Hysteretic Behavior of Exposed Column Bases In Buckling Restrained Braced Frames

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SUMMARY:
Column base connections are critical components in steel structures because they transfer axial forces, shear forces and moments to the foundation. Compared with moment resisting frames, the shear and axial force on column bases is more critical due to the contribution of braces in Buckling Restrained Braced (BRB) frames. Quasi-static tests of exposed column bases with BRB were conducted. The axial force acted on the column was varied as the BRB axial force was also considered in the test. The hysteretic behaviour of the specimens was summarized. Design procedure of the exposed column bases in BRB frames was suggested based on the test observations.

Keywords: Exposed Column Base, BRB Frames, Cyclic Loading, Anchor Rod

1. INSTRUCTIONS

Buckling restrained braces (BRBs) have an extremely stable hysteretic behavior under both tensile and compressive force and are commonly used as a type of energy dissipation device both in new construction and seismic retrofit projects. Exposed column bases are commonly used in low-to-medium rise building because of the easy construction and reliable seismic behavior. Such column bases are generally designed to consider the bending moment and axial force. Previous experimental studies on the seismic behavior of exposed column base in conventional braced frames (Hatanaka et al. 2002, Fukuhara et al. 2010) indicated that the anchor rods of exposed column base would deform severely in horizontal. Different from the conventional brace, BRB showed near equal tension and compression capacity. The different directions of the shear force caused by the BRB and the frame story drift are the unique behaviours for exposed column base with BRB. The effect of such different directions of the story drift and base plate shear on the hysteretic behavior of exposed column base is unclear. It is highly required to clarify the hysteretic behavior of exposed column base in BRB frames in order to develop the corresponding design procedures.

This paper presents a series of tests of the exposed column base with BRB in cyclic loading condition. The effects of the arrangement of anchor rods were investigated. Based on the test results, the characteristics of the hysteretic behavior of exposed column base with BRB was summarized and design procedure was suggested.

2. TEST PROGRAM

2.1. Test specimen

The test specimens were designed to simulate the interior column base connections. Three specimens were fabricated at approximately 2/3 scale, with all specimens having the global dimensions shown in Fig. 1. Each of specimens comprised a cold-formed square-tube cross sections column having the width of 200 mm and the thickness of 12 mm, a shop-welded hot-rolled square base plate (300 and 50 mm in the width and thickness, respectively), four or six machined anchor rods with the nominal diameter of 30 mm and a concrete foundation beam confined in a steel box. As indicated in the figure, the concrete foundation beam was confined by a steel box to ensure failure of the anchor rod itself rather than failure within the concrete. Because of the confinement of the steel box, the reinforcement of the concrete foundation is omitted. The anchorage of the anchor rods in concrete foundation beam was ensured by welding the anchor rods on the end plate of the steel box. The other advantage of using the steel box is to simplify the fixation of the specimens. A 40 mm thick grout mix was placed on the concrete foundation beam and the base plate was placed on it. The test variables and other important features of the test specimens are discussed as follows.

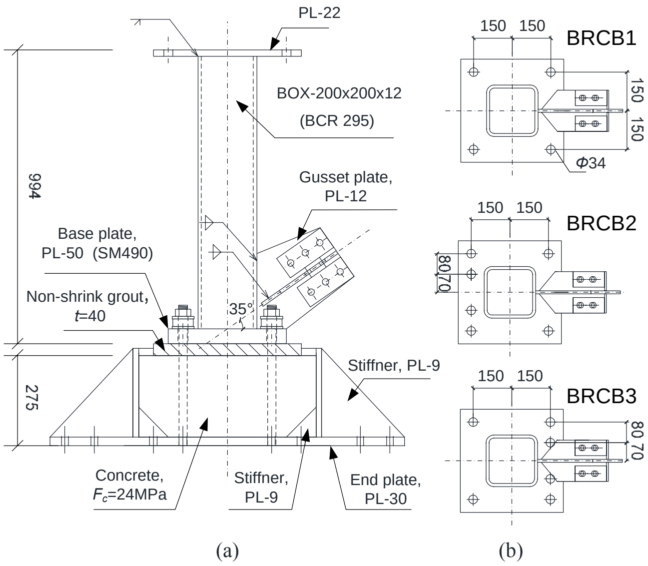

Figure 1. Test specimen: (a) front view; (b) anchor rods layout (unit: mm)

