EXPERIMENTAL STUDY ON TRI-AXIAL NON-LINEAR RESTORING FORCE CHARACTERISTICS OF R/C COLUMNS

K. Takiguchi[1)], K. Nishimura[2)], and T. Okuda[3)]

1) Professor, Dept. of Mechanical and Environmental Informatics, Tokyo Institute of Technology, Japan
2) Assistant Professor, Dept. of Architecture and Building Engineering, Tokyo Institute of Technology, Japan
3) Graduate Student, Dept. of Built Environment, Tokyo Institute of Technology, Japan
ktakiguc@tm.mei.titech.ac.jp, knishimu@tm.mei.titech.ac.jp, tokuda@tm.mei.titech.ac.jp

Abstract: Four reinforced concrete column specimens were prepared for tri-axial loading test. The specimens had 150x150mm square section and 600mm clear span. A new experimental apparatus that allows tri-axial translation and restricts tri-axial rotation of head of the specimens was developed. The specimens were subjected to three-directional cyclic loading in the range of 0.1 to 0.4 axial force ratio. As a result, it was verified that rotation of head of the specimens could be restricted, experimental data for understanding and modeling restoring force characteristics of the R/C columns subjected to anti-symmetric bending and varying axial force were obtained, and considerations regarding restoring force model by using the theory of plasticity were carried out.

1. INTRODUCTION

It is necessary to formulate restoring force characteristics of structures or members for earthquake response analysis, and tri-axial response analysis have been appealed. Experimental tests of structures or members are indispensable for understanding the restoring force characteristics. One-axial restoring force characteristics of R/C members are understood fairly well. Experiments of R/C members subjected to two-directional loading have been made in the past researches (for example, Takiguchi et al. 1979, and Takiguchi et al. 2001). However there are few experimental research focused on tri-axial behaviors of R/C structures and members.

Four reinforced concrete column specimens were prepared for tri-axial loading test. The specimens had 150x150mm square section and 600mm clear span. A new experimental apparatus that allows tri-axial translation and restricts tri-axial rotation of head of the specimens was developed. The specimens were subjected three-directional cyclic loading in the range of 0.1 to 0.4 axial force ratio. The purposes of this study are to verify validity of the new experimental apparatus, and to understand the tri-axial behaviors of R/C columns for modeling the restoring force characteristics by using the theory of plasticity, which is one of the macro modeling (for example, Takizawa and Aoyama 1976, and Nishimura and Takiguchi 2003).

2. EXPERIMENTAL PROGRAM

2.1 Apparatus

A new experimental apparatus for a column specimen subjected to tri-axial loading was developed.

Figure 1 represents loading and measuring system. Base of the column was fixed horizontally, and head of the column was allowed tri-axial translation and restricted tri-axial rotation. A system that consists of a cross of steel beams and eight hydraulic cylinders restricts lean of the head, and a parallel rule of link mechanism (Takiguchi et al. 1979) restricts rotation that causes torsion of the column. As shown in Figure 2, the system with hydraulic cylinders allows vertical translation and keeps horizontal. The eight hydraulic cylinders have capacity of 500kN, and were connected by sixteen ultra–high-pressure hoses of the same size. Strain gages were pasted to the beams of the cross at a distance of 1600mm from joints of beams and cylinders to measure loading of the each beam. The specimen is subjected to horizontal loading by two hydraulic jacks of 200kN capacity through loading beams, and axial force by one hydraulic jack of 500kN capacity. Load cells on the hydraulic jacks measure loading of these three jacks.

Five displacement transducers measured tri-axial rotation of head of the specimen as shown in Figure 1. The displacement transducers of No.1 to 3 decide the lean of the head, and No.4 and 5 measure the rotation regarding torsion. Four measuring instruments measured tri-axial translation. The measuring instrument connects head of the specimens and the other end through ball bearing of self-aligning rod-ends, and measures distance between the ends with displacement transducer. Tri-axial relative displacement of head to base of the specimen is calculated with these five displacement transducers and three out of four measuring instruments. Two measuring instruments regarding vertical direction make two results of relative displacement, and we take an average.

