EXPERIMENTAL STUDIES ON INELASTIC BEHAVIOR OF EXPOSED-TYPE STEEL COLUMN BASES UNDER BI-AXIAL BENDING

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ABSTRACT: Column base is one of the most important connections in a steel building because its mechanical behavior controls decisively the strength and rigidity of the structure. This paper presents a series of experiment performed on exposed type steel column bases under static cyclic biaxial bending. Cold-formed square-tube columns with column-base specimens with different failure types, bolt yielding and base plate yielding, were tested under uni-axial, biaxial but linear, and biaxial circular cyclic loading programs. Shape of hysteresis loop, moment capacity including bi-axial interaction surface, and rotation capacity are examined experimentally, and they are found affected by failure type and loading type as well.

Key Words: Exposed-type column base, bi-axial bending, Base-plate yielding type, Anchor-bolt yielding type, Load path

INTRODUCTION

Column bases are important parts of a structure, which transfer loads acting on upper structure to a foundation. They deform under shear forces and bending moments, particularly in rotation, when the structure is subjected to lateral forces. Their behavior under such loading strongly affects the overall behavior of the structure.

The existing literature on this field includes theoretical and experimental studies aiming to simulate the real behavior of column bases. It has already been proved that assuming them as pinned or fixed supports is not a suitable way to simulate their actual behavior because in most cases, column bases have strongly semi-rigid behavior highly affecting the overall behavior of the structure. The degree of semi-rigidity depends on the properties and the configuration of various elements that form the column base (i.e. base plate, anchor bolts, concrete, etc). To understand the actual behavior of the column bases, several researches have been conducted so far. However, these studies are mostly restricted to the in-plane behavior of the column bases.

On the other hand, according to the damage investigations after the earthquakes, the damage to the column base caused by two-directional seismic excitations is much more serious than anticipated for one-dimensional loading. Therefore it is very important to investigate the behavior under biaxial loading and it is more suitable to consider the effect of biaxial bending in the design of steel column bases. This paper presents an experimental study on semi-rigid behavior of exposed-type steel column bases under static cyclic biaxial bending. No axial load is applied to the column.

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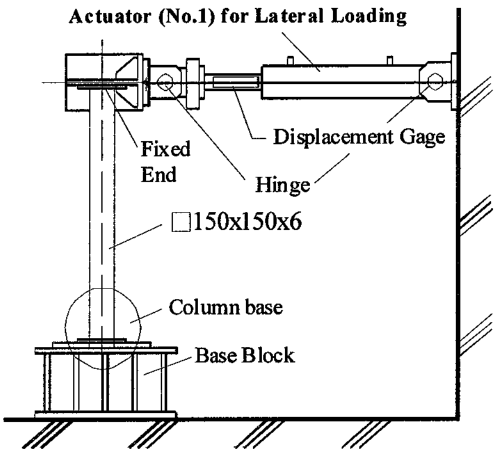


Figure 1. Test setup

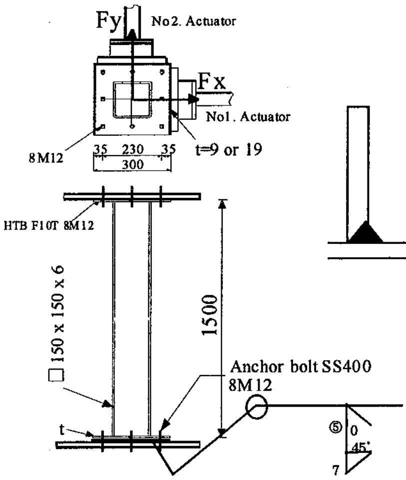


Figure 2. Dimensions of test specimen (mm)

OUTLINE OF EXPERIMENTAL PROGRAM

These studies are conducted on exposed-type steel column bases composed of a square hollow steel column, two types of base plates of thickness, 9mm and 19mm, anchor bolts all with screws and base block. The system composed of those elements is set up as a cantilever column and each test specimen is subjected to a different lateral displacement history.

