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TESTS OF REINFORCED CONCRETE INTERIOR BEAM-COLUMN JOINT SUBASSEMBLAGE WITH ECCENTRIC BEAMS

Fumio KUSUHARA[1], Keiko AZUKAWA[2], Hitoshi SHIOHARA[3] and Shunsuke OTANI[4]

SUMMARY

Eccentric beam-column joints are used in construction for a reinforced concrete exterior moment resisting frame in buildings. But the effect of the eccentricity on the behavior of joint is not well known, due to lack of test results. So three specimens of one third scale reinforced concrete interior beam-column subassembladges were constructed and loaded to failure by statically cyclic load simulating earthquake, to obtain fundamental data including three dimensional deformation of beam-column joint. The test results indicated that the eccentricity in the joints led to lower capacity in story shear and severe damage of concrete on the side to which the center line of beam shifted to. Increasing in the joint shear reinforcement on the side of beam shifted to was not effective to mitigate the concentration of concrete damage at large displacement reversals, whereas it was effective to reduce the crack width at the small story drift loading stages. In the case of eccentric joint, large deflection to out-of-plane direction occurred and it seemed to have accelerated the concrete damage on the side of the joint the beams shifted to.

INTRODUCTION

The design of beam-column joints is an important part of earthquake resistant design for reinforced concrete moment-resisting frames. Because of difficulty in repairing and retrofitting of the buildings damaged in beam-column joints due to the seismic attack and structural importance, recent building codes for reinforced concrete buildings (e.g. [1], [2]) provides allowable joint shear stress to preclude premature failure of beam-column joints before beam sway mechanism is developed.

Although the eccentricity of the axes of the beam from the column may lead beam-column joint to poor performance due to the torsional forces in column induced from beams connected to the column eccentrically, eccentric beam-column joints are frequently used for moment resisting exterior frame in buildings to get aligned outside surface of beam and joint in the construction practice. Current design code provisions [1][2] consider the effect of joint eccentricity on the joint strength by reducing the

[1] Research Associate, The University of Tokyo, Japan. E-mail: kusuhara@rcs.arch.t.u-tokyo.ac.jp
[2] Graduate Student, The University of Tokyo, Japan.
[3] Associate Professor, The University of Tokyo, Japan. E-mail: shiohara@rcs.arch.t.u-tokyo.ac.jp
[4] Professor, Chiba University, Japan. E-mail: shunsuke.otani@faculty.chiba-u.jp

effective area of joint. Using the effective area is simple and convenient way but is not based on the mechanics in the joints.

The information of the effect of the joint eccentricity on the strength, ductility and damage control performance are limited except several research works including one by Susanto et al [3]. So three specimens of one third scale reinforced concrete interior beam-column subassembladges of crucial form were constructed and loaded to failure by statically cyclic load with increasing amplitude simulating earthquake, to obtain fundamental data including three dimensional deformation of beam-column joint. This paper reports the test result and discusses the effect of the eccentricity in beams.

TEST PROGRAM

Specimen and Design Parameter

Three one third scale reinforced concrete interior beam-column subassembladges JE-0, JE-55 and JE-55S were tested. They are designed such that their failure should be of beam sway mechanism with flexural yielding of beam ends, based on the AIJ Guidelines. Amount of beam bars were chosen so that the joint shear demand is as high as possible within the allowable for joint shear stress specified in the AIJ Guidelines.

Test parameters are (a) with or without the eccentricity of beam and (b) amount of joint shear reinforcement. The specimen JE-0 is the joint without eccentricity in beam, while the specimen JE-55 and JE-55S have eccentric beams. In JE-55 and JE-55S, the center line of beams was shifted to the east side by 55 mm from the center line of columns. The ratio of the amount of eccentricity to the width of the joint is 0.17. The effective areas of beam-column joint calculated by the rule of AIJ Guidelines are same in all the specimens. So the joint shear capacity calculated with the AIJ Guidelines is the same for all specimens.

