. 13 (a) to 13 (f) shows the comparison of maximum displacement results from linear static and linear dynamic analysis for all member removal scenario.

From the Fig. 13(a) to Fig. 13(f), it is evident that the maximum displacement of joint above the removed column from linear dynamic analysis is close to maximum displacement from linear static analysis. The maximum displacement in scenario 3 to scenario 6 are of very small magnitude from linear static analysis and it tend to zero from linear dynamic analysis. The displacement magnitude for scenario 3 to scenario 6 are shown in Table 4. The displacement values in Table 4 shows that the bracing helps the building to resist the progressive collapse effectively.

6 Conclusion

In this study, the progressive collapse potential of 4-storey steel building is evaluated by performing linear static and linear dynamic analysis following the GSA guidelines. Effectiveness of inverted V type bracings on progressive collapse resistance of steel building is investigated. Demand Capacity Ratio (DCR) for flexure in case of beam, and DCR for column from linear static and linear dynamic analysis is calculated for selected critical members using Alternate Path Method (AM) under ten different column and/or bracing removal scenario. Also, the displacement time history for joint above removed column is plotted from linear dynamic analysis for all member removal scenario. Modelling and analysis of steel building is carried out using SAP2000 software. Based on the progressive collapse analysis of steel building considered for the present study, following conclusions are derived:

- Linear dynamic analysis governed the DCR values compared to linear static analysis for location exactly above the removed column and linear static analysis governed the DCR values as compared to linear dynamic analysis for left and right side of removed column for almost all cases.
- The value of DCR for flexure in case of beam, which exceed the permissible limit of 2, for moment resisting steel frame indicates that section of beam is not capable to resist progressive collapse under both middle and corner column removal scenario, So, it is required to strengthen the beam sections in order to increase their progressive collapse resistance.
- The provision of inverted V type of bracings in middle bays significantly reduces the DCR for flexure in case of beams under middle column removal scenario (scenario 3 to scenario 6). However, as bracings are provided in middle bays, their influence on progressive collapse resistance under corner column removal scenario is less, which is evident from the value of DCR exceeding permissible limit 2.
- DCR for column in moment resisting steel frame is within the permissible limit of 1 for various column removal scenario. However, provision of bracing causes significant reduction in DCR of columns in middle column removal scenario. There is no significant effect of provision of bracing in middle bay on DCR of column in corner column removal scenario.
- Displacement under removed column location is estimated 1% to 6% more in linear static analysis compared to linear dynamic analysis.

Disclosures

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