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Progressive collapse of steel frame-brace structure under a column-removal scenario

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Progressive collapse of steel frame-brace structure under a column-removal scenario

Zhongyuan Liu[1*] and Yanfei Zhu[1]

[1] Northwestern Polytechnical University, Xi'an, Shaanxi, 710129, P.R. China

zhongyuanliu@nwpu.edu.cn

Abstract. Progressive collapse attracted more attention of researchers in recent years, mainly due to the increasing number of terrorist incidents worldwide. Based on the GSA and DOD design guidelines, structural resistance mechanisms to progressive collapse of steel frame, V-shaped and X-shaped braced frame structures are studied by a comparative analysis. The results show that the robustness index (RI) of steel braced frame structure is significantly greater than steel frame structure, and the X-shaped brace is greater than the V-shaped brace. Furthermore, static pushdown and nonlinear dynamic analysis are performed to study dynamic effects attributed to a column removed. The results show that the ultimate failure modes are generally similar by these two analytical method. The presence of the column bracing reduces the dynamic displacement response for a column removed instantly, and the X-shaped brace is better than the V-shaped brace.

1. Introduction

Progressive collapse refers to the spread of an initial failure, caused by unconventional loads such as explosions, vehicle impact and heavy impact, to a chain reaction that leads to partial or total collapse of a building. The final state of failure is disproportionately greater than the initial failure.

At present, more researchers are focused on using alternate path method (APM) from the GSA and DOD design guidelines. The APM method is divided into linear static (LS), nonlinear static (NS), linear dynamic (LD), and nonlinear dynamic (ND). The results of nonlinear dynamic analysis are more accurate. This method can assess the structural reaction to progressive collapse, however, the structural residual bearing capacity and the possibility of collapse after removing key components cannot be predicted. The pushdown analysis method is similar to pushover method, which is used to analyze structural seismic reaction in nonlinear static analysis. The load-displacement curve of structural control point (top on the removed column) is obtained by applying gradually increasing vertical load to the structure until structure collapse, which is used to evaluate structural vertical ultimate bearing capacity and vertical collapse mode under the vertical load. However, the current research on the progressive collapse based on the pushdown analysis does not specify whether the immediate demolition of the column will affect the residual bearing capacity of the structure, nor the quantitative evaluation of the influence of different support systems on the progressive collapse resistance of the structure.

In these cases, quantitative comparative analysis is performed on the effect of brace on structural resistance to progressive collapse of the steel frame, V-shaped and X-shaped braced frame structure. Static pushdown (NS) and nonlinear dynamic analysis (ND) are used to assess the affection of instantly removing a column on residual bearing capacity and collapse mechanism of damaged structure.

2. FE analysis Modeling

In the current study, several 9-layers 2D models are established with SAP2000 software, which include steel frame structure, V-shaped steel brace and X-shaped brace systems, as shown in figure 1 to figure 3. The representative structure is a nine-story with six spans, 3.9 m floor-to-floor height, 9 m column space. The structural load curve of different bays is shown in figure 4. The section and property of each column beam and brace is shown in table 1. Based on AISC-360, the property parameters check proves the section to be safe and reliable.

Table 1. Parameters for section and property.

Components	Sections	Material
1-5 story column	W14×132	A992Fy50
6-9 story column	W14×120	
Beam	W16×40	
Brace	W16×40	

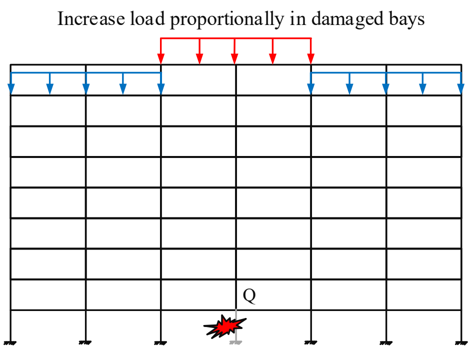


Figure 1. Steel frame system.

