# Experimental Study on Stress Transfer in Reinforced Concrete Corner Column and Beam Joints

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**SUMMARY:**
Reinforced concrete rigid frame structures generally have a corner column jointed with two beams in orthogonal directions. If plastic hinges are designed at the beam ends for ductile frame system, the longitudinal bars need to yield, and capacities of those anchorages and strength of the exterior joint must be evaluated. An objective of this experimental study is to examine a stress transfer mechanism in the corner column and beams joint. Three corner column and beams joint specimens were prepared for tests, and were subjected to static cyclic loads. As results, it can be said that strength at the joint can be evaluated by traditional method; the joint can fail under large displacement even if the joint has 1.5 times larger strength than the beams; the longitudinal bars in a perpendicular beam can effect as anchorage reinforcements; stiffness against torsion around a column axis declines after the damage at the joint.

*Keywords: R/C, exterior joint, bi-axial load, anchorage*

## 1. INTRODUCTION

Reinforced concrete rigid frame structures generally have a corner column jointed with two beams in orthogonal directions, and longitudinal bars in those beams anchor in the column, which part is exterior joint. If plastic hinges are designed at the beam ends for ductile frame system, the longitudinal bars need to yield and capacities of the anchorage and strength of the exterior joint must be evaluated. However, experimental studies on the reinforced concrete corner column and beams joints subjected to bi-directional loads are limited, and specimens in rare studies had quite higher flexural strength in a column than beams at the connection. When the exterior joint in the rigid frame is subjected to lateral load, a compressive strut of concrete is formed in the joint. And the longitudinal bars in the beams, which are anchored in the joint, are recommended to cross the compressive strut in the joint. However, the anchorage of longitudinal bars may be out of the compressive strut when the exterior joint is subjected to bi-directional loads; therefore there is a fear that actual strength of the beam may be the lower than calculation. A rational design method is necessary, which can evaluate performance of anchorage, effects of transverse bars in the joint, and torsion moment at the joint.

An objective of this experimental study is to examine a stress transfer mechanism in the corner column and beams joint when the beams yield in flexure, which the flexural strength of the column is a little larger than that of the beams. Three corner column and beams joint specimens of almost half scale were prepared for tests, and were subjected to static cyclic loads. The each of the specimens had a column of a story height and two beams of half a span. The beams were jointed at the centre of the column width. The column had 300 x 300 mm square section, and was subjected to shear load in diagonal direction of the section. The two beams had width of 150 mm and depth of 300 mm, and were subjected to vertical load mutually in the other direction. Calculated flexural strengths of columns were about 1.15 times larger than those of beams in all the specimens. Parameters of the test were diameter of longitudinal bars in the beams, which deformed bars of D13 and D16 were employed, and ratio of calculated shear strength of joint part to calculated flexural strength of the beam, which the aimed ratios were 0.7 and 1.5. The calculated shear strength of joint wasn't taken effect of transverse bars in the joint into account; therefore the strength is shear resistance of concrete. The stress transfer mechanism in the corner joint was considered based on the test results.

## 2. EXPERIMENTAL PROGRAM

### 2.1. Dimension of Specimens and Loading Setup

In this test, three specimens of corner column and beams joints were prepared. As shown in Fig. 2.1, all of them had identical column and beam sections those were 300 x 300 mm and 150 x 300 mm, respectively.