The test specimens are fabricated of cold-formed square hollow steel of size: B=150mm, D=150mm, t=6mm, effective height h=1500mm. The test setup and the dimensions of the test specimen are shown in **Figure 1** and **Figure 2**, respectively. The experiments are conducted in two series of uniaxial and four series of biaxial quasi-static cyclic loading tests on cold-formed □-150×150×6 columns connected by a semi-rigid column base to a rigid foundation. **Table 1** gives details of the test code.

Table 1. Tests Code

Loading Type	19 mm	9 mm
Uniaxial-Y (UY)	ECB19SCUY	ECB9SCUY
Biaxial-Linear (BL)	ECB19SCBL	ECB9SCBL
Biaxial-Circular (BC)	ECB19SCBC	ECB9SCBC

Note: ECB stands for 'Exposed Column Base' and SC stands for 'Static Cyclic'.

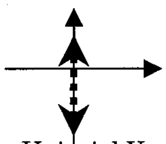
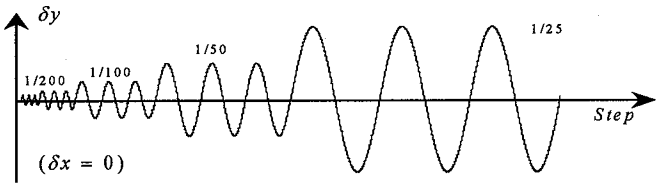
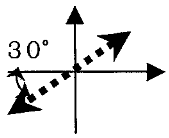
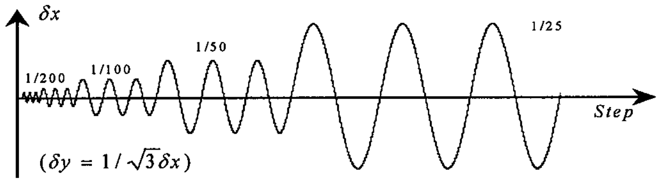
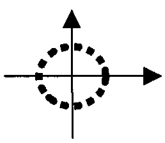
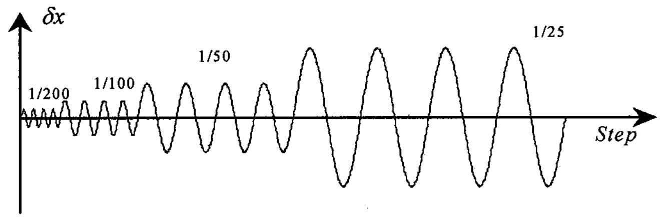
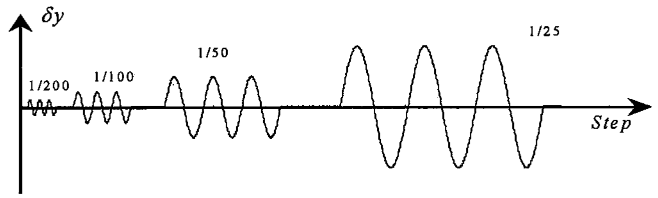
Loading Programs

During the cyclic loading tests under biaxial bending, the column is subjected to lateral force on each loading direction. The experiment is conducted in 6 series of tests, first uniaxial static cyclic loading in y-direction (SC-UY), then biaxial linear static cyclic loading (SC-BL), finally biaxial circular static cyclic loading (SC-BC) for 9mm and 19mm thick column bases. In order to ensure an accurate loading path in the X-Y plane, only the displacement control is adopted.

Due to the perpendicular arrangement of two actuators, the movement of one actuator changes the direction of the other actuator. To overcome that problem, the change in the direction of the actuator is evaluated and compensated by a computer. At the beginning of the tests, the target amplitude of δ/L ratio, which is the drift angle, is taken 1/200, where L denotes the effective length of column and δ denotes the displacement at the tip of the column.

