# Bi-axial Bending Behavior of RHS-columns Including Post-buckling and Deterioration Range

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**SUMMARY:**
In Japan, Rectangular Hollow Section (RHS) steel columns are generally used in steel buildings. Columns are subjected to bi-axial bending moment that because buildings behave 3-dimensionally under seismic excitations. However, most of previous studies on RHS columns were focused on the uni-axial bending behavior. In order to evaluate the seismic resistance of steel building structures, it is important to clarify the bi-axial bending behavior of RHS columns including deterioration range governed by local buckling. In this study, a series of cyclic loading tests on RHS columns under the condition of bi-axial bending moment were conducted. Primary parameter was the horizontal loading directions that were set to 0, 15, 30 or 45 degree from principal axis of the column cross-section. Effect of the horizontal loading direction on deterioration range was notable. Strength deterioration of the column that applied lateral force from the 0 degree direction is larger than other loading directions one.

*Keywords: RHS columns, Horizontal loading direction, Local buckling, Deterioration behavior*

## 1. INTRODUCTION

In Japan, Rectangular Hollow Section (RHS) steel columns are generally used in steel buildings. Columns are subjected to bi-axial bending moment that because buildings behave 3-dimensionally under seismic excitations. In order to evaluate the seismic resistance of steel building structures, it is important to clarify the bi-axial bending behavior of RHS-columns including deterioration range due to local buckling. However, there are very few of these studies, and enough researches were not done. Also, very few studies about the deterioration range of RHS-columns with local buckling, therefore, how RHS-columns under bi-axial bending moment deteriorate, compared to under mono-axial bending moment, is unclear.

In this study, a series of cyclic loading tests on RHS-columns under the condition of bi-axial bending moment were conducted. This paper presents the experimental investigation of bi-axial bending behavior of RHS-columns.

## 2. TEST PROGRAM

### 2.1. Specimens and Parameters

Specimens consisted of RHS-column; □-200×9 (BCR295, Width-to-thickness ratio: 22.2, length: 1734mm) and steel plates welded to both ends of RHS-column (Fig.1). The coupon tests of the flat part of RHS-column (JIS 1A type test piece) were conducted and the results are shown in Fig.2 and Table 1. The parameters were horizontal loading direction and axial force ratio. Horizontal loading direction was set to 0, 15, 30 or 45 degree from principal axis of the column cross-section. Constant axial force was applied to the specimen and axial force ratio was set to 0.2 or 0.4 for each of the loading direction. The test matrix is shown in Table 2.

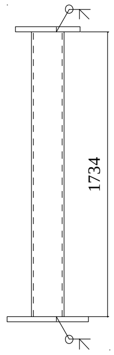



**Figure 1.** Test Specimen

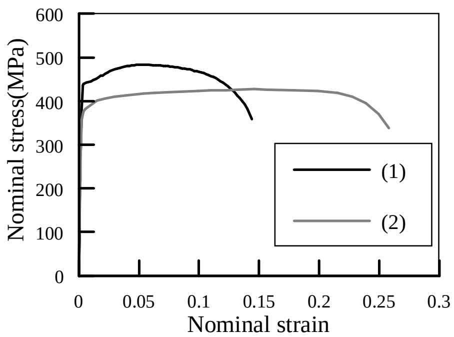
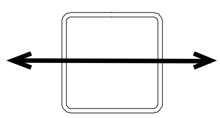
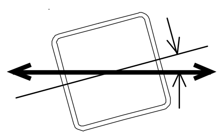
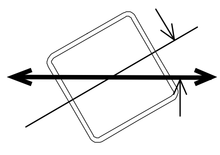
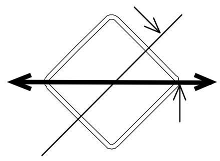



**Figure 2.** Nominal Stress-Strain Relationships

**Table 1.** Material Properties

| Material No. | Yield Strength MPa | Tensile Strength MPa | Yield Ratio % | Elongation % |
|---|---|---|---|---|
| 1 | 443 | 483 | 92 | 16 |
| 2 | 375 | 427 | 88 | 27 |