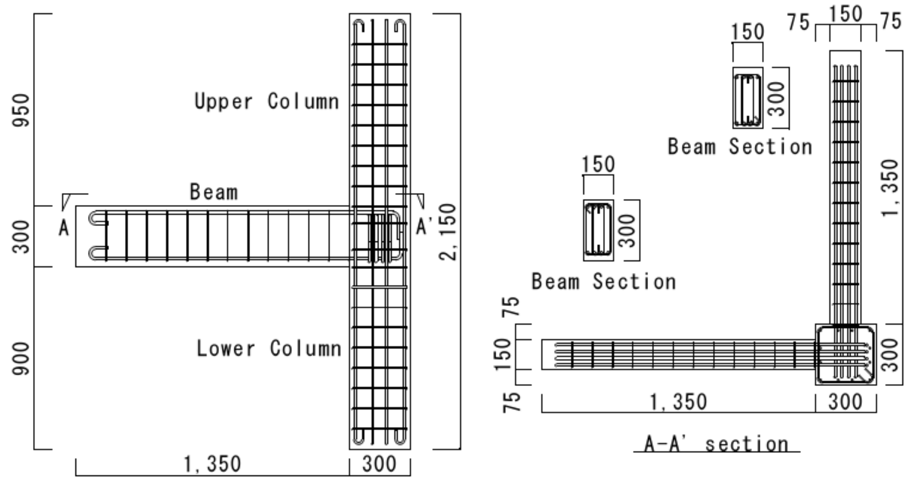



**Figure 2.1.** Dimension of Specimen [EXJ-D3 for bar arrangements]

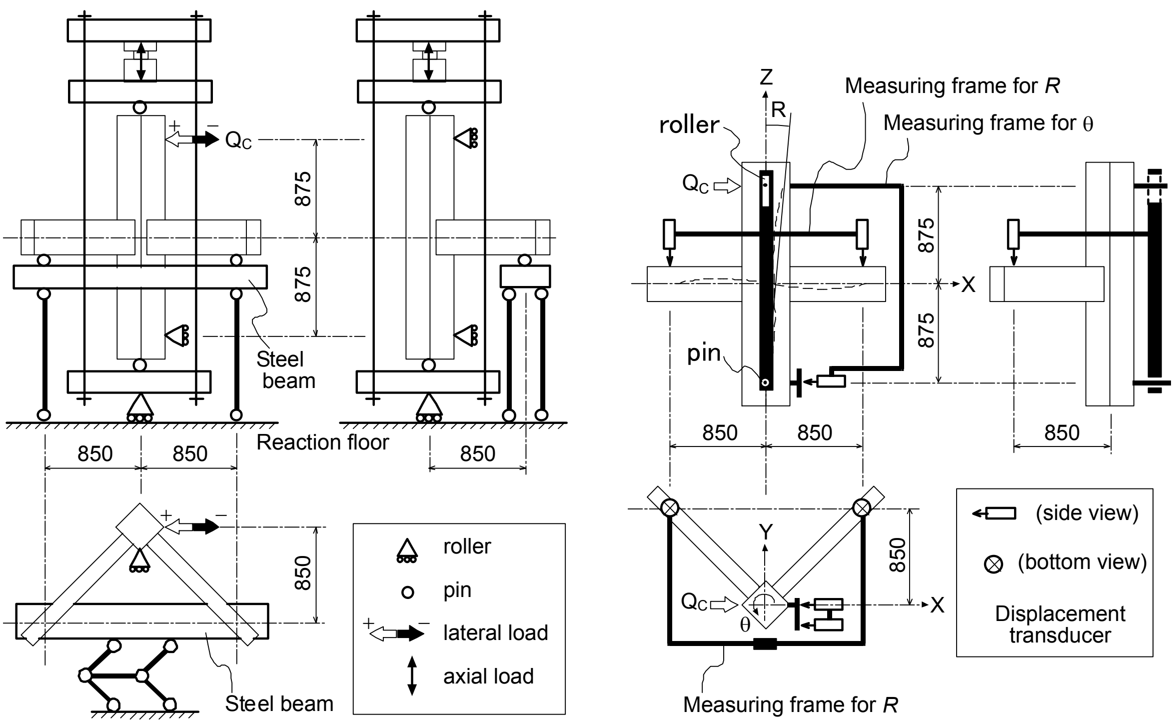


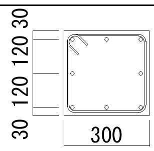
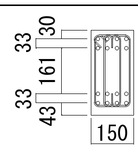
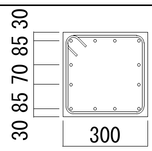
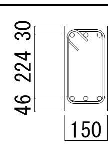
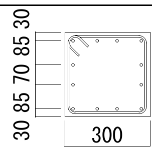
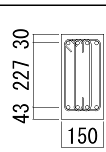
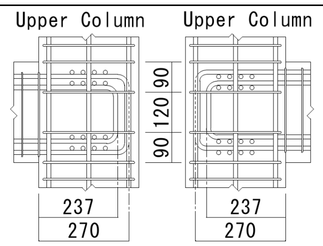
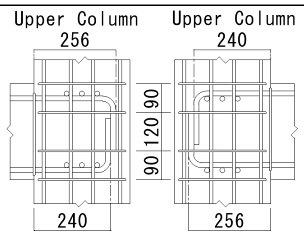
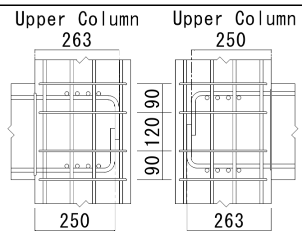

**Figure 2.2.** Loading Setup and Measuring System

Fig. 2.2 shows loading setup and measuring systems. The column was applied lateral load and axial load with actuators, and the two beams were supported with a steel beam that translate horizontally and is restricted rotation and vertical translation. A story drift angle, $R$, was measured with displacement transducers, which were fixed on a measuring frame supported with pin and roller at inflection points of the column. A frame for measuring a rotation angle around the column axis between the inflection points of the column, which was $\theta$, was fixed at those points of the column. Strain gages were pasted on longitudinal bars at the fix end section in one side of the column and one side of the beam, and square shaped transverse bars in the joint on the centres of four sides. The strain gages on the longitudinal bars in the column and the beam were located 25 mm apart from a beam face and a column face, respectively.

## 2.2. Parameters and Loading Plan

Table 2.1 and Table 2.2 show detail of the specimens and mechanical properties of deformed bars. Concrete strengths were about 34 N/mm$^2$. The detail of joint in Table 2.1 shows arrangement of reinforcements and anchorage length of longitudinal bars in the beams.

