Nonlinear Analysis of Eccentrically Braced Frames against Progressive Collapse

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Abstract. Eccentrically braced frame (EBF) incorporates the advantages of lateral resisting systems from moment resisting frame (MRF) and concentrically braced frame (CBF) into a single structural system. In order to investigate the effects of brace and link length in resisting progressive collapse, a finite element model of 10-story planar steel frame were built and analyzed with the SAP2000 software through nonlinear static analysis and nonlinear dynamic analysis respectively. The results show that brace can obviously improve the performance of the structure no matter which kind of brace is adopted. The inverted V-shaped (IV) eccentrically braced frame has the highest capacity against progressive collapse and the Y-shaped eccentrically braced frame has the highest energy absorption capacity of the structure. Increasing the link length leads to an increase in deformation and energy absorption of the structure. The results of nonlinear static analysis could reflect the structural performance basically.

Keywords. Eccentrically braced frame, progressive collapse, nonlinear static analysis, nonlinear dynamic analysis.

1. Introduction
Progressive collapse is a phenomenon that one or several components of the structure are damaged under sudden load and expand to the outside [1]. The alternative load path (ALP) method is mostly used in the analysis of progressive collapse. For the ALP method, removing the main components of the structure will release stored energy in the components and increase the force of other components. In the process of removing main components, the progressive collapse resisting capacity is obtained by observing whether the load can be transferred to the residual structure through new transmission paths.

After several notorious structural progressive collapse accidents, many countries have formulated codes to resist progressive collapse due to the failure of main components [2-4]. Code for Anti-Collapse Design of Building Structures (CECS329:2014) [5], issued by China Association for Engineering Construction Standardization, has filled the gaps of domestic code. The code referred to the latest scientific research achievements and supplemented existing norms which are lack of clear explanation or guidance through analyzing domestic and foreign cases.

The EBF system provides high elastic stiffness and energy absorption capacity during severe earthquakes. The length of link, which is short segment of the frame, is expressed by $e$. In the EBF system, yielding is only concentrated on links, and other members remain elastic in principle. Therefore, links can be regarded as structural fuses to provide energy-absorption capacity through stable and controllable plastic deformation [6].
With the development of EBF research in recent years, more and more people pay attention to its performance in resisting progressive collapse. Khandelwal et al. [7] analyzed a ten-story building with two kinds of braces. The results indicated that EBF system shows better behavior than CBF system. Naji [8] discussed stiffness, deformation and energy absorption capacity on the basis of Khandelwal's research. Salmasi et al. [9] have shown that frames with eccentric braces usually have ideal strength against progressive collapse but different kinds of braces have different capacity.

In this paper, eccentrically braced steel frames are analyzed through nonlinear static (NS) method and nonlinear dynamic (ND) method in order to provide reference for EBF system in the resisting of progressive collapse.

2. Designs and Finite Element Models

A three-bay by ten-story steel frame [10] was designed based on GB50010-2017 [11] and JGJ99-2015 [12] codes. The story height is 3m and the span length is 6m. The peak ground acceleration is 0.2 g with a 10% probability of exceedance in 50-year period and moderately firm ground conditions. All structural components use Q345 steel whose elasticity modulus is $2 \times 10^{11}$ MPa and the Poisson ratio is 0.3. The design dead load (DL) is 4.8 kN/m$^2$ while the design live load (LL) for the floors and roofs are 2 kN/m$^2$ and 0.5 kN/m$^2$ respectively. In order to investigate the effects of braces in resisting progressive collapse, the inverted V-shaped (IV, figure 1 (a)), Y-shaped (Y, figure 1 (b)) and V-shaped (V, figure 1(c)) eccentric braces are considered. The structural component sections are shown in table 1 and configurations of various braced frames are shown in figure 1.