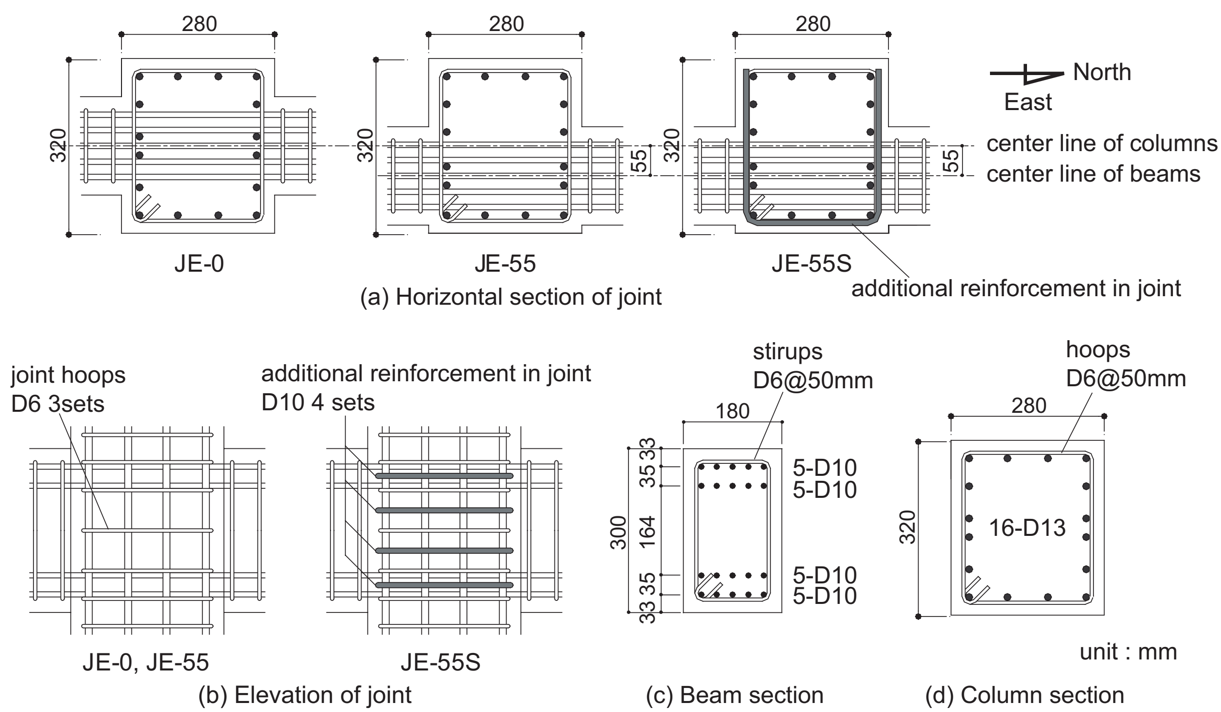

Figure 1: Geometry and reinforcing details of specimens

The specimens JE-0 and JE-55 used conventional reinforcing detail for joint core confinement. Three sets of hoops of D6 were placed in beam-column joint; the amount of joint shear reinforcement is 0.3 %, which is the minimum requirement of the AIJ Guidelines. In the specimen JE-55S, amount of joint shear reinforcement is increased with four sets of D10 bars shaped C (See Fig. 1) only in the side beams shifted to. All the other properties are common for JE-0, JE-55 and JE-55S. The cross section of the columns and beams were 320x280 mm and 180x300 mm respectively. Five D10 bars were arranged on the first and second layer at the top and bottom of beam section respectively. Reinforcements in the columns are 16-D13 bars.

Material

Normal portland cement concrete with design compressive strength of 18 MPa was used. The average compressive strength of the concrete was 27.0 MPa by cylinder test. The SD345 steel was used for longitudinal bars in columns and beams while SD295 steel was used for hoops and additional joint shear reinforcement in the specimen JE-55S. The mechanical properties of the concrete and deformed bars are listed in Table 1 and Table 2.

