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SEISMIC PROGRESSIVE COLLAPSE ANALYSIS OF CONTROLLED STEEL FRAME STRUCTURES

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Any element loss in the concentrically-braced frames (CBF) system significantly affects its seismic performance. The research presented in this paper aimed to understand the behavior of this system against seismic progressive collapse due to the failure of a column. A collapse of this magnitude may lead to the entire collapse of the structure, or else it could avoid or even localize the disaster by redistributing the released load to the surrounding structure. The progressive collapse phenomenon was investigated through analyzing a building equipped with CBF system during a seismic event. Four cases of failed beams were considered, depending on the location of the column loss and the configuration of the braces surrounding them. Through OpenSees simulation, the results showed the seismic and gravity loads increased and rapidly reached the ultimate state of the structure from 0.6 sec after the time of failure. The model for each scenario, regardless of the direct collapse of the structure due to the column loss, indicated the CBF system limited the plastic hinge formation around the failed element. Finally, the results showed the braces working in tensile are more reliable in terms of collapse resistance than those working in compression.

Keywords: Concentrically-braced frames, Seismic progressive collapse, OpenSees.

1 INTRODUCTION

Seismic progressive collapse is defined as the collapse of a large part of the structure due to the failure of a small part of it during a seismic event. So avoiding or slowing down the spread of the initial failure is important for the structural safety of a building. Widely-used for their earthquake-resisting abilities, the collapse resistance of concentrically-braced frames (CBF) is investigated by this paper. Some studies such as Kapil *et al.* (2009), Cambier (2009), and Asgarian *et al.* (2012), offer a first impression of the issue. After a general overview, they present a method to assess the behavior of the CBF during a seismic progressive collapse by understanding their capacity to enhance the loss of column in different parts of a steel structure. After studying a controlled steel frame structure under seismic and gravity load due to the loss of one column, the reaction and the plastic analysis of the CBF system before and after the failure was presented. Through these results, a better comprehension of the CBF behavior against the seismic progressive collapse was examined.

2 SEISMIC PROGRESSIVE COLLAPSE WITH CBF

There are several causes of weakness or failure on the members of steel construction. Corrosion can seriously weaken a structure or impair its operation, as can fatigue and the age of the element. Above all, human factors, such as gas explosions, sabotage, or terrorism, must be considered. Many configurations are possible in CBF, such as diagonal bracing, V-bracing, chevron bracing, and multistory X-bracing.

The redistribution of the released load by the removed element is the obvious response of the structure to find its equilibrium state. Depending on the surrounding elements of the failed beams, the consequence of the overload on some elements increases the formation of plastic hinge. The amount of axial force due to the seismic load acting on the CBF system changes and alters their performance. In this study, the diagonal bracing is investigated to illustrate the effect of the column loss. Four cases are identified according to the location of the column loss and the braces investigated (Figure 1):

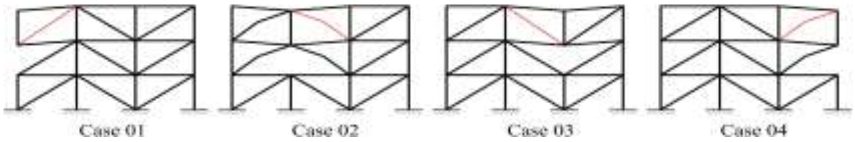


Figure 1. Four scenario cases for diagonal bracing.

During a seismic event, one main vertical element of the structure is suddenly removed. The failed column transfers the weight it was bearing to the adjacent elements of the structure. A sequence of plastic hinges through the structure is inevitable due to the extreme load to which it is being subjected. The plastic analysis of the steel structure was conducted according to the bending moment of the cross section of the beams and columns (Wong 2009). Through Matlab implementation, the moment-curvature relationship was used to find the yield moment M_y. The extreme fibers of the section start to yield at a value more than or equal to M_y, and enter into the plastic state when the plastic moment M_p is reached (see Eq. 1). These values were inserted into the simulations as the criteria of plastic-hinge formation as shown in Eq. 2). S is a shape factor.

$$M_p = SM_y \tag{1}$$

$$\begin{cases} M \geq M_y & \textit{Yield state reached} \\ M \geq M_p & \textit{Plastic state reached} \end{cases} \tag{2}$$

By assuming the mass remains unchanged and the extremity of the failed beam stays on the same direction of its initial location, the equilibrium law of forces presented at the ultimate deflection of the failed beam was used for the reaction analysis of each case (see Figure 2). In aim to understand the influence of the axial force, F_{bt} (brace tensile) and F_{bc} (brace compression) on the failed beams, the following equations (Eq. 3, Eq. 4, Eq. 5, and Eq. 6) are found according to Case 01, Case 02, Case 03 and Case 04, respectively.