**Table 2.1.** Detail of Specimens

| Name of specimens | EXJ-D1 | | EXJ-D2 | | EXJ-D3 | |
|---|---|---|---|---|---|---|
| $F_C$ *1 [N/mm$^2$]<br>$E_C$ *2 [N/mm$^2$] | 33.6<br>2.6 x $10^4$ | | 34.7<br>2.5 x $10^4$ | | 34.9<br>2.6 x $10^4$ | |
| Part | Column | Beam | Column | Beam | Column | Beam |
| Section |  |  |  |  |  |  |
| Longitudinal bar<br>($p_g$ *3 or $p_t$ *4 [%]) | 8-D13<br>(1.1) | 2x8-D13<br>(2.7, 2.8) | 12-D10<br>(0.95) | 2x3-D16<br>(1.8, 1.6) | 12-D10<br>(0.95) | 2x4-D13<br>(1.3, 1.3) |
| Shear reinforcing bar ($p_w$ *5 [%]) | □-D6@50<br>(0.42) | ▥-D4@50<br>(0.75) | □-D6@100<br>(0.21) | □-D6@100<br>(0.42) | □-D6@100<br>(0.21) | ▥-D4@100<br>(0.37) |
| Axial load [kN]<br>($\eta$ *6) | 302<br>(0.1) | N/A | 109<br>(0.035) | N/A | 78.5<br>(0.025) | N/A |
| Reinforcing bar in joint | 2x□-D6 | | | | | |
| Detail at joint [mm] |  | |  | |  | |

*1: compressive strength of concrete cylinder, *2: 1/3 secant modulus of concrete,
*3: gross reinforcement ratio of column, *4: tensile reinforcement ratio of beam, *5 shear reinforcement ratio,
*6: ratio of axial load divided by product of section area and $F_C$.

**Table 2.2.** Mechanical Properties of Deformed Bar

| Name of deformed bar | D4 | D6 | D10 | D13 | D16 |
|---|---|---|---|---|---|
| Nominal section area [mm$^2$] | 14.05 | 31.67 | 71.33 | 126.7 | 198.6 |
| Yield strength [N/mm$^2$] | 357* | 347* | 336 | 353 | 317 |
| Tensile strength [N/mm$^2$] | 490 | 475 | 491 | 505 | 466 |
| Yong's Modulus [x$10^5$ N/mm$^2$] | 2.1 | 1.9 | 1.7 | 1.9 | 1.9 |

*: 0.2 % offset method.