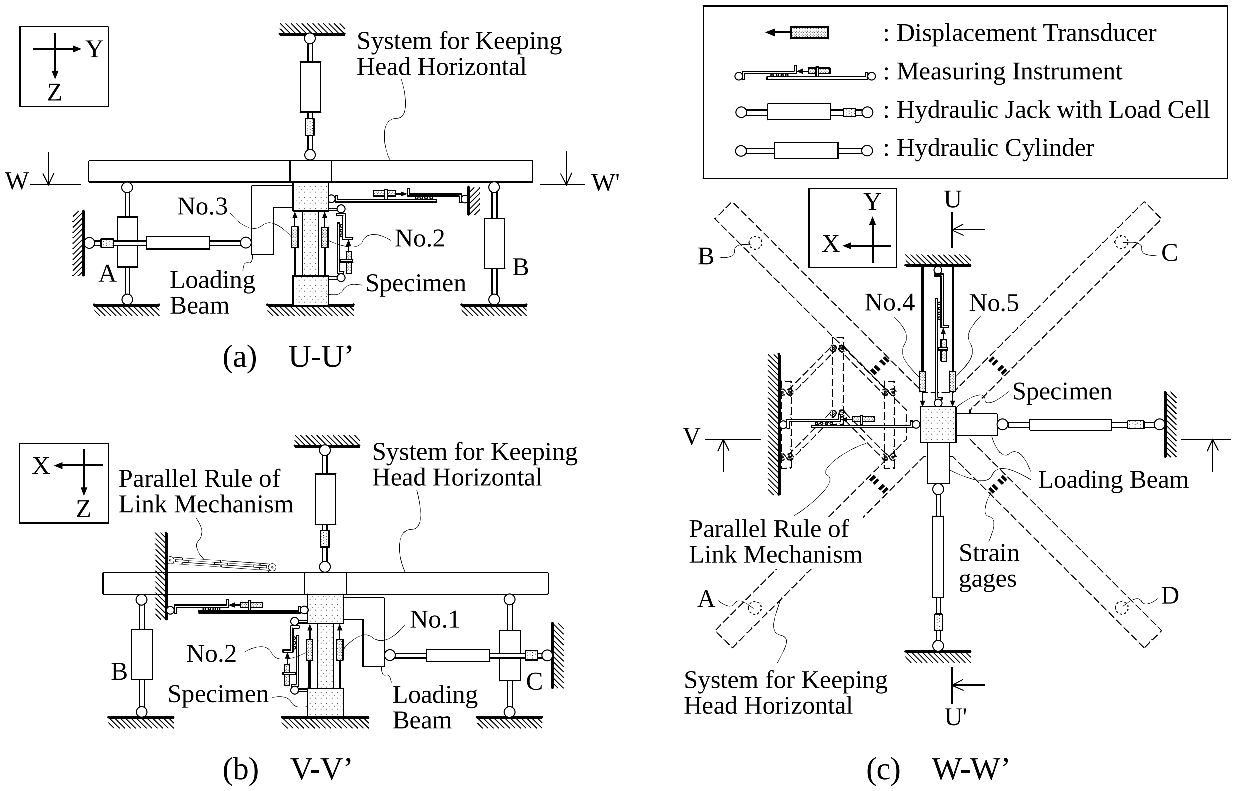


Figure 1 Loading and Measuring System

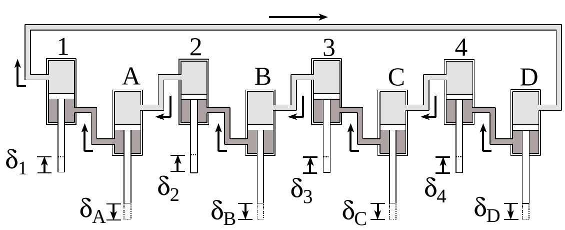


Figure 2 System of Eight Hydraulic Cylinders

2.2 Specimens and Loading Plan

Four reinforced concrete column specimens were prepared for the test. Table 1 shows dimensions of specimens and mechanical properties of concrete and reinforcements, and Figure 3 shows details of specimen. Shear span-to-depth ratios of specimens are equal to 2.0. Deformed bar and round bar, D10 and 4ϕ, are used for longitudinal bars and shear reinforcements, respectively. The specimens were designed to yield in flexural and not to fail in shear. The specimens were subjected to tri-axial cyclic loadings. Axial force was varied in the range of 0.1 to 0.4 axial force ratios.