Table 1. Structural component sections.

| Story | Columns (mm) | Beams (mm) | Links (mm) | Braces (mm) |
|-------|-------------|------------|------------|-------------|
| 10    | H380×380×15×20 | H280×100×8×15 | H200×100×4×15 | H250×200×12×16 |
| 9     | H450×450×20×25 | H340×150×10×15 | H250×150×6×15 | H250×200×12×16 |
| 8     | H500×500×20×30 | H360×150×12×20 | H300×150×8×20 | H250×200×12×16 |
| 7     | H520×520×20×30 | H360×200×12×20 | H330×150×8×20 | H250×200×12×16 |
| 6     | H550×550×20×30 | H390×200×14×20 | H320×150×10×20 | H250×200×12×16 |
| 5     | H580×580×20×30 | H430×200×14×20 | H350×150×10×20 | H300×200×12×16 |
| 4     | H600×600×20×35 | H400×250×15×20 | H320×200×12×20 | H300×200×12×16 |
| 3     | H630×630×20×35 | H420×250×15×20 | H340×200×12×20 | H300×200×12×16 |
| 2     | H640×640×20×35 | H440×250×15×20 | H350×200×12×20 | H300×200×12×16 |
| 1     | H640×640×20×35 | H460×250×15×20 | H370×200×12×20 | H300×200×12×16 |

Figure 1. Configurations of various braced frames.

The length of link is one of the key parameters to control stiffness, strength, ductility and deformation of EBF system. The link length ratio [13] is defined by equation (1).

$$\rho = e / (M_p / V_p)$$

where $M_p$ is the plastic moment capacity and $V_p$ is the plastic shear capacity of the link.

If $\rho \leq 1.6$, shear yielding controls the link behavior. If $1.6 < \rho < 2.6$, shear and flexural yielding control...
the link behavior. If $\rho \geq 2.6$, flexural yielding controls the link behavior. Roeder’s [14] and Hjelmstad’s [15] experimental study showed the performance of short links was better than that of long links under cyclic loads. Ji et al. [16] have shown that there is a great different performance between short links and very short links. In this article, the shear yield links with different lengths are analyzed and link length ratios are calculated in table 2.

**Table 2.** Link length ratio.

| Length of link (m) | Story 1 | Story 2 | Story 3 | Story 4 | Story 5 | Story 6 | Story 7 | Story 8 | Story 9 | Story 10 | Average |
|-------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|
| 0.3               | 0.40   | 0.40   | 0.40   | 0.41   | 0.44   | 0.37   | 0.37   | 0.38   | 0.38   | 0.40    |         |
| 0.6               | 0.79   | 0.80   | 0.80   | 0.81   | 0.87   | 0.88   | 0.73   | 0.74   | 0.76   | 0.80    |         |
| 0.9               | 1.19   | 1.20   | 1.21   | 1.22   | 1.31   | 1.33   | 1.10   | 1.11   | 1.14   | 1.15    | 1.19    |
| 1.2               | 1.59   | 1.60   | 1.61   | 1.62   | 1.74   | 1.77   | 1.46   | 1.48   | 1.52   | 1.54    | 1.59    |

Plastic hinges are defined as follows: M3 flexural plastic hinge is designed in both ends of the beam. V2 shear plastic hinge is designed in the middle of the link. PM-2M3 axial-flexural plastic hinge is designed in both ends of the column. P axial plastic hinge is designed in the middle of brace element.

In this article, the ALP method is used for NS and ND analysis of frame structures. Considering the most unfavorable failure mode of the structure, remove the brace associated with the column while A or B column fails in the first floor (noted as A1 or B1). The NS analysis adopts displacement-controlled pushdown analysis method. In this method, dynamic load increase factor $\Omega_n$ is used to simulate dynamic effect of structural components failure. A gradually increasing vertical displacement is applied to the upper end of the failure component until the structure collapse. The imposed loads for NS analysis are shown in figure 2(a). According to GSA2013 [3] and CECS 329:2014 [5], the load combination is shown in equations (2) and (3) where $\Omega_n$ is 1.35.

\[
G = 1.0(1.2DL + 0.5LL) \quad \text{(2)}
\]

\[
G_N = 1.35(1.2DL + 0.5LL) \quad \text{(3)}
\]

Comparing with NS analysis, ND analysis reflects the performance of the structure more accurately. The analysis employed the equivalent load transient unloading method considering the initial state. The damping ratio of the structure is assumed to be 0.02. In order to obtain the load-displacement curve of the residual structure, equivalent gravity loads of various scales, expressed by load factors, are applied to the structure. Load factor increases until the dynamic analysis does not converge. Different load factors cause different peak displacements. The load combination of ND analysis is shown in equation (4). The imposed loads and loading curves for ND analysis are shown in figure 2(b) where $P$ is the reaction of internal force of failure components. The failure time, $t_1 - t_2$, were calculated by 1/10 of the first vertical natural vibration period of the residual structure.

\[
G = m(1.2DL + 0.5LL) \quad \text{(4)}
\]

where $m$ is the load factor.