Three specimens were designed following the provisions of Recommendation for Design of Connections in Steel Structures (AIJ, 2006) in which the column base for moment resisting frames were introduced. Specimen 'BRCB1' was fabricated as a baseline specimen. Four anchor rods were used and the rod layout was 250 mm square as shown in Fig. 1. The anchor rod holes were 34 mm in diameter as recommended in JSSC (2009). This specimen was designed to fail at the column base connection rather than the column. And the shear resistance when the BRB in tension was designed intentionally smaller than the shear force provided by the BRB. To improve the shear resistance of the baseline specimen, six anchor rods were used for specimens 'BRCB2' and 'BRCB3', as shown in Fig.1 (b). The contribution of the extra two anchor rods in different places was investigated. The material properties are shown in Table 2.1. The designed capacities of the specimens are shown in Table 2.2.

Table 2.1 Material Properties

		Yield strength, σ_y (N/mm^2)	Tensile strength, σ_u (N/mm^2)
Column	□-200x12, BCR 295	438	468
Anchor rod	M30, ABR490	361	558

Table 2.2 Designed Capacities

Spec.	Brace in tension		Brace in compression	
	M_{bp} (kNm)	Q_{bp} (kN)	M_{bp} (kNm)	Q_{bp} (kN)
BRCB1	138	318	260	766
BRCB2	270	419	260	766
BRCB3	138	636	341	994

2.2. Test setup

The test specimen was placed in the loading frame shown in Fig. 2. The foundation steel box was clamped to the reaction floor. The column top was clamped to two hydraulic jacks, one is the horizontal direction and the other in the vertical direction. The gusset plate was clamped to one hydraulic jack, which was used to reproduce the BRB behavior. The positive loading was defined when the BRB was in tension. The positive loading directions of each jack are illustrated in Fig. 2.

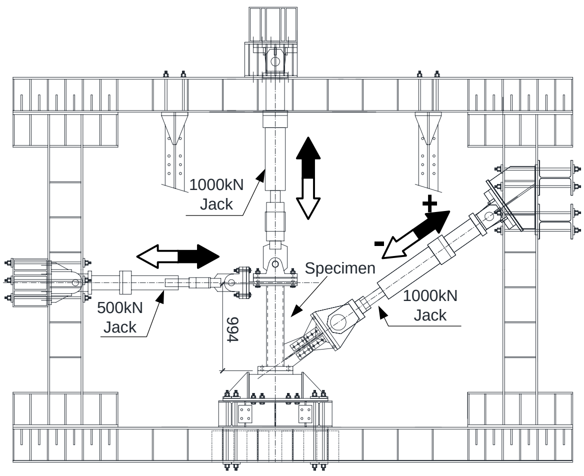

Figure 2. Elevation of loading system (unit: mm)

A displacement-controlled cyclic load was applied in the horizontal direction. The displacement was expressed in terms of the relative drift angle, defined as the horizontal displacement between the top of column and the base plate relative to the height of the column ($\Delta_r/2H$ in Fig. 3(b)). Drift angles of 0.005, 0.01, 0.02, 0.03, and 0.04 rad were adopted, and two cycles were performed at each drift angle.

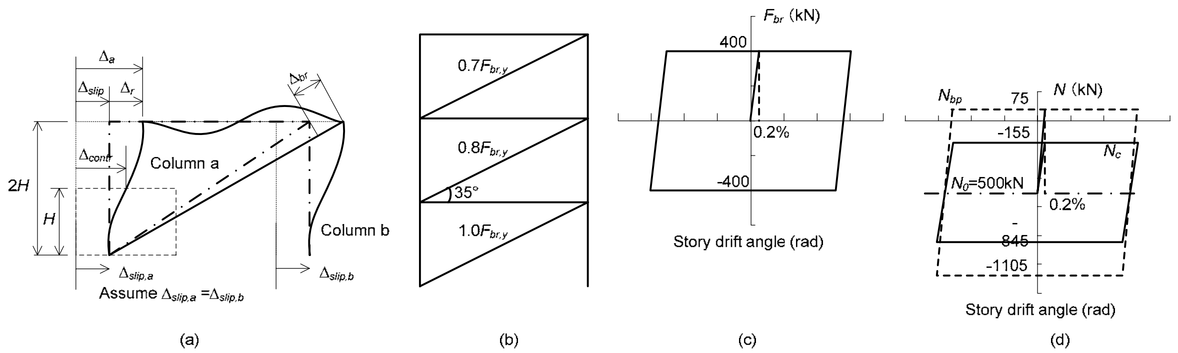

Figure 3. (a) Frame deformation; (b) prototype frame;
(c) BRB hysteresis behavior; (d) axial force hysteresis behavior