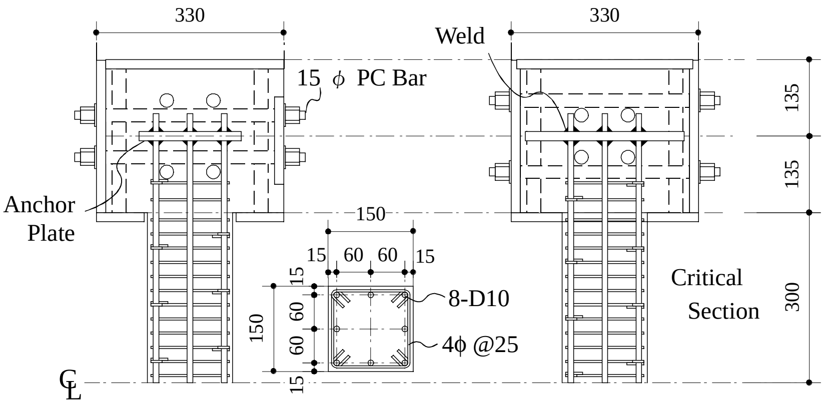


Figure 3 Detail of Specimen

Table 1 Dimension of Specimens and Properties of Reinforcements and Concrete

Name of Specimen	Section b×D (mm)	Length of Clear span (mm)	Reinforcements: Main Reinf.	Reinforcements: Shear Reinf.	Concrete: Age at Column Test (days)	Concrete: Compressive Strength σ_B(N/mm^2)	Concrete: Splitting Tensile Strength σ_T (N/mm^2)	Axial Force Ratio (%)
CBS-3D-1	150×150	600	8-D10 σ_y = 356 N/mm^2 p_g = 2.56 %	4ϕ @25 σ_y = 411 N/mm^2 p_w = 0.67 %	51-54	33.56	2.97	32
CBS-3D-2					57-60	33.56	2.94	10-40
CBS-3D-3					56-60	31.14	2.93	10-40
CBS-3D-4					63-66	31.78	2.81	15.5-33.4
					Curing in air after 7days moist curing			

3. TEST RESULTS AND CONSIDERATION

3.1 Verification of Apparatus

Displacements and forces of test results are expressed on rectangular coordinate, and compressive axial displacement and force are taken as positive, as shown in Figure 4.

Figure 5 shows rotation of the test results. It can be said that the system with hydraulic cylinders and the parallel rule of link mechanism could restrict the rotation of head of specimen, and those had equal ability. The maximum rotations of four specimens were 0.0012 rad, 0.0027rad, and 0.0035 rad in r_X, r_Y, and r_Z, respectively.

The maximum forces, which acted on hydraulic cylinders through the beams of system for keeping horizontal the head of specimens, were 2.5kN, 3.7kN, 2.7kN, and 1.6kN compressive force on the tests of CBS-3D-1, CBS-3D-2, CBS-3D-3, and CBS-3D-4, respectively. These maximum forces were quite smaller than axial force that the specimens were subjected. The force, which acted on the hydraulic cylinder, was obtained by calculating curvature of beam of the cross with Navier's assumption and strain measured by strain gages posted on the beam. The system for keeping horizontal the head of specimens could restrict rotation of the head without bearing axial force.