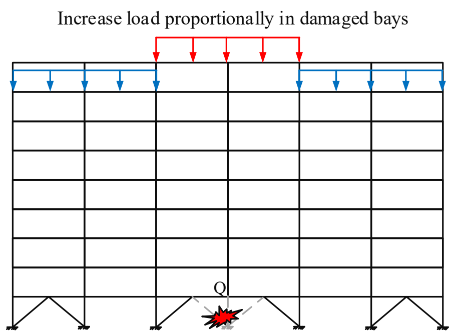


Figure 2. V-shaped braced frame.

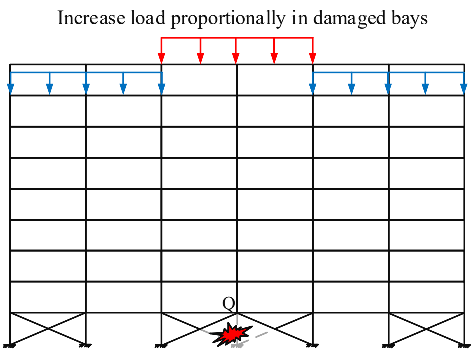


Figure 3. X-shaped braced frame.

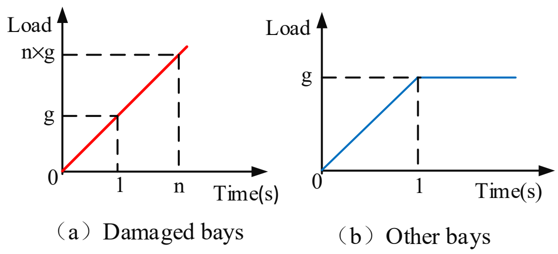


Figure 4. Load curve in different bays.

3. Static Pushdown analysis

Static Pushdown analysis ignores the dynamic response with the instantly removal of column. Increased vertical load is applied on the initially damaged bays and other bays are nominally loaded, as shown in figure 1 to figure 3. Structural residual bearing capacity can be assessed by comparing the curve between vertical displacement δ of the top on the removed column versus the applied load.

In this paper, the structural residual bearing capacity is quantified by the robustness index (*RI*) given by:

$$RI = \left| \frac{P_c\delta_{\max} - P_n\delta_n}{P_c\delta_{\max}} \right| + \left| \frac{P_e\delta_e - P_n\delta_n}{P_e\delta_e} \right| \quad (1)$$

where, P_n is the nominal vertical design load and δ_n is vertical displacement of top on the removed column under static analysis, corresponding time t =1.0 s. P_c is structural collapse load under a column removed and $\delta_{\max}$ is the ultimate vertical displacement when structure collapses. P_e and δ_e are the applied load and vertical displacement when the first plastic hinge occurs in some beam.

Based on the GSA design guidelines, nominal vertical design load P_n=g=1DL+0.25LL, the parameter DL represents Dead Load, and the LL represents Live Load. The GSA specifies maximum plastic hinge rotation and ductility as acceptance criteria for progressive collapse potential. Ductility (μ) is the ratio of the maximum displacement ($\delta_{\max,1}$) to the yield displacement (δ_e). The GSA guideline recommends the ductility limit of 20 for steel beams, namely, $\mu=\delta_{\max,1}/\delta_e \le 20$, so the maximum displacement $\delta_{\max,1}$ is $\mu\delta_e$. Rotation angle (θ) is obtained by dividing the maximum displacement ($\delta_{\max,2}$) to the length (L) of the member, namely, $\theta=\delta_{\max,2}/\mathrm{L}\le 0.21$. It is noted that maximum displacement $\delta_{\max,2}$ is θL. Then, structural progressive collapse occurs when the vertical displacement of the point Q reaches minimum value between $\delta_{\max,1}$ and $\delta_{\max,2}$. The analysis results, corresponding to steel frame structure, V-shaped steel brace and X-shaped brace systems, are shown in figure 5.