**Table 2.** Test Matrix

| Specimen Name | C00_0.2 | C00_0.4 | C15_0.2 | C15_0.4 | C30_0.2 | C30_0.4 | C45_0.2 | C45_0.4 |
|---|---|---|---|---|---|---|---|---|
| Axial Force Ratio | 0.2 | 0.4 | 0.2 | 0.4 | 0.2 | 0.4 | 0.2 | 0.4 |
| Material No. | (1) | (1) | (2) | (2) | (2) | (2) | (1) | (1) |
| Loading Direction |  0 [Deg] | |  15 [Deg] | |  30 [Deg] | |  45 [Deg] | |

## 2.2. Test Setup

The test specimen was placed in the loading frame shown in Fig. 3. Both ends of the column were clamped to the reaction jig and the horizontal loading jig. The specimen was subjected to a horizontal force by the horizontal jack through the horizontal loading jig. Constant axial force was applied by vertical jacks through the reaction jig. To load under the condition of double curvature bending moment, the reaction jig was controlled horizontally. The rotation angle of the column was calculated by Eq. (2.1). Axial force and bending moment applied to the specimen were calculated by Eq. (2.2) and Eq. (2.3).

$$\theta = \tan^{-1}\{\delta_h/(L-\delta_v)\} \tag{2.1}$$

$$N = N_e + N_w + F_{rv} \tag{2.2}$$

$$M = F_h(L-\delta_v) + N \cdot \delta_h/2 \tag{2.3}$$

where

$L$ : column length
$\delta_h$ : story drift
$\delta_v$ : vertical displacement
$\theta$ : rotation angle of the column
$F_h$ : shear force
$N_e$ : vertical force by vertical jack (E side)

$N_w$ : vertical force by vertical jack (W side)
$F_{rv}$ : vertical force by reaction beam
$N$ : axial force
$M$ : bending moment applied to the column end

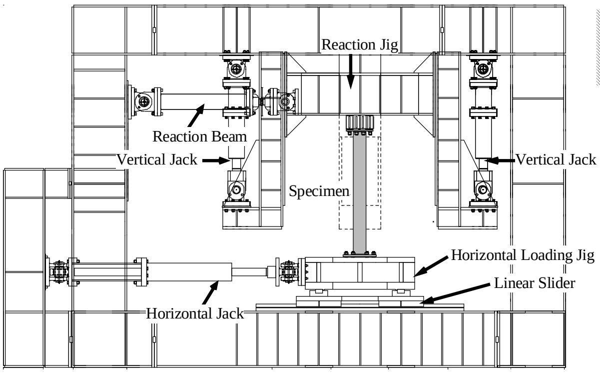



**Figure 3.** Elevation of the Loading System

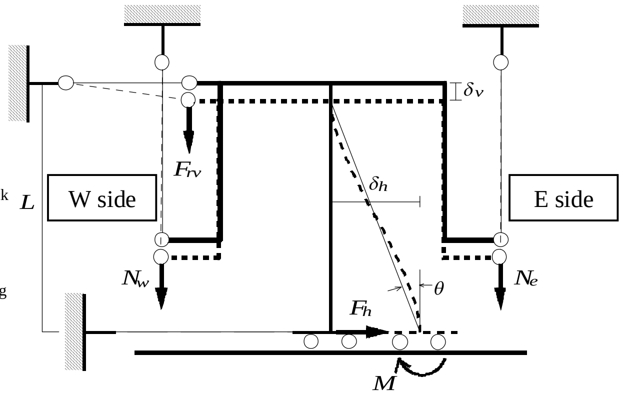



**Figure 4.** Measurement System

## 2.3. Loading History

A displacement-controlled cyclic loading was applied in the horizontal direction. The loading history was the incremental displacement amplitude with intervals of $2\theta_{pc0}$ as shown in Fig.4. Where, $\theta_{pc0}$ is the elastic column rotation corresponding to the full plastic moment with axial force of the column under uni-axial bending $M_{pc0}$. Moreover, to investigate the small amplitude hysteresis loops in the post local buckling and deterioration range, $2\theta_{pc0}$ was adopted as small amplitude in this test and was set in the loading history of deterioration range.