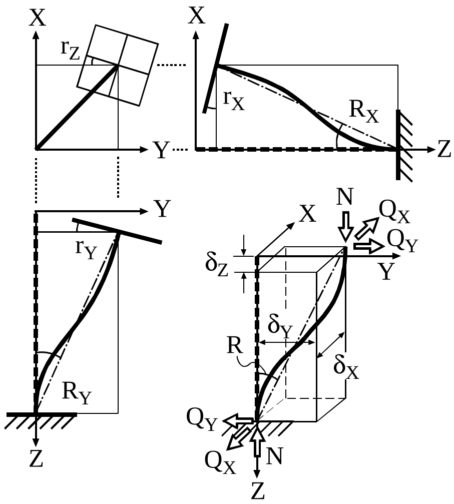


Figure 4   Displacements and Forces

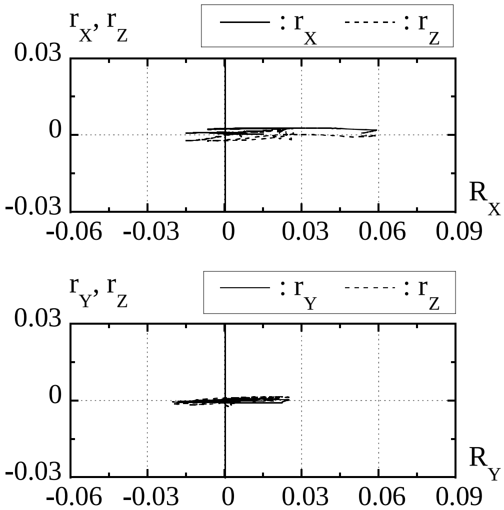


Figure 5   Rotation of Head of CBS-3D-2

3.2 Test Results and Consideration

Figure 6 to 9 show test results of four specimens. The maximum R, which was lean of axis of member to Z-axis as shown in Figure 4, were 0.032 rad, 0.043 rad, 0.061 rad, and 0.081 rad in CBS-3D-1, CBS-3D-2, CBS-3D-3, and CBS-3D-4, respectively. Loading history influenced the maximum lateral displacement. Tendency could be seen that cyclic lateral loading under higher axial force made the lower maximum lateral displacement.

Dotted lines shown in Q_X-N and Q_Y-N relationships of Figure 7 to 9 represent strength curve that have parabola in Q_X-N and Q_Y-N relationships and circle in Q_X- Q_Y relationship. The parabola is approximated curve of strength given by the additional theorem, perfectly rigid-plastic assumption on stress-strain relationships of concrete and reinforcement, and anti-symmetric bending moment distribution of the specimen. Compressive strength of concrete and yield strength of reinforcement obtained through test of material are used for calculation. It can be said that strength of the column specimens can be estimated with the strength curve as shown in Figure 7 to 9 and the strength curve can be regarded as yield surface.

CBS-3D-1 was subjected to alternate one-directional lateral loading in X and Y direction under a constant axial force, as shown in Figure 6. First, X-directional loading was dealt in the range of –6 mm to 6 mm with no Y-directional loading, and next Y-directional loading was dealt in the same range with no X-directional loading. These processes were repeated as displacement was increased. Figure 10 shows the results of CBS-3D-1, which Q_X- δ_X and Q_Y- δ_Y relationships are drawn on the same sheet. It can be said that restoring force characteristics aren't influenced by loading history in the direction lied at right angle because Q_X- δ_X and Q_Y- δ_Y relationships are almost equal.