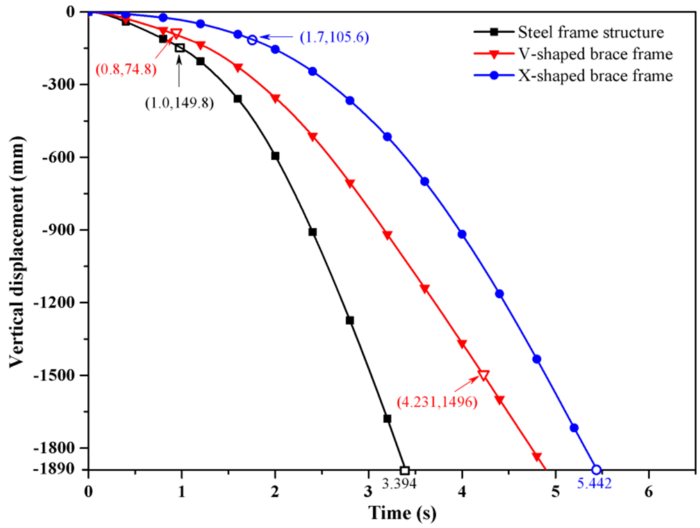


Figure 5. Static pushdown curve of steel and braced frame structures.

Based on the analyzed results, beams among steel frame structure, V-shaped and X-shaped braced system appear the first plastic hinges at different time, and vertical displacement of point Q reaches limit value $\delta_{\max}$ at different time, as shown in table 2.

Table 2. Analysis results of three systems.

Categories	Steel frame structure	V-shaped braced frame	X-shaped braced frame
t_e (s)	1.000	0.800	1.700
δ_e (mm)	-149.8	-74.8	-105.6
$t_{\max}$ (s)	3.394	4.231	5.442
$\delta_{\max}$ (mm)	-1890.0	-1496.0	-1890.0
δ_n (mm)	-149.8	-103.0	-34.02

Notes:

1) t_e is time when the first plastic hinge occurs in some beam.

2) $t_{\max}$ is time when structure collapses.

The RI of steel frame structure, V-shaped and X-shaped braced system are shown in table 3.

Table 3. The LRR of three systems.

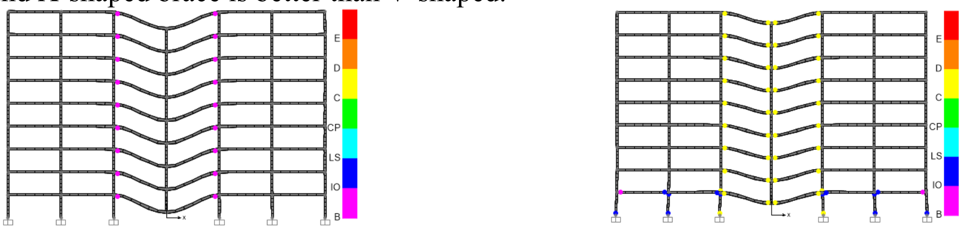
Categories	Steel frame structure	V-shaped braced frame	X-shaped braced frame
RI	0.977	1.705	1.807

RRI	——	42.7%	45.9%

Notes: The RRI is relative robustness index, RRI= [RI(braced frame)-RI(frame)]/ RI(braced frame)×100%.

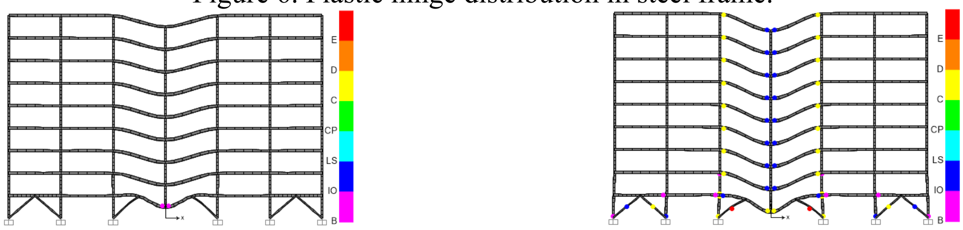
The results of the analysis indicate that the RI of V-shaped braced system is 1.705, improving by 42.7% with respect to steel frame structure. The RI of X-shaped braced system is 1.807, a relative increase of 45.9%. It is noted that the structural residual bearing capacity can be greatly improved by adding column brace, and X-shaped brace is better than V-shaped.