The BRB was assumed yield at the story drift of 0.2% as shown in Fig. 3 (c). The BRB force is calculated based on the measured deformation of the BRB (Δ_{br} in Fig. 3(a)) using the Equation (2.1).

$$F_{br} = K_{br} \cdot \Delta_{br} \text{ , if } \left|F_{br}\right| < \left|F_{br,y}\right| \qquad (2.1)$$

in which, Δ_{br}=$\Delta_r$cos35°. It should be noted that the relative story drift angle ($\Delta_r/2H$ in Fig. 3 (a)) was used in this test to control the horizontal load and the BRB behavior by assuming the displacement of the columns are the same, as illustrated in Fig. 3(a).

Varied axial force was applied on the specimen. A BRB frame as shown in Fig. 3(b) was assumed as the prototype frame. The axial force on the 1st story column was affected by the BRB on the other stories, and follow Equation (2.2).

$$N = N_0 - 1.5F_{br} \cdot \sin 35^{\circ} \qquad (2.2)$$

in which, N_0 is the axial force contributed by the moment-resisting frame, 500 kN in this test, and F_{br}sin35° is the vertical component of the BRB force. The hysteresis behavior of the applied axial force (N_c) and the axial force on the base plate (N_{bp}) are shown in Fig. 3(d).

3. TEST RESULTS

No damage was observed in the concrete foundation during the test. All the anchor rods experienced sever lateral deformation as shown in Fig. 4 and the slip of the base plate during the loading is rather large compared with the column base connection of moment resisting frame. The test results of maximum moment and shear force on the base plate are listed in Table 3.1.