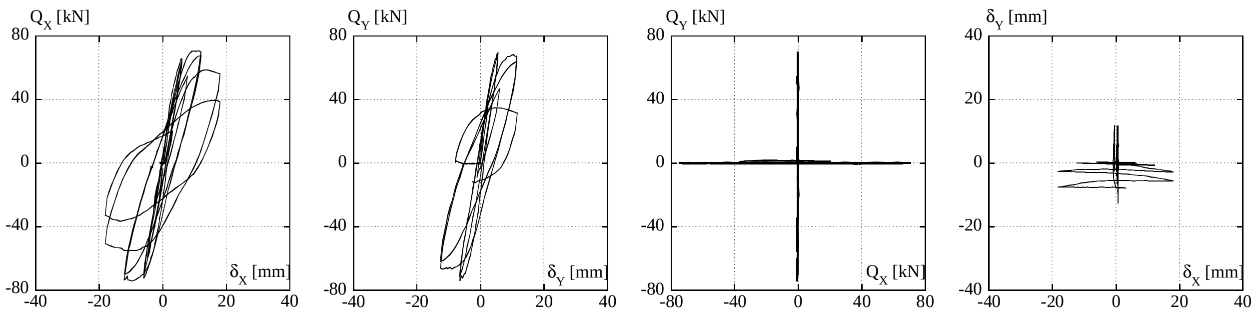


Figure 6   CBS-3D-1

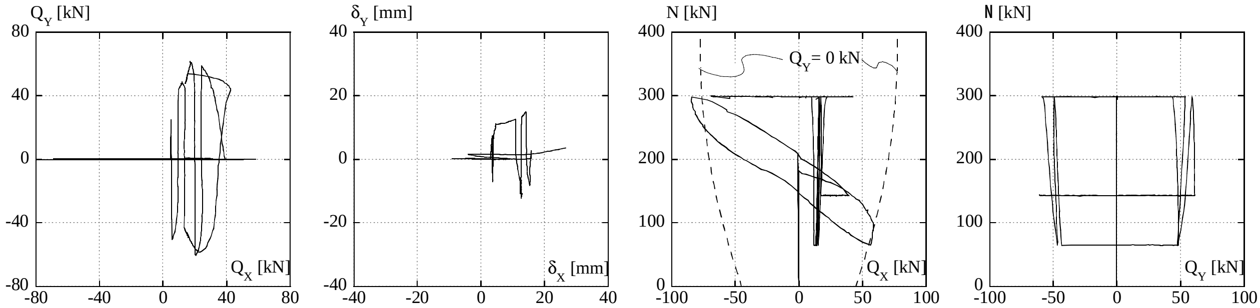


Figure 7 CBS-3D-2

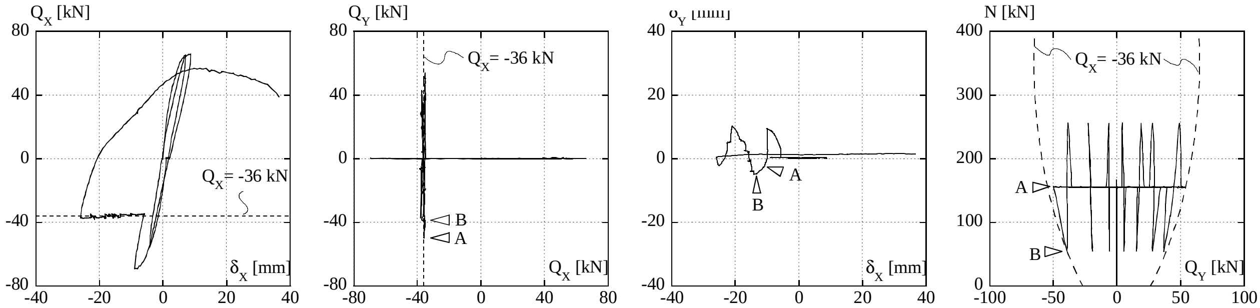


Figure 8 CBS-3D-3

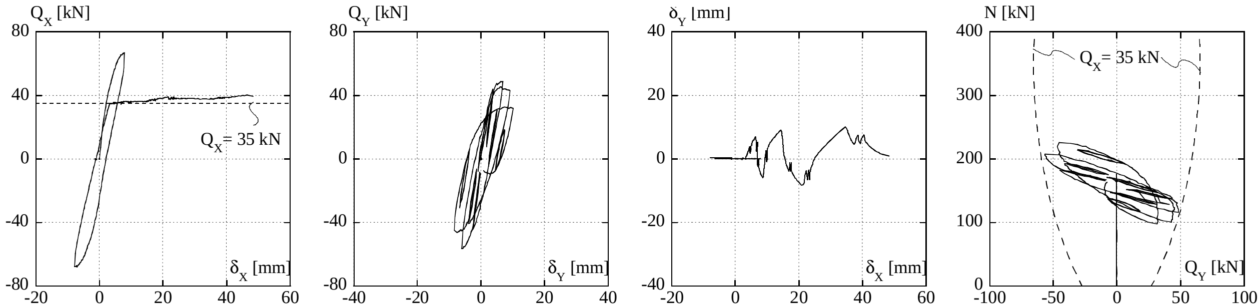
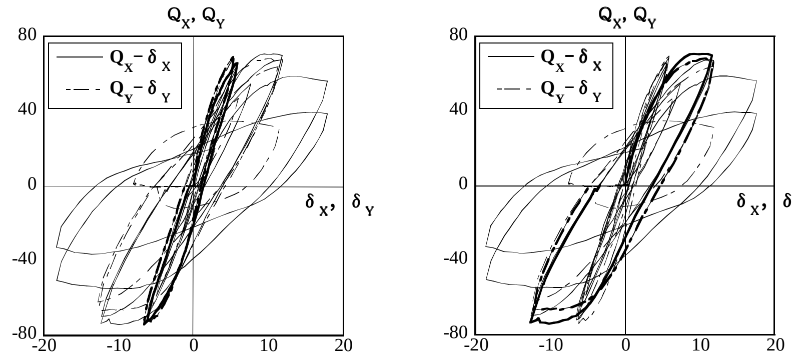