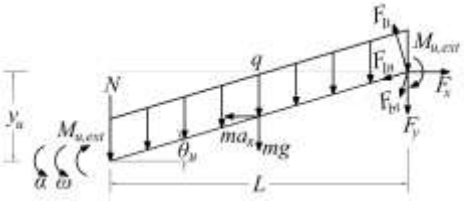


Figure 2a. Case 01.

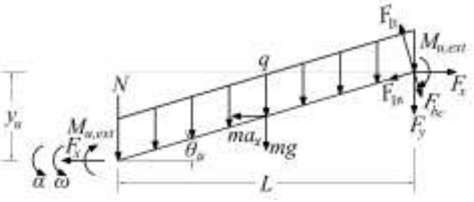


Figure 2b. Case 02.

$$F_y = \cos\theta\left(F_{It} - F_{bt}\right) - \sin\theta F_{In} \\ -mg - qL - N \qquad (3.a)$$

$$F_x = \cos\theta\left(F_{In} + F_{bt}\right) + \sin\theta F_{It} \\ \pm m a_x \qquad (3.b)$$

$$F_y = \cos\theta\left(F_{It} - F_{bc}\right) - \sin\theta F_{In} \\ -mg - qL - N \qquad (4.a)$$

$$F_x = \cos\theta\left(F_{In} - F_{bc}\right) + \sin\theta F_{It} \\ \pm m a_x \qquad (4.b)$$

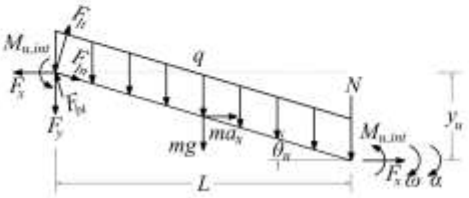


Figure 2c. Case 03.

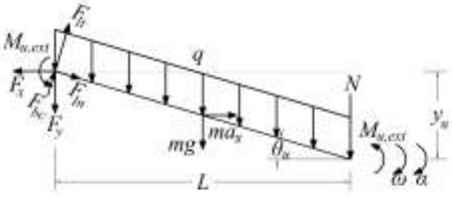


Figure 2d. Case 04.

$$F_y = \cos\theta\left(F_{It} + F_{bt}\right) - \sin\theta F_{In} \\ -mg - qL - N \qquad (5.a)$$

$$F_x = \cos\theta\left(F_{In} - F_{bt}\right) + \sin\theta F_{It} \\ \pm m a_x \qquad (5.b)$$

$$F_y = \cos\theta\left(F_{It} + F_{bc}\right) - \sin\theta F_{In} \\ -mg - qL - N \qquad (6.a)$$

$$F_x = \cos\theta\left(F_{In} + F_{bd}\right) + \sin\theta F_{It} \\ \pm m a_x \qquad (6.b)$$

Figure 2. Forces and reactions on the failed beam.

With:

$$F_{It} = m\frac{L}{2}\alpha \qquad (7.a)$$

$$F_{In} = m\frac{L}{2}\omega^2 \qquad (7.b)$$

Inclined with angle θ, with added mass m, and distributed load q on its length L, the beam is subjected to gravity and seismic loads which are g and a_x, respectively. F_x and F_y are the reaction forces due to the failed beam on the adjacent element of the structure such as beams and columns, respectively. ω and α are the angular velocity and the tangential acceleration of the failed beam respectively. And F_{It}, F_{it} and M_u are the forces and moment intern of the failed beam.

3 SIMULATION AND RESULTS

A 2D building model, from Rezvani *et al.* (2012), with three bays of 6.0 m each and a story height of 3.2 m was modelled in OpenSees finite element program (Mazzoni *et al.* 2007). The dead and live loads of 6.5 kN/m^2 and 2 kN/m^2 were used for the gravity load for all stories. The El Centro earthquake with 0.313 g was the input as seismic load with ground-motion factor 1.5. Table 1 gives all details of the structural members:

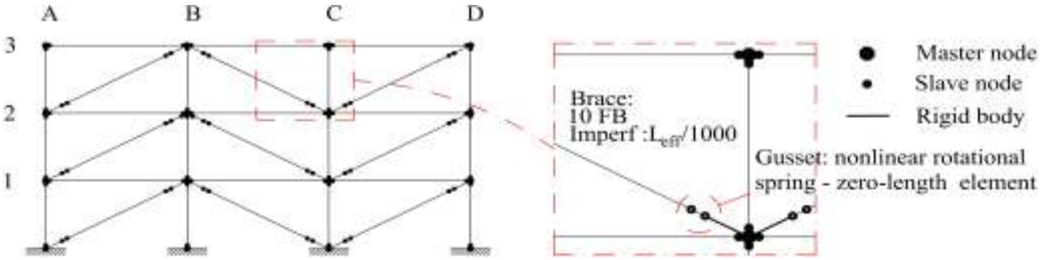


Figure 3. OpenSees implementation.

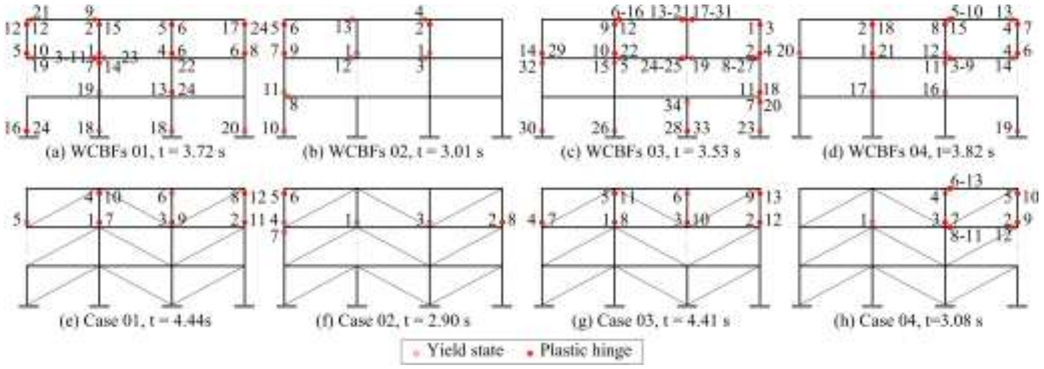
Table 1. Cross-section for all members (B: Box Section in mm).

Story	Column		Beam	Brace
	A and D	B and C		
3	B175x175x15	B175x175x15	IPE360	B150x150x10
2	B200x200x15	B225x225x20	IPE360	B150x150x10
1	B200x200x15	B225x225x20	IPE360	B150x150x10

The plastic hinge analysis was done according to the plastic moment of each cross-section on the structure during a seismic event. After applying the gravity load on the structure, the time of the removal column for each the failure cases were synchronized at $t=2.40\ s$ after the beginning of the seismic load. Figure 4 shows the plastic analysis comparison between an uncontrolled and controlled steel structure. The structures without concentrically-braced frames (WCBF), and those with CBF are represented by the following (a) - (b) - (c) - (d) and (e) - (f) - (g) - (h), respectively. Notice that the fourth spot on the CBF sequence cases is the first reaction of the structure after the column loss (see Figures 4e, 4f, 4g and 4h).

4 DISCUSSIONS AND CONCLUSION

The plastic-hinges analysis shows the uncontrolled structure has been subjected to several series of plastic hinge on each story. In the other hand, only the top floor of the controlled structure was weakened by the seismic load, due to the junction of two different cross-sections of the column. Past the removal time, the beams in Cases 02 and 04 failed directly, and pulled the members of the top structure near their limits. In Cases 01 and 03, the braces transferred the released force to the beam-column they were connected with. Consequently, plastic hinges were gathered on the columns nearby. The drift for each floor, as per Figure 6, showed an increase for Case 01. As for the structure collapse for the Cases 02 and 04, only 2.91 sec was recorded and been analyzed. The angular velocity–time of the braces acting in tensile did approximately match the results from the intact structure equipped with CBF (see Figures 7a and 7b). In contrast, irregularities of the angular velocity are observed in Figures 7c and 7d, just 0.05 sec after the column loss.


(a) WCBFs 01, t = 3.72 s (b) WCBFs 02, t = 3.01 s (c) WCBFs 03, t = 3.53 s (d) WCBFs 04, t=3.82 s

(e) Case 01, t = 4.44s (f) Case 02, t = 2.90 s (g) Case 03, t = 4.41 s (h) Case 04, t=3.08 s

Figure 4. Plastic analysis comparison between an uncontrolled and controlled steel structure.