After the completion of every 3 loading cycles, the displacement amplitude is increased to 1/ 100, 1/50, 1/25, one after another. For the all test loading is done quasi-statically, slower than 0.001 m/sec. In uni-axial static cyclic loading in y-direction (SC-UY), the load is applied uniaxially only in y-direction; there is no loading in x-direction. In biaxial linear static cyclic loading (SC-BL), the ratio of δ_x / δ_y is taken $1/\sqrt{3}$, which means that the loading direction makes an angle of 30 degrees with the y-axis. In biaxial circular static cyclic loading (SC-BC), the column rotates in a circular manner around the axis passing through the center of the base plate along its length. In biaxial circular static cyclic loading (SC-BC), there is a uniaxial loading between each three cycles.

Table 2. Loading Program

Loading Type	Displacement path	Control program for top displacement
SC-UY	 Uniaxial-Y	
SC-BL	 Biaxial-Linear	
SC-BC	 Biaxial-Circular	 

* δ : displacement of the top of the column

Test setup and loading

For all test series, a □-150×150×6 column with 9 mm and 19 mm base plate thickness, which is placed on a base block and to which hydraulic actuators are attached in both x and y directions is used as a test specimen. The capacity of each actuator is 100kN. The displacement path and cycling history are controlled by the help of a computer and two hydraulic pumps, each attached to one actuator. The test specimen is securely clamped to the loading head and the base block. The column is attached to the base block by 8M12 anchor bolts all with screw and the upper end of the column is attached to the loading head, which connects the actuators to the column, by 8 high-tension bolts. Displacement gages are attached to both sides of each hydraulic actuator to measure the displacement at the top of the column.

During the tests, after setting-up the test specimen, lateral cyclic loads are applied quasi-statically according to the displacement control controlled by the computer. During the cyclic loading, the displacement and the load applied by each actuator, the column rotations, displacement of the anchor bolts, strain values obtained from strain gages are recorded using a digital recorder.

On the test specimen, 8 strain gages, 2 on each face of the column, are pasted at a distance of 25cm from the bottom of the column. An aluminum frame is attached around the lower part of the column and on each side of that frame a displacement gage is placed to measure the rotation of the column base. On each anchor bolt, a displacement gage is placed to measure uplift of each bolt during the cyclic loading in the experiment. The test specimen, the aluminum frame and actuators can be seen in **Photo 1.**

Generally, when introducing tension into an anchor bolt the pre-tension needs to be managed carefully, because it contributes to the performance of column bases. In the tests, the anchor bolts are screwed by torque wrench so that pretension at each anchor bolt is 50 MPa.

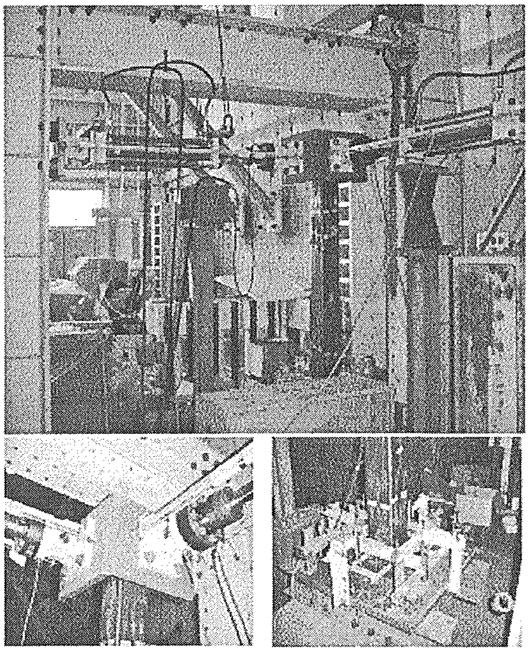


Photo 1. General views of test setup

Material properties

The material properties for the steel plates were determined from tensile tests on strip cuts taken from different parts of the plates forming the steel square tube. Furthermore, in case of anchor bolts, ten pieces were chosen randomly and tested.

The yield stress σ_y and the tensile strength σ_u of base plates with 9mm, 19mm thickness, square hollow steel and the tension load capacity of each type of anchor bolt are summarized in **Table 3.**

Table 3. Material properties (in MPa)

	σ_y	σ_u
Base plate 9mm (JIS SS400)	270	450
Base plate 19mm (JIS SS400)	250	430
SHS 150x150x6 (JIS STKR 400)	784	901
		(in kN)
	T_y	T_u
M12 A. bolt (All with screw)	44	48

TEST RESULTS

Hysteretic responses

Generally, when any load is applied to a column base, bending at the base plate and tension at the anchor bolts are induced. During the tests, the SHS steel column remained elastic.