Figure 9 CBS-3D-4



(a) First Cycle (b) Second Cycle

Figure 10 Hysterisis Loops

Figure 11 shows a stage from A to B the test result of CBS-3D-3 shown in Figure 8. In the stage, axial force was decreased after the specimen was yielding. displacement increment vector of the test result lied in direction of loading in the stage from A to B. When the column specimen was yield and its displacement directed toward loading, force-displacement relationship were analogous to the theory of plasticity (for example, Chen 1994), because plastic displacement increment vector of calculation roughly lied in normal direction of yield surface, as shown in Figure 11. The plastic displacement increment was given by subtracting elastic displacement increment from total displacement increment of the test result, where elastic displacement increment was calculated by multiplying force increment of the test result and inverse of elastic rigidity together. Elastic rigidity was decided on inclination of line that was regarded as linear relationship on initial force-displacement curve of the test result.

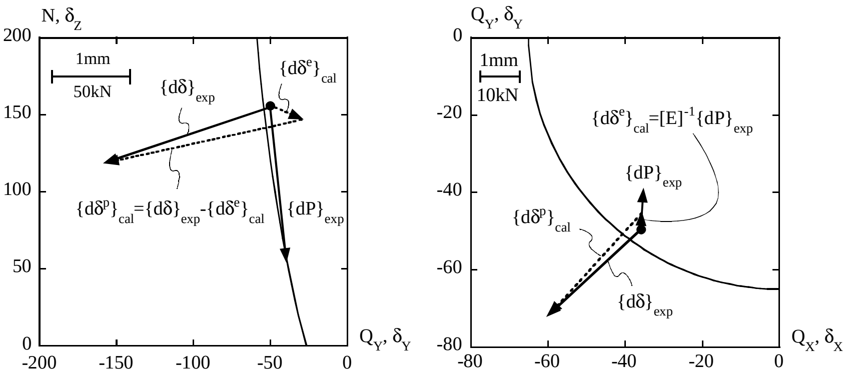


Figure 11 Plastic Flow

4. CONCLUSIONS

Four reinforced concrete column specimens were prepared for tri-axial loading test. The specimens had 150x150mm square section and 600mm clear span. A new experimental apparatus that allow tri-axial translation and restrict tri-axial rotation of head of specimens was developed. The specimens were subjected to three-directional cyclic loading in the range of 0.1 to 0.4 axial force ratio. As a result, the following conclusions were found.

[1] Rotation of head of specimens could be restricted, and experimental data for understanding and modeling restoring force characteristics of the R/C columns subjected to anti-symmetric bending and varying axial force were obtained.

[2] Surface, which was calculated with the additional theorem, perfectly rigid-plastic assumption on stress-strain relationships of concrete and reinforcement, and anti-symmetric bending moment distribution of a column, could estimate strength of the R/C columns, where compressive strength of concrete and yield strength of reinforcement obtained through test of material were used.

[3] One-axial restoring force characteristics under a constant axial force weren’t influenced by loading history in the direction lied at right angle.

[4] When the R/C columns were yielding and those displacements directed toward loading, force -displacement relationships were analogous to the theory of plasticity.

References:

Takiguchi, K., Nishimura, K., and Hirai, K. (2001), “Experimental study on two-dimensional restoring force characteristics of R/C columns under varying axial force,” *Journal of Structural and Construction Engineering*, Architectural Institute of Japan, 539, 111-118, (in Japanese).

Takiguchi, K., Kokusho, S., Kobayashi, K., Ishida, A., and Kimura, M. (1979), “Study on the Restoring Force Characteristics of Reinforced Concrete Columns to Bi-Directional Displacements, Part 1 Development and Examination of Loading Apparatus for Testing Reinforced Concrete Columns Subjected to Bi-directional Horizontal Forces and Axial Force,” *Journal of Structural and Construction Engineering*, Architectural Institute of Japan, 286, 29-35, (in Japanese).

Takizawa, H., and Aoyama, H. (1976), “Biaxial effects in modeling earthquake response of R/C structures,” *Earthquake Engineering and Structural Dynamics*, 4, 523-552.

Nishimura, K. and Takighchi, K. (2003), “Tri-Axial Non-Linear Restoring Force Model of R/C Structures by Using an Analogy to the Plastic Theory,” *Journal of Structural and Construction Engineering*, Architectural Institute of Japan, 566, 113-120, (in Japanese).

Chen W.F. (1994), “Constitutive Equations for Engineering Materials, 2,” Elsevier.