Fig. 2.3 shows parameters of this experiment. The parameters of the tests were diameter of longitudinal bars in the beams and ratio of calculated shear strength of joint part to calculated flexural strength of the beam. Therefore arrangements of longitudinal bars in the beams were different to adjust the ratios of the calculated strengths, which the specimens EXJ-D1, EXJ-D2, and EXJ -D3 had ratios of 0.72, 1.46, and 1.65, respectively. The shear strength of the joint were calculated according to AIJ Guidelines (Architectural Institute of Japan (call AIJ below) 1999), which was not taken an effect of shear reinforcements into account and was an elliptical interpolation of two calculated shear strengths of the joint in planes of structures perpendicular to each other. The deformed bars in the beams of the specimens EXJ-D1, EXJ-D2, and EXJ-D3 were D13, D16, and D13, respectively. The specimen EXJ-D2 had thicker longitudinal bars in the beam than the other two specimens.

The calculated flexural strengths of columns were about 1.15 times larger than those of beams in the three specimens. In order to adjust this ratio constant, axial loads acted on the columns were different among the three specimens, as shown in Table 2.1. The calculated strength of the column was reduced to 0.85 times lower than the strength around principal axis of the R/C column section (AIJ 1999). Ratios of transverse bars in the columns and beams of the specimens were designed not to fail in shear against flexural strength in the each member according to AIJ Standard (AIJ 2010).

Fig. 2.4 shows a loading plan of the three specimens. Turns of loading path were numbered with parentheses. Allowable strengths in Fig. 2.4 were calculated according to AIJ Standard (AIJ 2010).