For all directions, the load-deflection curve of the test with a thick base plate showed a pinched hysteretic behavior with anchor bolt yielding. On the other hand, for the test with a thin base plate, we observed less pinched hysteresis loop, but it includes slight pinching.

Uniaxial-Y (UY)

The hysteresis loops for uniaxial cyclic loading for ECB19SC-UY and ECB9SC-UY are shown in **Figure 3**.

The hysteresis loops of 19mm and 9mm base plate thickness were stable and exhibited good energy dissipation characteristics until the drift angle reached to point of 0.04 rad. From the second cycle of each group of 3 cycles, the base plastic, the hysteresis loops overlapped each other and they appeared to have no degradation. In the around of the 0.04 drift angle, both of the connections reached their ultimate capacities without fracture. But their maximum resistance forces are different.

Examination of the hysteresis loop for ECB9SC-UY proves that the column base behavior was ductile. And also, the hysteris loop began to show pinching from the second cycle of each drift angle because the base plate lifted partially. But pinching effect is not so severe. In this column base, the main failure was initiated by the inelastic out of plane deformation of the base plate located along the column flanges entirely.

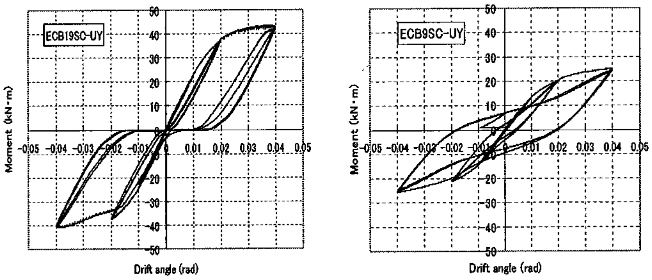


Figure 3. Hysteresis loops for SC-UY

Biaxial-Linear (BL)

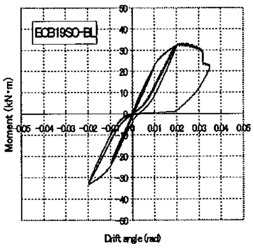
The moment-drift angle curve for biaxial linear cyclic loading for ECB19SC-BL and ECB9SC-BL are shown in **Figure 4**.

Although any failure did not occur for uniaxial loading, in case of biaxial cyclic loading for ECB19SC-BL, a bolt failure occurred when the drift angle on x-component has just passed the 0.03 radian and then we stopped the test. Its pinched hysteresis loop is similar to uni-axial cyclic loading. It seems that the distance between the location of failure bolt and plastic hinge region became longer than that in the uni-axial case. For ECB9SC-BL case, any bolt failure did not occur but welding failure is observed at the corner of the SHS column. In the first cycle of each 3-cycle group we have bilinear characteristics, but at the 2nd and 3rd cycle of each cycle group, the stiffness increases and obtained pinched loops are observed. Strength degradation in consecutive loops at the same displacement level was slightly observed.

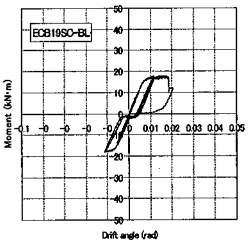
Biaxial-Circular (BC)

The hysterisis loops for biaxial-circular cyclic loading for both ECB9SC-BC and ECB19SC-BC are shown in **Figure 5**.