![Figure 2. Imposed loads for progressive collapse analysis.](image-url)
3. Results and Discussions

3.1. Nonlinear Static Analysis

In the displacement-controlled pushdown analysis, the equivalent gravity load is corresponding to each vertical displacement. Load factor is the ratio of equivalent load to the gravity load. The load factor of unbraced frame is 3.79 when A1 column is removed and 4.31 when B1 column is removed. Load factors of frame structures with different braces and links are calculated and analyzed respectively.

The bearing capacity of braced frame is better than that without braces except Y-shaped braced frame with a link length of 0.3m. Among varies of braced frames, the bearing capacity of IV-shaped braced frame is the highest. Capacity of V-shaped braced frame is better than that of Y-shaped braced frame when A1 members are removed. Capacity of Y-shaped braced frame is better than that of V-shaped braced frame when B1 members are removed. The load factor of frame with A1 members removed is generally higher than that with B1 members removed. The longer the link is, the higher the bearing capacity becomes. When A1 members are removed, capacity of V-shaped EBF is the best when link length is 1.2 m, which is increased by 95.2% compared with unbraced frame. When B1 members are removed, capacity of IV-shaped EBF is the best when link length is 1.2 m, which is increased by 32.7% compared with unbraced frame.

Figure 3 shows the pushdown curves of residual frames described by load factor and upper node displacement of removed column. The results show that sudden collapse and brittle behavior of the IV-shaped and V shaped braced frames are obvious, which is related to the links failed almost at the same time. The Y-shaped braced frame remains high residual bearing capacity after the failure of links. While the bearing capacity of braced frame is improved, the vertical deformation capacity of braced frame is lower than that of unbraced frame. The ductility of IV-shaped braced frame is the worst, and that of Y-shaped braced frame is the best. The correlation between link length and ductility is positive.

The energy absorption capacity, shown in table 3, is calculated by the area under load factor-displacement curve. The longer the link is, the higher the energy absorption capacity becomes. Generally speaking, energy absorption capacity of Y-shaped braced frame is higher than that of IV-shaped and V-shaped braced frame. When the link length is 1.2 m with A1 members removed, the
energy absorption capacity of Y-shaped braced frame is 51.4% and 33.7% higher than that of IV-shaped and V-shaped braced frame. When the link length is 1.2 m with B1 members removed, the energy absorption capacity of Y-shaped braced frame is 74.2% and 119.8% higher than that of IV-shaped and V-shaped braced frame. In particular, when the link is 0.3 m, the energy absorption capacity of IV-shaped braced frame is the best with A1 members removed while V-shaped braced frame is the best with B1 members removed.

Table 3. Energy absorption by NS analysis.

| model | length of link (m) | 0.3 | 0.6 | 0.9 | 1.2 |
|-------|-------------------|-----|-----|-----|-----|
| IV-A1 |                   | 259.17 | 380.86 | 525.94 | 604.98 |
| Y-A1  |                   | 242.37 | 440.04 | 657.89 | 916.05 |
| V-A1  |                   | 232.64 | 377.34 | 532.82 | 685.25 |
| IV-B1 |                   | 142.49 | 237.09 | 351.11 | 484.81 |
| Y-B1  |                   | 134.24 | 321.66 | 571.03 | 844.62 |
| V-B1  |                   | 147.99 | 245.56 | 269.74 | 384.35 |

3.2. Nonlinear Dynamic Analysis
The peak displacement and bearing capacity can be obtained by using different load factors through ND analysis. Load factor increases until the dynamic analysis does not converge. The load factor of unbraced frame is 4.1 when A1 column is removed and 4.4 when B1 column is removed, slightly higher than those of NS analysis.