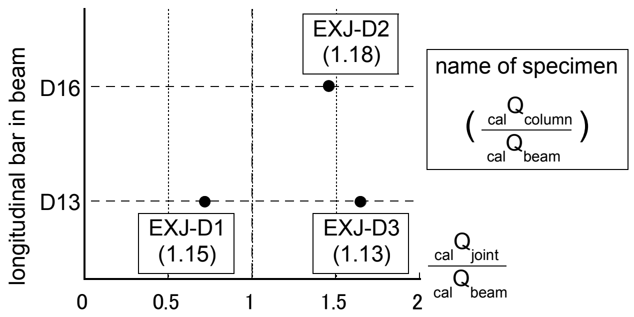



**Figure 2.3.** Parameters

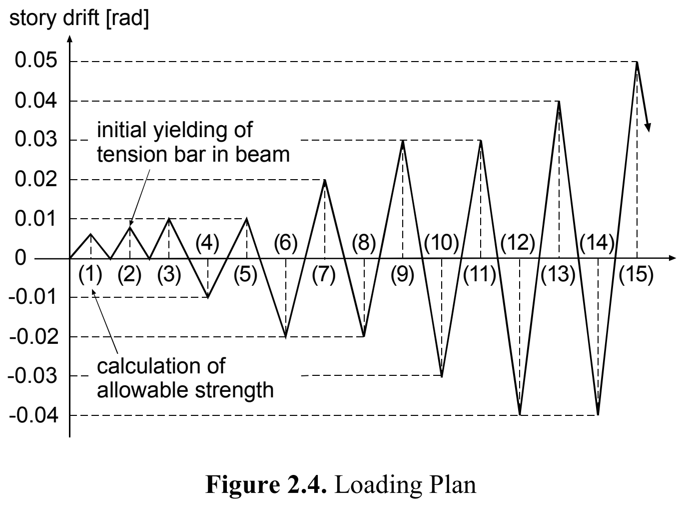



**Figure 2.4.** Loading Plan

## 3. TEST RESULTS

### 3.1. Specimen EXJ-D1

Fig. 3.1 shows relationship between shear load on column and story drift. As shown in this Figure, at a story drift of 0.01 rad, the specimen showed the larger resistance than calculated shear strength of the joint. The peaks of load in both positive and negative side followed yielding of longitudinal bars in beams, which were at story drifts of 0.03 rad and -0.02 rad. After that, the specimen didn't keep its strength under larger displacement, and hysteresis loops became narrow and pinching. Fig. 3.2 shows rotation around the column axis and a photo after the test. Fig. 3.3 shows strains of shear reinforcements in the joint. In Fig. 3.3, horizontal axis expresses time history; a label in lower axis means the loading path those numbers are corresponded with Fig. 2.4; a label in upper axis means story drifts those are corresponded with the turns of loading path shown in Fig. 2.4. The strains reached about 0.5% at a point of loading path of (6) that corresponded to a story drift of -0.02 rad. Shear cracks on a surface of the joint became more visible at this moment. Then, as shown in Fig. 3.2, the specimen showed large rotation around the column axis, and the joint considerably damaged. It can be said that failure of EXJ-D1 was resulted from damage at the joint.