Steel frame structure, V-shaped and X-shaped brace system collapse in 3.394s, 4.231s, and 5.442s, respectively. Meanwhile, the distribution of structural plastic hinge is shown in figure 6 to figure 8, respectively. As shown in the analysis, beams in the damaged bays are entirely failure, and columns in V-shaped brace frame suffer a far greater destruction comparing with in X-shaped braced frame. It is noted that brace can enhance residual carrying capacity of damaged structure due to energy dissipation of brace, and X-shaped brace is better than V-shaped.



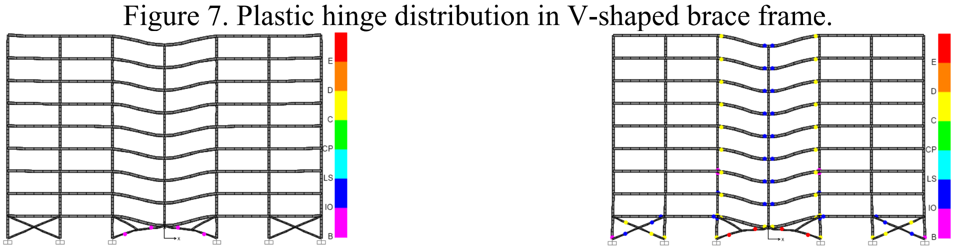
(a) t=1.000s (b) t=3.394s

Figure 6. Plastic hinge distribution in steel frame.



(a) t=1.000s (b) t=4.231s

Figure 7. Plastic hinge distribution in V-shaped brace frame.



(a) t=1.000s (b) t=5.442s

Figure 8. Plastic hinge distribution in X-shaped brace frame.

4. Dynamic analysis

Dynamic analysis considers the dynamic response when remove column instantly. The axial force P of structural middle column is obtained through the Nonlinear static analysis (NS), and then vertical upward force changing by the time is applied to the point Q where column has been removed, as shown in figure 9(c). The structural load curve of different bays is shown in figure 9(a) and figure 9(b). Apply the dynamic load combination as shown in figure 10. Perform nonlinear time history analysis without initial conditions in SAP2000. The nonlinear dynamic analysis results are shown in figure 11, corresponding to steel frame structure, V-shaped steel brace and X-shaped brace systems, respectively.

Steel frame structure, V-shaped and X-shaped brace system reach maximum dynamic displacement response in 2.106s, 1.591s, and 1.522s, respectively. Meanwhile, the distribution of structural plastic hinge is shown in figure 12 to figure 14. As shown in the analysis, beams in the damaged bays form plastic hinges, the situation about steel frame structure is most critical comparing with other types of structures. V-shaped braced frame suffer a far greater destruction comparing with X-shaped braced frame. It is noted that column bracing can slow down structural dynamic response attributed to a column removed, and the X-shaped brace is better than the V-shaped brace. Moreover, displacement response obtained by static pushdown analysis (NS) and nonlinear dynamic analysis (ND) are list in table 4. It can be found that a constant amplification coefficient applied in the nonlinear static analysis may lead to results inconsistent with those obtained from the nonlinear dynamic analysis approach.