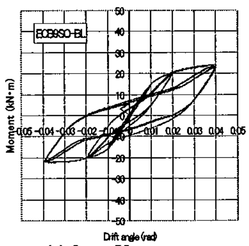
According to the **Figure 5(a)**, which is biaxial-circular cyclic loading for ECB19SC-BC case in x-direction, the bolt failure started just before the drift angle reaches its maximum value of 0.04 radians. During the linear loading in x-direction, the first bolt failure occurred, and the rest of the bolts failed in one cycle after the first bolt failure. There was practically no energy dissipation. In both x and y components of ECB19SC-BC case, strength degradation is observed per each cycle when the drift angle reaches to 0.02 radian. In biaxial-circular cyclic loading for ECB9SC-BC, any bolt failure is not observed. The hysterisis loops for biaxial-circular and for biaxial-linear cyclic loading for 9 mm plates are both similar to bilinear model but the shape is different. In the case of the latter, pinching effect did not occur. Additionally, it is observed that the Hysteresis for the biaxial-circular path became more rounded at the unloading point.



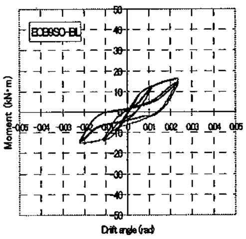
(a) 19mm X-component



(b) 19mm Y-component

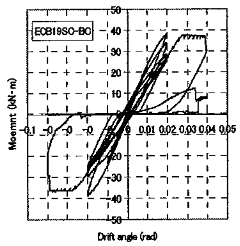


(a) 9mm X-component

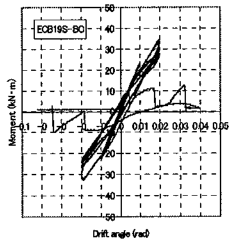


(b) 9mm Y-component

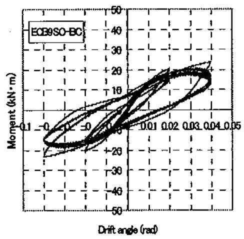
Figure 4. Hysteresis loops for SC-BL



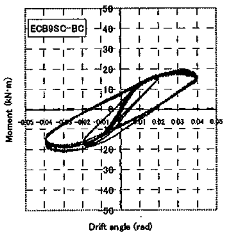
(a) 19mm X-component



(b) 19mm Y-component



(a) 9mm X-component

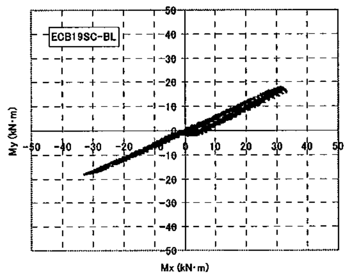


(b) 9mm Y-component

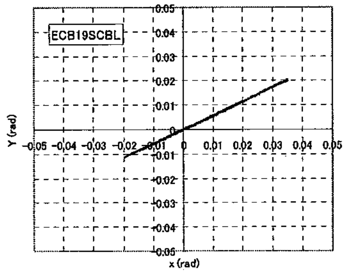
Figure 5. Hysteresis loops for SC-BC

Moment locus and drift angle locus

Figure 6, 7, 8, and 9 present the moment loci as well as the drift angle loci for the biaxial loading cases. In the biaxial linear loading, the moment locus is a little inconsistent with the completely linear drift angle locus. For example, the drift angle locus of ECB19SC-BL is inclined with an angle of 30 degrees clearly, but moment locus does not incline with the angle in the inelastic range.

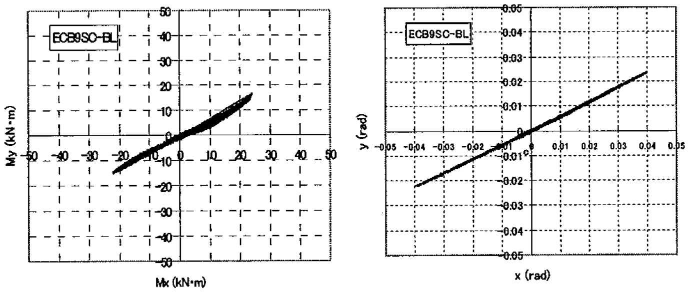


(a) Column base moment path



(b) Drift angle path

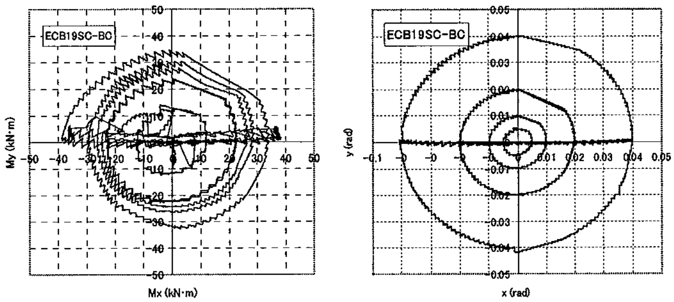
Figure 6. Path in the biaxial space (ECB19SC-BL)