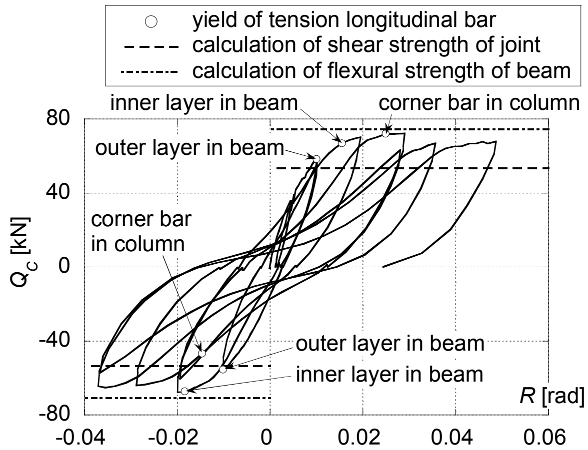



**Figure 3.1.** Shear Load on Column – Story Drift Curve [EXJ-D1]

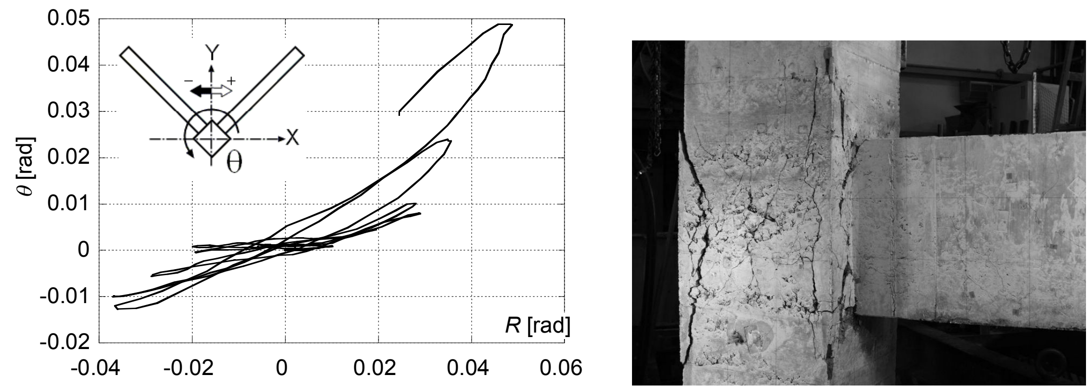



**Figure 3.2.** Rotation around Column Axis and Photo after the Test [EXJ-D1]

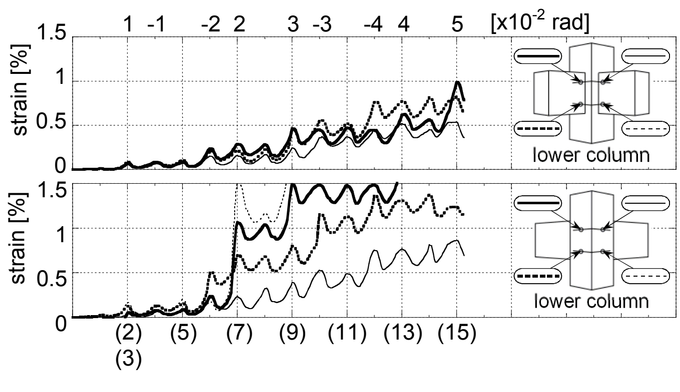



**Figure 3.3.** Strains of Shear Reinforcements in Joint [EXJ-D1]

### 3.2. Specimen EXJ-D2

As shown in Fig. 3.4, which is shear load on the column and story drift curve, strength of this specimen showed good agreement with calculated flexural strength of the beam. The specimen showed large area of hysteresis loops up to cyclic displacement of 0.02 rad. After that, the hysteresis loop became narrower. This change corresponded with increasing of rotation around the column axis and strains of shear reinforcements in the joint, as shown in Fig. 3.5 and 3.6. Finally, decrease of the lateral load followed increase of the rotation around the column axis, and the joint considerably damaged as shown in Fig. 3.5. It can be said that EXJ-D2 yielded in flexure of the beams, and its failure was resulted from damage at the joint under large displacement.

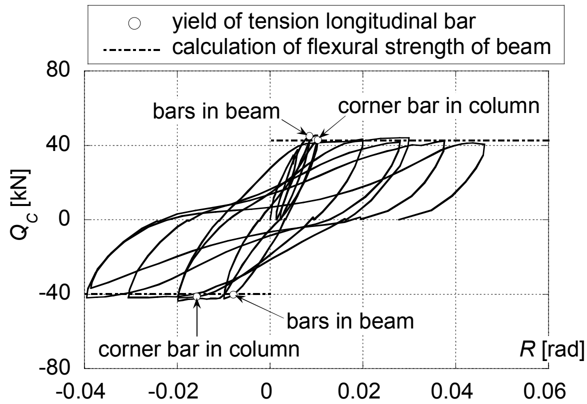



**Figure 3.4.** Shear Load on Column – Story Drift Curve [EXJ-D2]

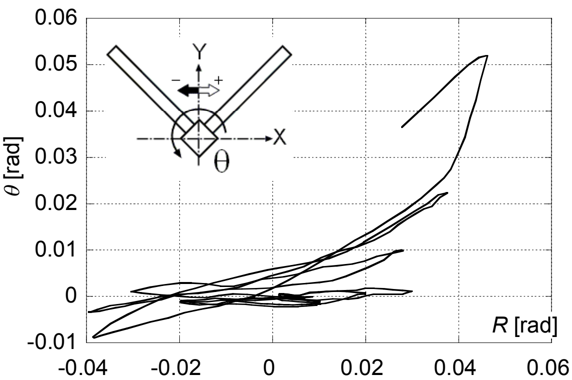



**Figure 3.5.** Rotation around Column Axis and Photo after the Test [EXJ-D2]

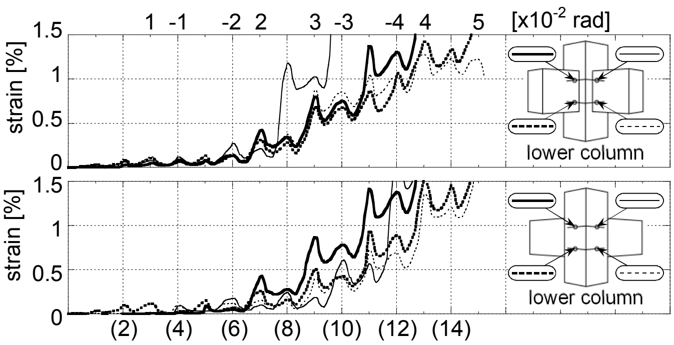



**Figure 3.6.** Strains of Shear Reinforcements in Joint [EXJ-D2]

### 3.3. Specimen EXJ-D3

Fig. 3.7 shows shear load on the column and story drift curve of EXJ-D3. The specimen showed good agreement with calculated flexural strength of the beam and good hysteresis loops to the end of loading. Fig. 3.8 shows rotation around the column axis and a photo after the test. Fig. 3.9 shows strains of shear reinforcements in the joint. The rotation around the column axis was less than 0.01 rad, and the strains of shear reinforcements were less than 0.5 % until cyclic story displacement of amplitude of 0.04 rad. The photo in Fig. 3.8 shows slight damages at the joint. It can be said that EXJ-D3 yielded in flexure of the beams, and showed the typical restoring force characteristics of flexural yielding.