Table 1: Mechanical properties of concrete

Compressive Strength (MPa)	Young's modulus (GPa)	Tensile Strength (MPa)
27.0	28.7	2.38

Table 2: Mechanical properties of steel

Reinforcing Bars		Sectional Area (mm^2)	Yield Point (MPa)	Tensile Strength (MPa)	Young's modulus (GPa)
D6	SD295	32	364*	510	182
D10	SD295	71	359	502	188
D10	SD345	71	387	542	193
D13	SD345	127	345	485	194

* 0.2% offset strength

Test Setup, Loading Sequence and Measurement

The loading set up is shown in Fig. 2. The specimens were supported in vertical position. Statically cyclic lateral load was applied at the top of the column. A servo-controlled hydraulic actuator was used to apply the load. The beam ends were supported by horizontal rollers, while the bottom of column was supported by mechanical hinge. In case of JE-55 and JE-55S, the columns were supported at the center line of beams to avoid eccentric loading in the out-of-plane direction (See Fig. 2 (b)). The distance between two loading points for beams and columns were 2,700 mm and 1,470 mm respectively. Horizontal cyclic load was applied by displacement control with the horizontal actuator with capacity of 200 kN. As the columns were not supported at the center of them, no vertical load was applied to avoid additional moment in the out-of-plane direction by axial load in columns.

The load history is shown in Fig. 3. After the cycles of 0.125% story drift and 0.25% story drift, two cycles of the same amplitude in story drift were repeated before each displacement amplitude was increased from story drift of 0.5% to 6.0%.

Each specimen was instrumented to monitor applied displacement, loads, the resulting strains and deformation with emphasis on joint deformation. The system for measuring three dimensional joint deformations is explained in Appendix.