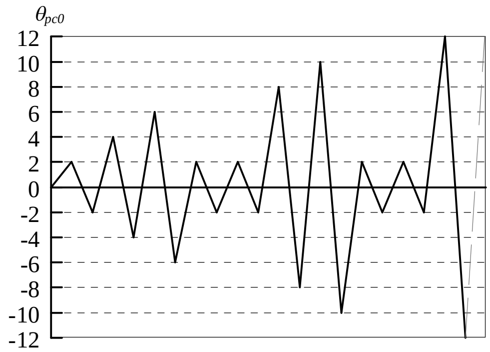



**Figure 5.** Loading History

# 3. TEST RESULTS

## 3.1. Moment-Rotation Relationships

Fig. 6 shows the moment-rotation relationships for all eight specimens that were normalized $M_{pc0}$ and $\theta_{pc0}$. Loading was continued either until the specimen completely lost their axial force supporting capacity or until reaching the limit of the loading system capacity. The triangle symbol (▼) represents the maximum strength of the specimen. The maximum strength of all specimens was determined by local buckling.

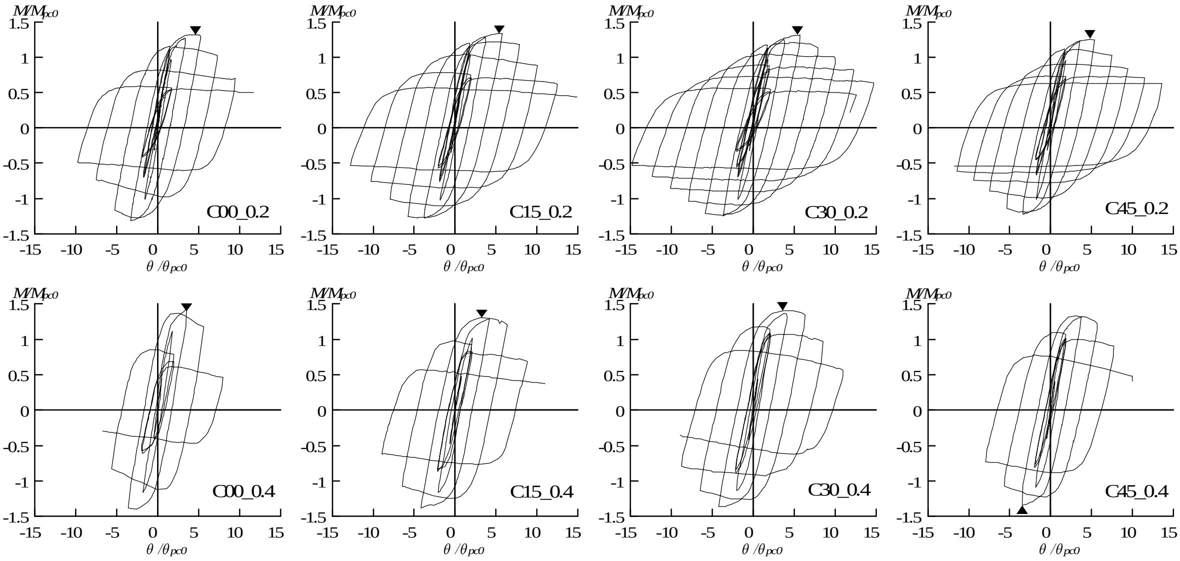



**Figure 6.** Moment-Rotation Relationships

### 3.2. Vertical Displacement

Fig. 7 shows the vertical displacement versus normalized cumulative deformation ($\Sigma|\theta|/\theta_{pc0}$). In the post local buckling and the deterioration range, each specimen vertical displacement became larger due to the progression of local buckling deformation of plate elements. When compared the loading direction, the vertical displacement of the specimens subjected to the lateral force from the 0 degree direction is larger than other loading directions one. This phenomenon is estimated that the progression of local buckling is changed by the effect of the loading direction. When columns are subjected to lateral force from diagonal direction of the column cross-section, the progression of local buckling deformation of plate elements is restrained by corner elements of the columns.