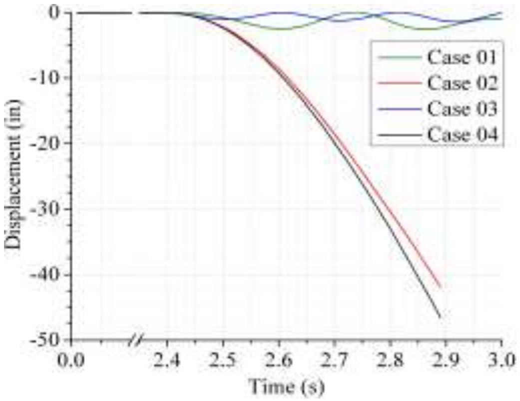


Figure 5. Displacement–time of the failed beams.

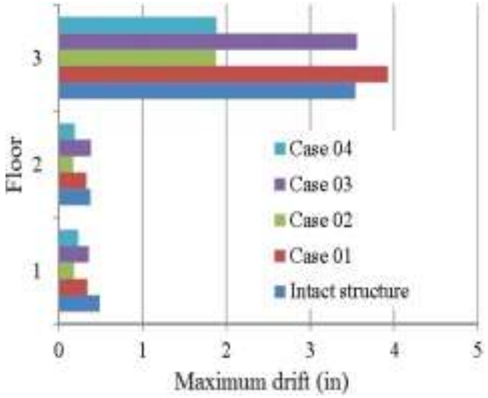


Figure 6. Maximum drift. Recorded drifts before collapse for the cases 02 and 04.

The braces working in tensile are more efficient against progressive collapse than the ones holding the failed beams from below. Through the results of the diagonal bracing mentioned above, a controlled structure with CBF system is not only able to absorb seismic loads but also capable to restricting the expansion of an initial failure in the structure. More brace systems might avoid progressive collapse, but it would surely

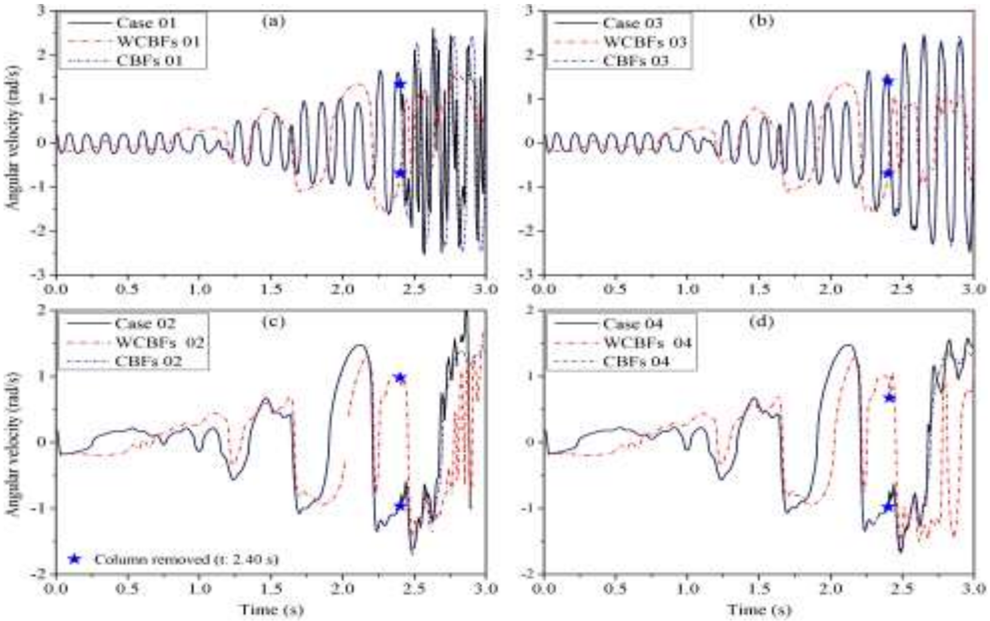


Figure 7. Comparison of the angular velocity–time for each case.

affect the safety of the building against seismic events. It is well known that all CBF configurations have to be designed depending on the building characteristics. So a retrofit design of CBF system with installation of braces in tensile at the main elements of the structure is advised. As this study's purpose was to show the behavior of a structure equipped with CBF under bi-directional load, and to affirm that CBF are capable to protect against progressive collapse, some research on implementing the failure criteria of CBF under seismic progressive collapse is still ongoing.

Acknowledgments

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