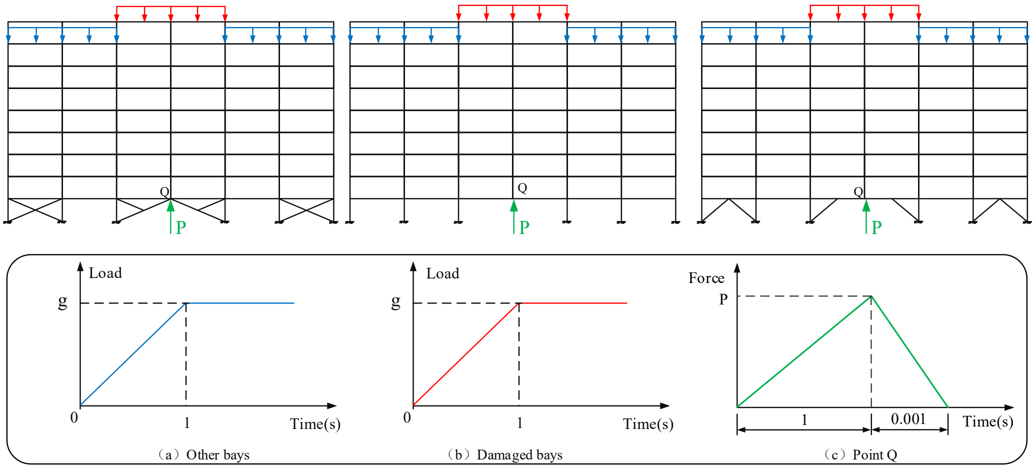


Figure 9. Load applied on the different bays and on the top of removed column.

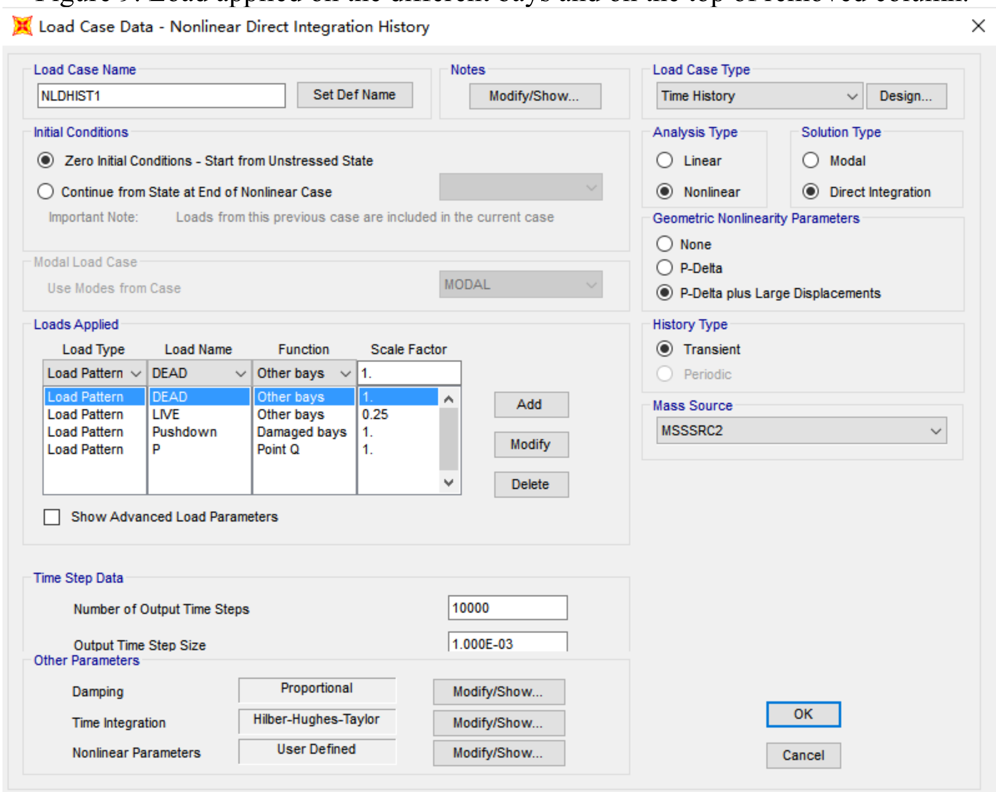


Figure 10. Nonlinear dynamic analysis case definition in SAP2000.