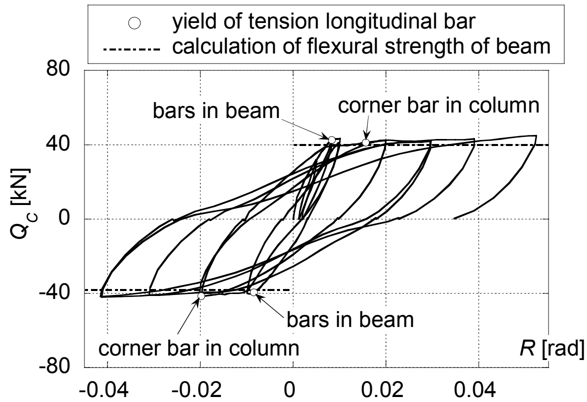



**Figure 3.7.** Shear Load on Column – Story Drift Curve [EXJ-D3]

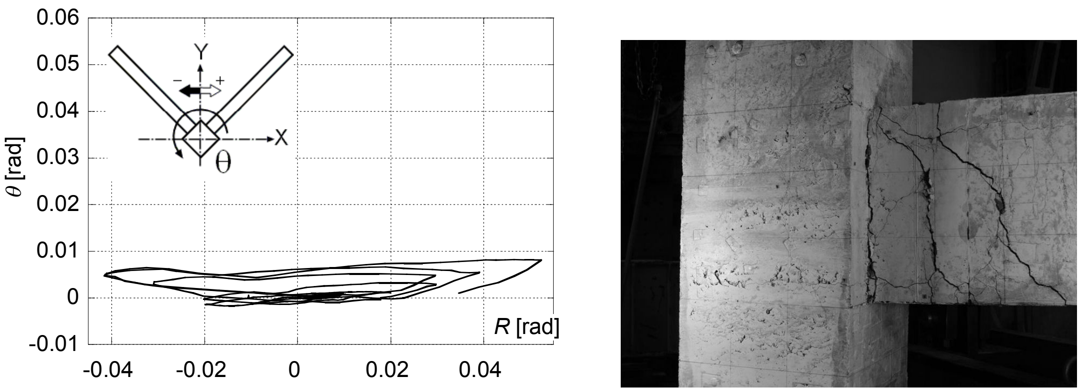



**Figure 3.8.** Rotation around Column Axis and Photo after the Test [EXJ-D3]

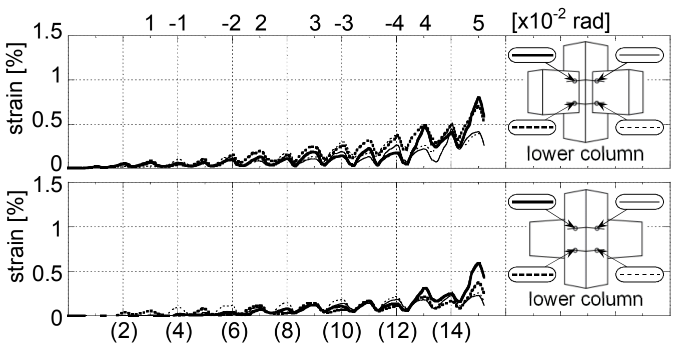



**Figure 3.9.** Strains of Shear Reinforcements in Joint [EXJ-D3]

## 4. CONSIDERATIONS

### 4.1. Evaluation of Strength

As mentioned above, the strengths of specimens EXJ -D2 and EXJ-D3 can be evaluated with calculation of the flexural strength of the beam, and the specimens reached their strength at the story drift of about 0.01 rad. Regarding the strength of specimen EXJ-D1, the maximum value was resulted from yield of longitudinal bars in beam. However, large deformations were needed to reach the maximum those were 0.03 rad in positive side and -0.02 rad in negative side. Moreover, the failure of this specimen was resulted from damage at the joint.