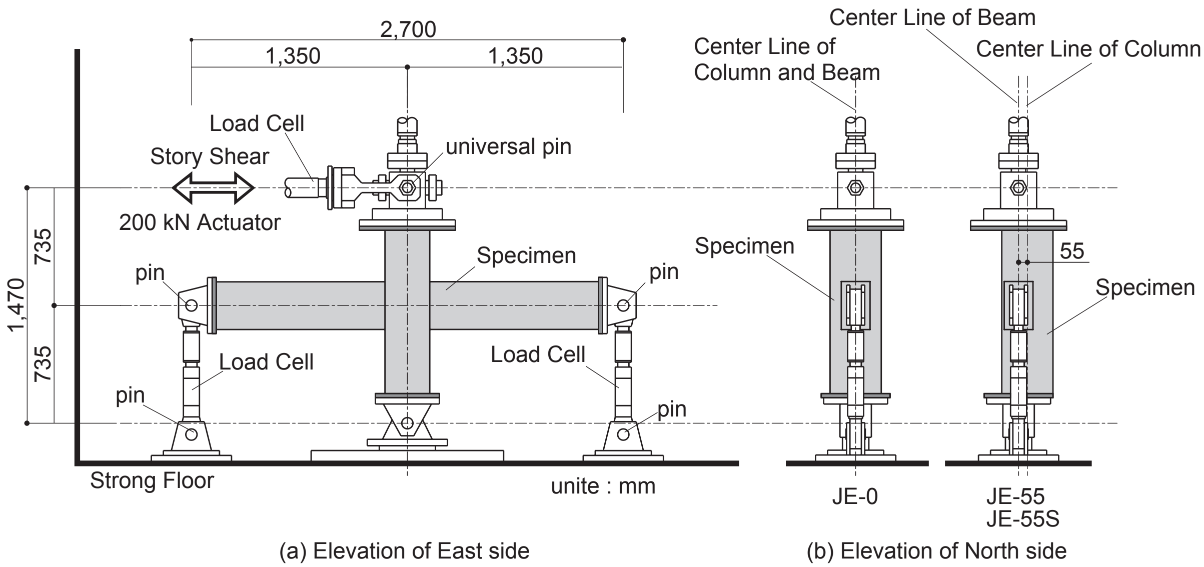

Figure 2: Loading System

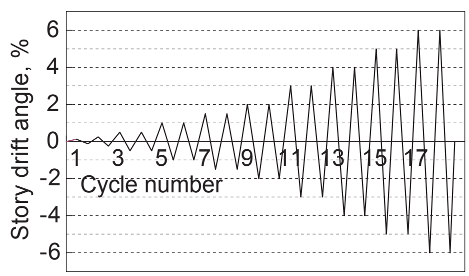

Figure 3: Loading history of story drift

TEST RESULTS AND DISCUSSION

Development of Cracks

The cracking patterns in the joint of each specimen at story drift of 1 %, 3 % and 6 % is shown in Fig. 4. Cracking started on the both side of joint panel during the third cycle with the story drift of 0.5 % in specimen JE-0 and JE-55. In specimen JE-55S, cracking started on the east side, to which the center line of beam shifted to, only at story drift of 0.5 %, while cracking on the west side started at the story drift of 1 %. As the story drift increased, number of cracks increased and extended to the column regions in all specimens. In the specimen JE-55 and JE-55S, cracking caused by torsional forces started on the north and south side at the seventh cycle with story drift of 1.5 %. Concrete crushing started at the center of the joint on the east side in eccentric joints at the ninth cycle with the story drift of 2 %, while the other side had only minor cracks during whole the tests. In specimen JE-0, the specimen without eccentricity of beam, concrete crush in the joint occurred on the both side of the joint at 15th cycle with the story drift of

5 %, but the damage was not so severe as the joint with eccentricity. Comparing JE-55 and JE-55S, increasing in the joint shear reinforcement was not effective to mitigate the concentration of concrete damage at the final stage of the loading with large displacement reversals (See Fig. 4 (b) and (c)). However, it was effective to reduce the crack width at the loading stages before beams yield (See Fig. 4 (a)).

Story Shear-Story Drift Relation

Story shear-story drift relation for specimen JE-0, JE-55 and JE-55S are compared in Fig. 5. Maximum story shear was attained at first cycle of 3 % story drift. Attained maximum story shear was 93.9 kN, 88.9 kN and 91.5 kN for specimen JE-0, JE-55 and JE-55S respectively. The strength of the specimen JE-55, with eccentric beams, was 94 % of that of the specimen JE-0, without eccentricity in beams. The strength of the specimen JE-55S, with eccentric beams and increased joint shear reinforcement, was improved to 97 % of that of the specimen JE-0. At the story drift of 1 %, some of the tensile reinforcement in beams yielded at the column face in all specimens. Yielding of bars in columns occurred at the story drift of 2 %. All the specimens show a degradation of story shear and pinching loops due to joint shear deformation.

The envelope curves of story shear and story drift relations are plotted in Fig. 6(a). The behavior of all the specimens is similar. No sudden degradation of story shear was observed in all specimens. At 6 % story drift, the story shear was kept 74 %, 67% and 75% of maximum strength for specimen JE-0, JE-55 and JE-55S respectively.