(a) Column base moment path (b) Drift angle path

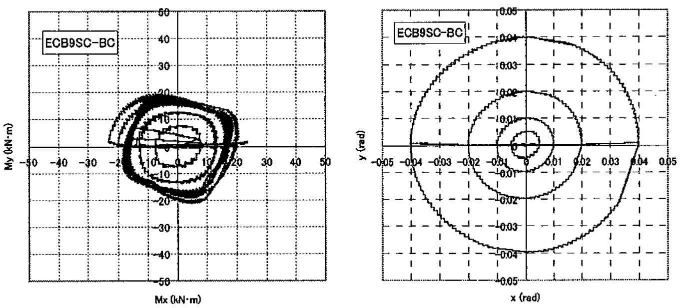
Figure 7. Path in the biaxial space (ECB9SC-BL)

In the biaxial circular loading, shape of the moment path is recorded for ECB19SCBC, which keeps shape almost circular until bolts fail. On the other hand, change of the shape and the rotation of the moment path are recorded for ECB9SC-BC, which shows a circular shape in the elastic range and changes to a square shape with rounded corners in the inelastic range.



(a) Column base moment path (b) Drift angle path

Figure 8. Path in the biaxial space (ECB19SC-BC)



(a) Column base moment (b) Drift angle path

Figure 9. Path in the biaxial space (ECB9SC-BC)

The resultant response shows a reasonable comparison between biaxial and uniaxial curves in terms of effective strength and effective deformation (both magnitudes of vectors) in **Figure 10**. In the case of the thick base plate with bolt yielding type, the effective rotation angle at the effective moment capacity becomes a bit smaller when loaded bi-axially. In case of thin base plate with base plate yielding, the effective moment capacity in case of bi-axial linear loading was a bit higher.

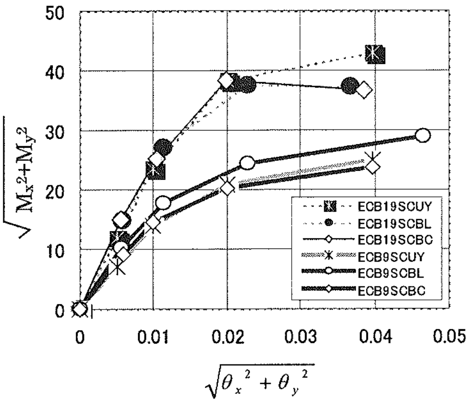


Figure 10. Moment-Drift angle responses

CONCLUSIONS

This paper examined the test results of the experiment on the exposed type steel column base under static cyclic bi-axial loading. The conclusion drawn from this experimental study is as follows:

(1) In all directions, the case with anchor bolt yielding type showed pinched hysteretic behavior. On the other hand, the case with base plate yielding type showed a less pinched but a slight degradation of hysteresis behavior. The hysteretic loop for base plate yielding type began to show pinching from the second cycle of the each drift angle, but pinching effect is not so severe.

(2) In the case of bolt yielding type, the effective rotation angle at the effective maximum capacity becomes a bit smaller when loaded bi-axially. In the base plate yielding type, the effective moment capacity of bi-axial linear loading was a bit higher than that of uni-axial case.

(3) The shape of bi-axial interaction surface is different for bolt yielding type and base plate yielding type in the biaxial circular loading. Bolt yielding type keeps almost circular shape until bolts failure. On the other hand, base plate yielding type showes a circular shape in the elastic range and changes to a square shape with rounded corners in the inelastic range, which leads to the approximation that strengths about two axes may be assumed independent under such a square-shaped interaction surface.

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