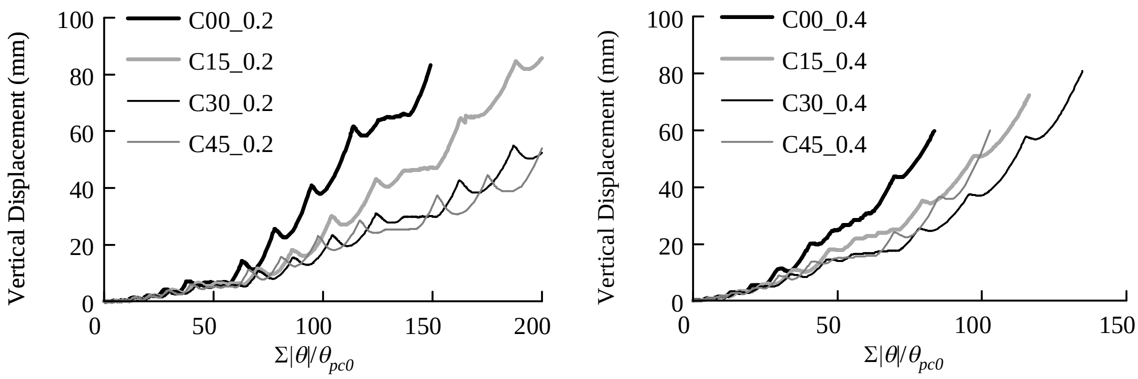



**Figure 7.** Vertical Displacement-Cumulative Deformation Relationships

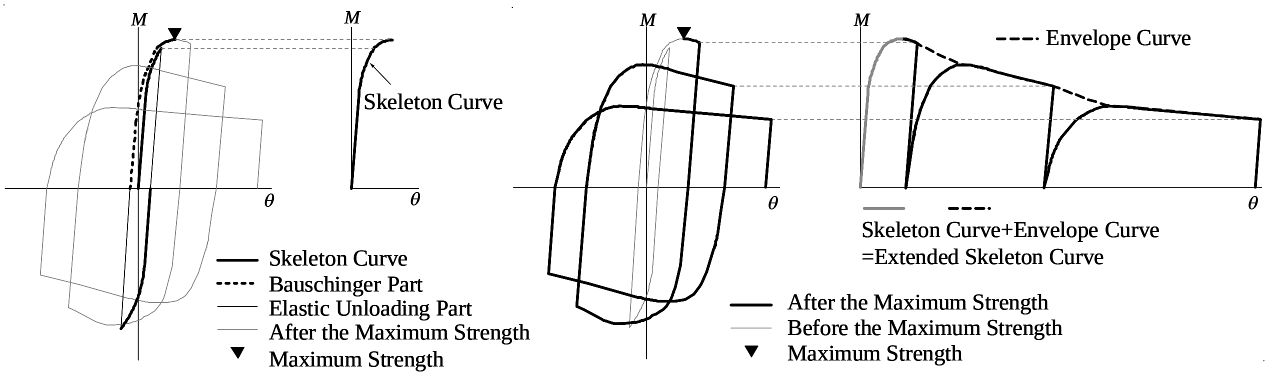
## 4. EVALUATION OF BI-AXIAL BENDING BEHAVIOR BASED ON SKELETON CURVE AND EXTENDED SKSLETON CURVE

### 4.1. Skeleton Curve and Extended Skeleton Curve

Before reaching the maximum strength, the load-deformation hysteresis loops of steel members under cyclic loading can be decomposed into three parts: the skeleton part, Bauschinger part and elastic unloading part, as illustrated Fig.8 (1). Here, the skeleton curve is obtained by connecting parts of the load-deformation relationship sequentially when the steel member first experienced its maximum load (both positive and negative). It is observed that the load-deformation relationships of the steel members under monotonic loading have an approximate correspondence to the skeleton curves under cyclic loadings.

Moreover, after reaching the maximum strength, in the post local buckling and the deterioration range, it is observed that the envelope curve obtained by connecting the hysteresis curve in each half cycle have an approximate correspondence to the load-deformation relationships of the steel members under monotonic loading.

In this study, the curve obtained by connecting the skeleton curve and envelope curve is defined as extended skeleton curve (Fig. 8 (2)).




(1) Before Reaching the Maximum Strength (2) After Reaching the Maximum Strength

**Figure 8.** Skeleton Curve and Extended Skeleton Curve

## 4.2. Comparison of Skeleton Curve

The skeleton curves of both the positive and negative loading sides derived from the load-deformation relationships are shown in Fig.9. The maximum strengths and the deformation of the skeleton curve when reaching the maximum strength are shown in Table. 3. Similar skeleton curve can be observed each specimen from each specimen. Also, the maximum strengths and the deformation of the skeleton curve when reaching the maximum strength are almost same. Before reaching the maximum strength, the plastic deformation capacity of RHS-columns is almost same regardless of the loading directions.