Figure 4. Deformation of anchor bolts after the test

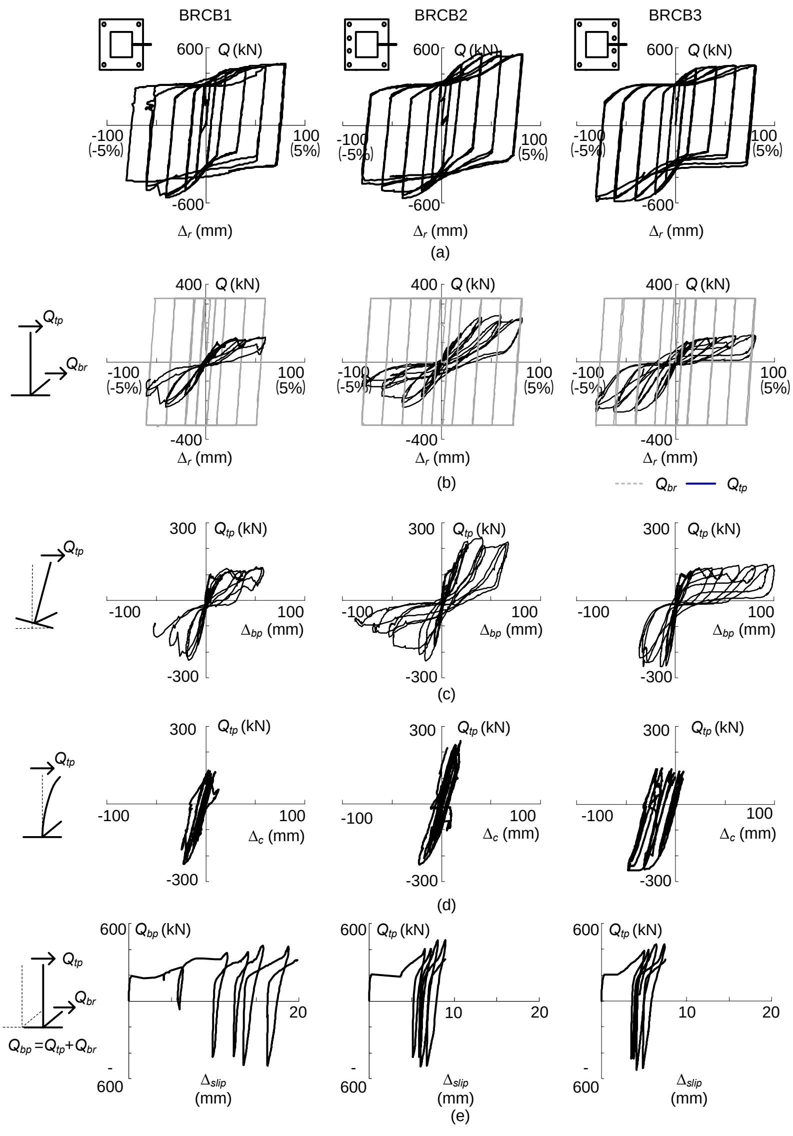

Figure 5. (a) Q_f-Δ_r relationship (b) Q_{tp} /Q_{br}-Δ_r relationship;
(c) Q_{tp}-Δ_{bp} relationship; (d) Q_{tp}-Δ_c relationship; (e) Q_{bp}-Δ_{slip} relationship

Table 3.1 Test results

Spec.	Brace in tension		Brace in compression	
	M_{bp} (kNm)	Q_{bp} (kN)	M_{bp} (kNm)	Q_{bp} (kN)
BRCB1	132	456	246	560
BRCB2	248	574	246	562
BRCB3	138	462	340	586

Figure 5 showed the force-deformation relationships for all three specimens. The relationship of the shear force of the story ($Q_{tp} + Q_{br}$) and the relative story drift (Δ_r) is shown in Fig. 5(a). The story shear ($Q_{tp} + Q_{br}$) is decomposed into the shear force applied at the top of the column (Q_{tp}) and the shear force provided by BRB (Q_{br}) in Fig. 5(b). The story drift (Δ_r) is decomposed into the deformation caused by the column base plate rotation (Δ_{bp}) and the bending of column (Δ_c) in Fig. 5(c) and (d), respectively.

Specimen 'BRCB1' showed the smallest shear resistance in both loading directions. The hysteresis curves of the story shear and story drift is unsymmetry. The shear force applied on the top of column in not reduced after the maximum strength was achieved in positive loading, while serious strength deterioration was observed in negative loading. The column base connection lost its shear resistance around 3% story drift in negative loading (brace in compression), as shown in Fig. 5 (b). Specimen 'BRCB2' showed the largest resistance, around 80% in moment resistance (M_{bp}) in the positive loading. Strength deterioration was observed in negative loading, too. Specimen 'BRCB3' showed similar shear resistance in positive loading as Specimen 'BRCB1' and it yielded at the bottom of column in negative loading.

The base shear (Q_{bp}) – slip (Δ_{bp}) at the base plate relationships of the specimens within the story drift of 1% were shown in Fig. 5(e). It is noticed that the slip was suddenly increased when the shear force at the base plate (Q_{bp}) is around 200kN for all the specimens. It is primary because the friction force lost as the vertical force on the base plate was reduced by the vertical components of BRB tensile force. There is a flat part of the curves in the very beginning in Fig. 5(e). The base shear was increased when the slip was around 4 mm, which is the same as the clearance between the anchor rods and the hole of the base plate. It is speculated that the shear forces in column base may be resisted by the base plate bearing against anchor rods. Specimen 'BRCB1' showed the largest slip. The slips were effectively reduced from 15 mm to 5 mm and 3.5 mm for Specimen 'BRCB2' and 'BRCB3', respectively, by increasing the number of anchor rods.

4. CHARACTERISTICS OF HYSTERESIS CURVE

The results of Specimen 'BRCB1' were used to discuss the characteristics of the hysteresis behavior of exposed column base with BRB. The relationship of moment and rotation of column base connection, the relationship of the shear force on the column base connection and slip of the base plate were shown in Fig. 6 (a), (b), and (c), respectively. The compression force on the column base (C) and slip of the base plate relationship was shown in Fig. 6 (d). Points **a** and **c** indicated the peak of story drift in positive loading and negative loading, respectively. Points **b** and **d** indicated the BRB yield force changed from one direction to the other direction. Points **b'** and **d'** indicated the story drift of the column base is zero. Note that the axial force on the base plate is 1075 kN in compression at Points **b** , **b'** and **c** 75 kN in tension at Points **a, d'** and **d**. Point **e** indicated the loss of the friction force. The hysteresis loops follow the sequence of "a-b-c-e-d". The force resisting mechanisms of the exposed column base at each loading state were shown in Fig. 7.