It is necessary to examine the strength of EXJ-D1 from the viewpoint of structural design. Specifically, the following points must be considered: damages at the joint are undesirable; calculation of the shear strength of the joint is not taken effects of shear reinforcements into account (AIJ 1999 and AIJ 2010); it is better to evaluate the strength of column-beam joint assembly at almost the same deformation level as the other type of failures such as flexural failure of beam or column. Considering deformation at the moment when the specimens EXJ-D2 and EXJ-D3 yielded in flexure, the story drift of 0.01 rad can be an index for evaluating strength of the column and beam joint specimens in this test. And, at this moment, the damage at the joint was slight because the strains of shear reinforcements were less than 0.2 % that meant almost elastic range. Moreover, the strains considerably increased under larger displacement than 0.01 rad. It is appropriate to compare the resistance at 0.01 rad with calculated shear strength of the joint, and those showed good agreement as shown in Fig. 3.1. Therefore, it can be said that the strength of the joint part can be evaluated by traditional method that is an elliptical interpolation of two calculated shear strengths of the joint in planes of structure perpendicular to each other.

### 4.2. Effects of Thick Deformed Bar

The specimens EXJ-D2 and EXJ-D3 had almost the same calculated strength of beam and the same ratios of calculated strengths of joint and column to calculated strength of beam (see Fig. 2.3). The parameter for these two specimens was diameter of deformed bars in the beams. The deformed bars in EXJ-D2 were thicker than those in EXJ -D3 (see Table 2.1 and Fig. 2.3). The specimens EXJ-D2 and EXJ-D3 had the ratios of calculated strength of joint to beam of 1.46 and 1.65, respectively.

The restoring force characteristics were almost agreed between these specimens until cyclic displacements of 0.02 rad amplitude. After that, the strains of shear reinforcements in the joint and rotation around the column axis of EXJ-D2 increased as shown in Figs. 3.5 and 3.6, and narrowing and pinching of hysteresis loops followed as shown in Fig. 3.4. And then the joint part considerably damaged as shown in the photo in Fig.3.5. It can be said, when deformed bars of large diameter are employed for longitudinal bars in beam, the joint can damage under large cyclic displacement even if calculated shear strength of the joint is 1.5 times lager than calculated flexural strength of the beam.

### 4.3. Behaviours after Damage at Joint

Usually, exterior joint of a single beam tend to shows narrow loop because of slipping at anchorage. However, in this test, all the specimens showed large loops until the joint part damaged, and behaviours of slipping at the anchorages couldn't be seen in the loops as shown in Figs. 3.1, 3.4, and 3.7. I can be considered that longitudinal bars in a perpendicular beam effected as anchorage reinforcements against tension of longitudinal bars in the beam of the other side. This effect must be examined in detail in future.

The significant results could be seen in this experiment that the damage at the joint caused a considerable lowering of stiffness against torsion around the column axis. Because the corner columns were located away from the centre of stiffness against torsion on floor plans in general, the lowering of stiffness against torsion around the column axis can result unexpected large displacement by a torsion response of a frame structure.

## 5. CONCLUSIONS

Three corner column and beams joint specimens were prepared for static cyclic loading tests, which two beams were jointed to the column perpendicular to each other. The columns and the beams had square and rectangle sections, respectively. Lateral load was applied on the column in diagonal direction of the column section as the two beams were subjected to vertical force mutually in the other direction. The parameters of the test were diameter of longitudinal bars in the beams and ratio of calculated shear strength of joint part to calculated flexural strength of the beams. The calculated flexural strengths of columns were about 1.15 times larger than those of beams in these three specimens. As results, the following conclusions could be found.

1. Strength of a joint part can be evaluated by traditional method that is an elliptical interpolation of two calculated shear strengths of the joint in planes of structure perpendicular to each other.

2. When deformed bars of large diameter are employed for longitudinal bars in beam, the joint can damage under large cyclic displacement that makes hysteresis loops narrow even if calculated shear strength of the joint is 1.5 times lager than calculated flexural strength of the beam.

3. Longitudinal bars in a perpendicular beam can effect as anchorage reinforcements against tension of longitudinal bars in the other beam.

4. The damage at the joint part causes a considerable lowering of stiffness against torsion around a column axis.

**ACKNOWLEDGEMENT**
This work was supported by KAKENHI (23760519, Grant-in-Aid for Young Scientists (B), the Japan Society for the Promotion of Science (JSPS)). The materials for this experiment, cement and PC steel bars, were presented from TAIHEIYO CEMENT CORPORATION and NS HOKKAI SEISEN Co., Ltd., respectively. The authors acknowledge all these supports.

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