Among three kinds of braced frames, bearing capacity of IV-shaped braced frame is the highest and that of Y-shaped braced frame is the lowest relatively. The longer the link is, the higher the bearing capacity becomes. Capacity with A1 members removed is higher than that with B1 members removed, which is similar to NS analysis. When A1 members are removed, capacity of IV-shaped braced frame with the link of 1.2 m is increased by 90.2% compared with unbraced frame. When B1 members are removed, capacity of Y-shaped braced frame with the link of 1.2 m is increased by 31.8% compared with unbraced frame.

Figure 4. Load factor-displacement curves of ND analysis.
Figure 4 shows the bearing capacity curves of the frame in ND analysis. The ductility of Y-shaped braced frame is the best, and that of V-shaped braced frame is the worst relatively. The bearing capacity of Y-shaped braced frame with the link of 0.3m does not reach the ultimate value when links are failed. After failure of the links, the mechanical response and behavior characteristic of the structure is similar to that of unbraced frame. In addition, longer link provides better ductility and higher energy absorption capacity for the structure. The energy absorption capacity of the frame before the failure of links is shown in Table 4. When A1 members are removed, the results of ND analysis are greater than that of NS analysis. When B1 members are removed, the results of ND and NS analysis are roughly the same.

### Table 4. Energy absorption by ND analysis.

| Model  | Length of link (m) | 0.3 | 0.6 | 0.9 | 1.2 |
|--------|-------------------|-----|-----|-----|-----|
| IV-A1  |                   | 266.96 | 462.18 | 640.12 | 949.95 |
| Y-A1   |                   | 244.56 | 526.48 | 827.68 | 1139.96 |
| V-A1   |                   | 246.90 | 377.83 | 636.93 | 797.02 |
| IV-B1  |                   | 113.09 | 210.20 | 312.04 | 423.36 |
| Y-B1   |                   | 113.45 | 305.81 | 513.71 | 824.27 |
| V-B1   |                   | 158.34 | 203.91 | 295.00 | 374.82 |

3.3. Comparison of ND and NS Analysis

ND analysis reflects the performance more accurately comparing with NS analysis. In the process of bearing capacity analysis, the biggest error is 7.8%, occurring to IV-shaped braced frame with A1 members removed, and the others are less than 5%. Therefore, the results of NS analysis could approximately reflect the bearing capacity of the structure. In this section, peak axial force of the column adjacent to each removed column, energy absorption capacity, peak vertical and horizontal displacement with different load factors are compared in detail.

Figure 5 shows the peak axial forces in the columns next to each removed column with different load factors. The X-axis is axial forces by ND analysis and the Y-axis is axial forces by NS analysis. The closer a data symbol is to the diagonal, the smaller error of NS analysis is. Therefore, the peak axial forces calculated by NS analysis based on pushdown method are accurate.

Figure 6 shows the comparison of energy absorption capacity by NS and ND analysis. Generally speaking, the energy absorption capacity in the process of NS analysis is always smaller than that of ND analysis. With the increase of load factor, the data between NS and ND analysis becomes closer.

Figures 7 and 8 show the comparisons of peak vertical and horizontal displacement by two analysis
methods. The vertical displacement of NS analysis is smaller than that of ND analysis, but the difference is little. Difference of removing A1 members is slightly larger than that of B1 members. When B1 members are removed, the difference of horizontal displacement between NS and ND analysis is acceptable, while difference is a little large when A1 members are removed. The NS analysis method does not reflect the horizontal displacement of the structure accurately.

4. Conclusion
This paper analyzed the progressive collapse resisting capacity of EBFs with different braces and links. The following conclusions are obtained:

1) In most cases, eccentric braces can improve the bearing capacity of the frame. Capacity of IV-shaped braced frame is the highest and that of Y-shaped braced frame is the lowest relatively. Longer length of the links leads to higher bearing capacity.

2) Deformation capacity of EBF is worse than that of unbraced frame. The energy absorption capacity of Y-shaped braced frame is the best among varies of braced frames. The energy absorption capacity of IV-shaped braced frame is slightly higher than that of V-shaped braced frame. Longer links provides better energy absorption capacity.

3) The peak axial force of the column adjacent to each removed column, energy absorption capacity, peak vertical displacement with different load factors by NS and ND analysis are similar. It can be considered that the NS analysis is accurate in these areas, while the results of horizontal displacement by NS analysis are slightly inaccurate.

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