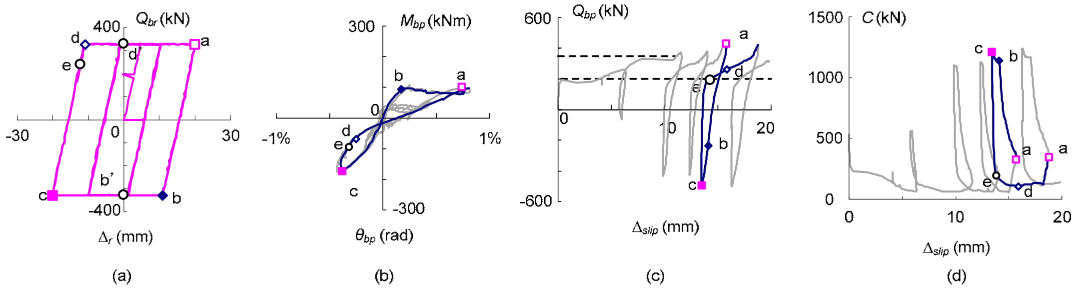

Figure 6. (a) Brace behavior; (b) column base slip behavior;
(c) column base rotation behavior; and (d) C-Δ_{slip} relationship

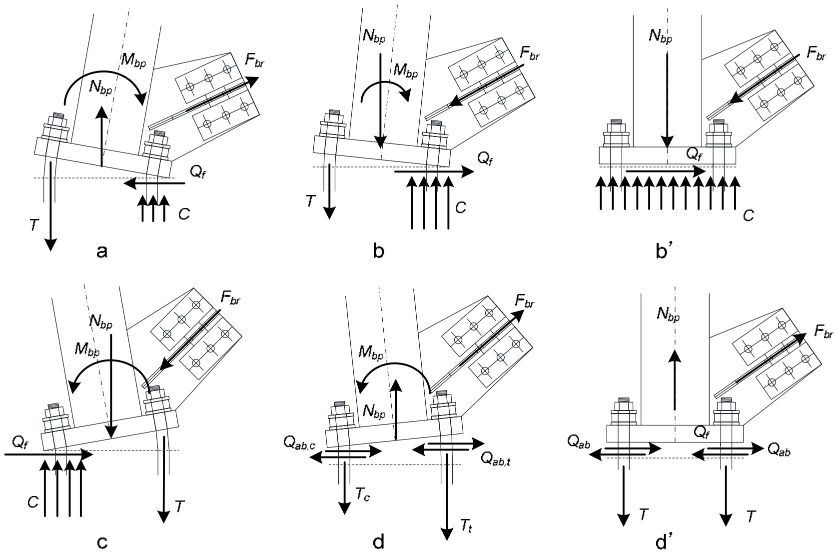

Figure 7. Resisting mechanism of column base with BRB

As shown in Fig. 6, the slip was relatively small, and the compression force on the base plate was relatively large when BRB force was in compression. It is indicated that the shear force was resisted by the friction force between base plate and grout layer when BRB force was in compression as described in Fig. 7. As shown in Fig. 6(c), the slip started increase when the friction force was broken (Point e). The slip increased significantly in the loading "e-d-a". The compression between the base plate and grout layer was rather small till the base plate contacted with foundation again as shown in Fig. 6 (d). The friction force between the base plate and the grout layer was broken and the slip of base plate occurred. All of the anchor rods contributed to resist the shear force after the friction force was broken as shown in Fig. 7. The friction force between base plate and grout layer was recovered as the story drift increased.

5. CONCLUSIONS

1. The horizontal component of the BRB axial force increases the shear resistance demand of the base plate of exposed column bases. And the vertical component of the BRB axial force changes the axial force on the exposed column bases significantly. The moment-rotation hysteresis curve of the column base is pinched but not symmetry as that of the exposed column base in moment resisting frames.
2. The anchor rods experienced large lateral deformation due to the tensile and shear force on the base plate. And significant slip of the base plate was observed when the BRB force changed from compression to tension.

3. The interaction of shear and axial stress of the anchor rods is suggested to be considered to evaluate the maximum moment resistance of the exposed column bases in BRB frames.
4. The arrangement of anchor rods controlled the maximum moment resistance of the exposed column bases in BRB frames. The slip of base plate was slightly affected by the arrangement of anchor rods.
5. The shear resistance of the exposed column bases in BRB frames is suggested to be provided by the friction force or other method rather than the anchor rods. In the design, not only the shear resistance should be checked, but also the deformations at serviceability and ultimate limit state.

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