Table 4. Displacement response of three structure systems.

Categories	Steel frame structure	V-shaped braced frame	X-shaped braced frame

NS	-149.8	-103.0	-34.02
ND	-854.9	-355.0	-183.7
Amplification coefficient	5.71	3.45	5.40

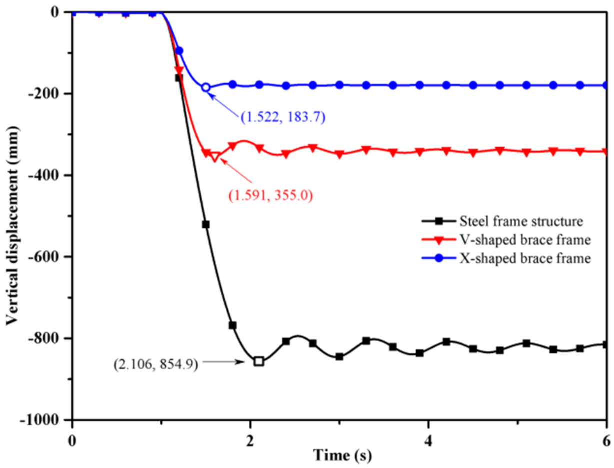


Figure 11. Load applied on the different bays and on the top of removed column.

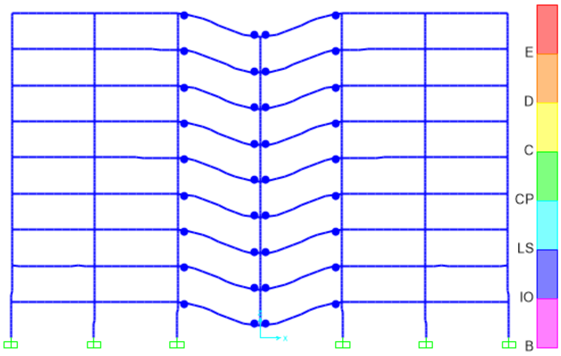


Figure 12. Plastic hinge distribution in steel frame (t=2.106s).

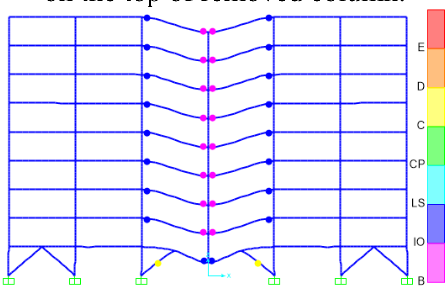


Figure 13. Plastic hinge distribution in V-shaped brace frame (t=1.591s).

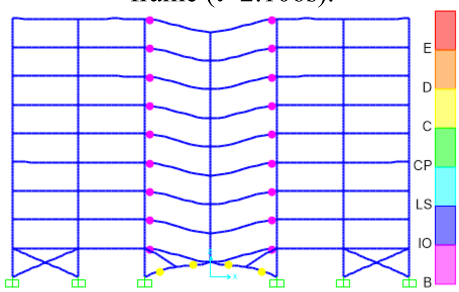


Figure 14. Plastic hinge distribution in X-shaped brace frame (t=1.522s).

5. Conclusion

The effects of column support on the continuous collapse resistance of the structure are compared and analyzed by static pressure analysis and nonlinear dynamic analysis. Conclusions are summarized as following:

(1) The structural residual bearing capacity can be quantified by the proposed robustness index (RI).

(2) Brace can enhance residual carrying capacity of damaged structure due to energy dissipation of brace, and X-shaped brace is better than V-shaped.

(3) Brace can slow down structural dynamic response attributed to a column removed, and the X-shaped brace is better than the V-shaped brace.

(4) A constant amplification coefficient applied in the nonlinear static analysis may lead to results inconsistent with those obtained from the nonlinear dynamic analysis approach.

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