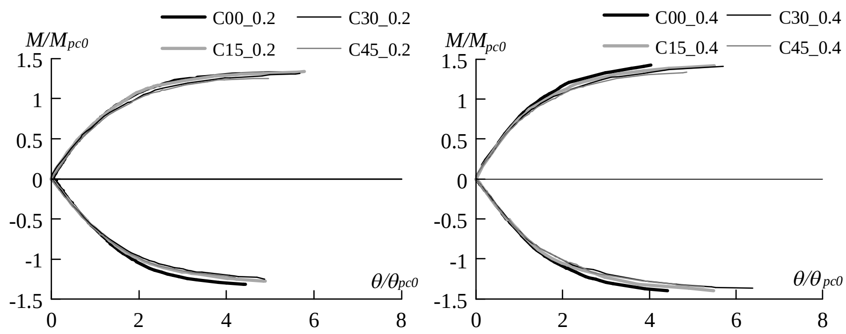



**Table 3.** Maximum Strength of Specimens

| | $M_{max}/M_{pc0}$ | $\theta_{max}/\theta_{pc0}$ |
|---|---|---|
| C00_0.2 | 1.33 | 5.37 |
| C15_0.2 | 1.34 | 5.78 |
| C30_0.2 | 1.32 | 5.68 |
| C45_0.2 | 1.26 | 4.96 |
| C00_0.4 | 1.43 | 4.04 |
| C15_0.4 | 1.42 | 5.50 |
| C30_0.4 | 1.41 | 5.70 |
| C45_0.4 | 1.34 | 5.26 |

**Figure 9.** Comparison of Skeleton Curve

## 4.3. Comparison of Extended Skeleton Curve

The extended skeleton curves of both the positive and negative loading sides derived from the load-deformation relationships are shown in Fig.10. Effect of the horizontal loading direction on the post-buckling and deterioration range was notable. The strength deterioration of the specimens subjected to the lateral force from the 0 degree direction is larger than other loading directions one. This phenomenon is estimated that the progression of local buckling is changed by the effect of the loading direction. When columns are subjected to lateral force from diagonal direction of the column cross-section, the progression of local buckling deformation of plate elements is restrained by corner elements of the columns.

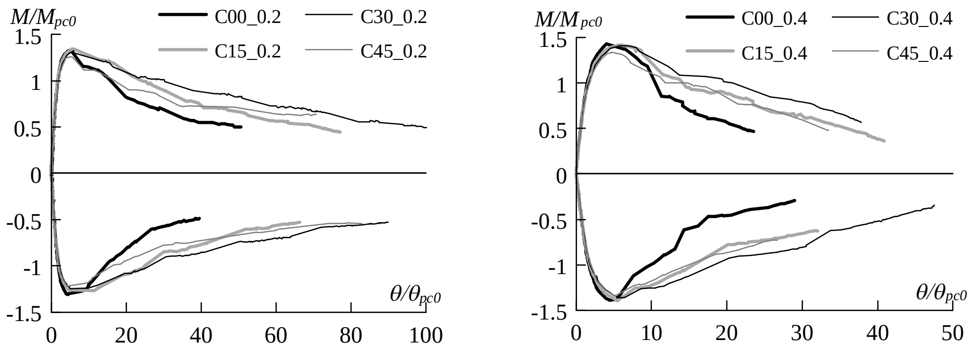



**Figure 10,** Comparison of Extended Skeleton Curve

## 5. CONCLUSIONS

To investigate the bi-axial bending behavior of RHS-columns, a series of cyclic loading tests on RHS-columns under the condition of bi-axial bending moment were conducted. In this test, constant axial force and cyclic bending were applied to the specimen. Primary parameter of the tests was the horizontal loading directions that were set to 0, 15, 30 or 45 degree from principal axis of the column cross-section. Axial force ratio was set to 0.2 or 0.4 for each of the loading direction. Maximum strengths of each specimen were governed by local buckling. Effect of the horizontal loading direction on the post-buckling and deterioration range was notable. Strength deterioration and axial shortening of RHS-columns subjected to lateral force from the 0 degree direction are larger than other loading directions one. This tendency is similar for each axial force ratio. This phenomenon is estimated that the progression of local buckling is changed by the effect of the loading direction. When columns are subjected to lateral force from diagonal direction of the column cross-section, the progression of local buckling deformation of plate elements is restrained by corner elements of the columns.

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