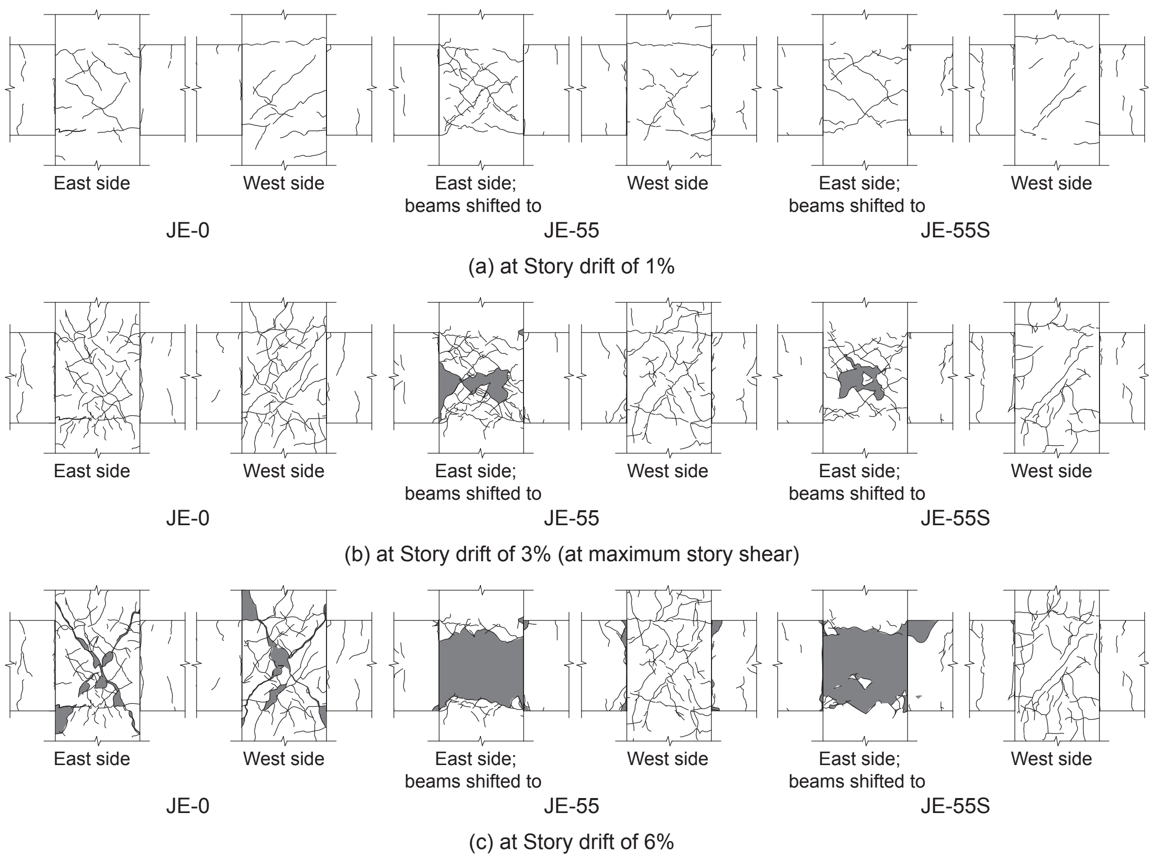

Figure 4: Observed crack pattern

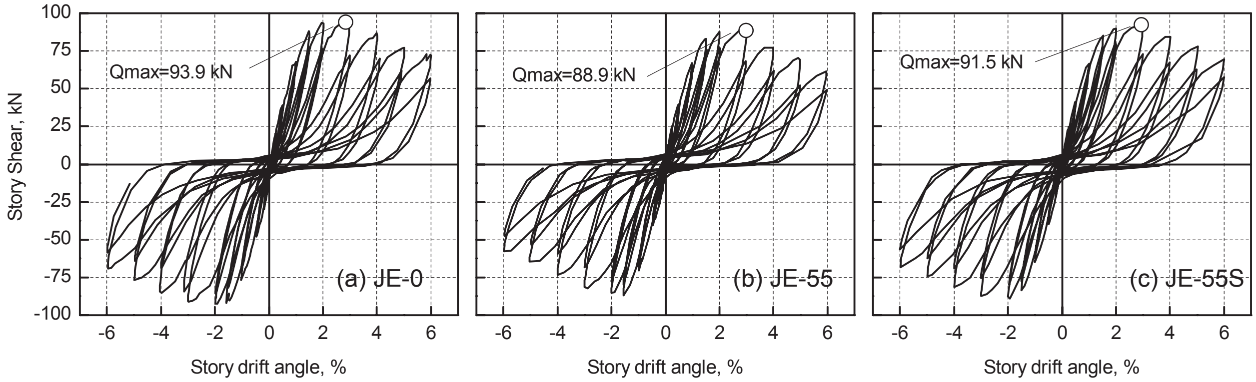

Figure 5: Story shear-story drift relation

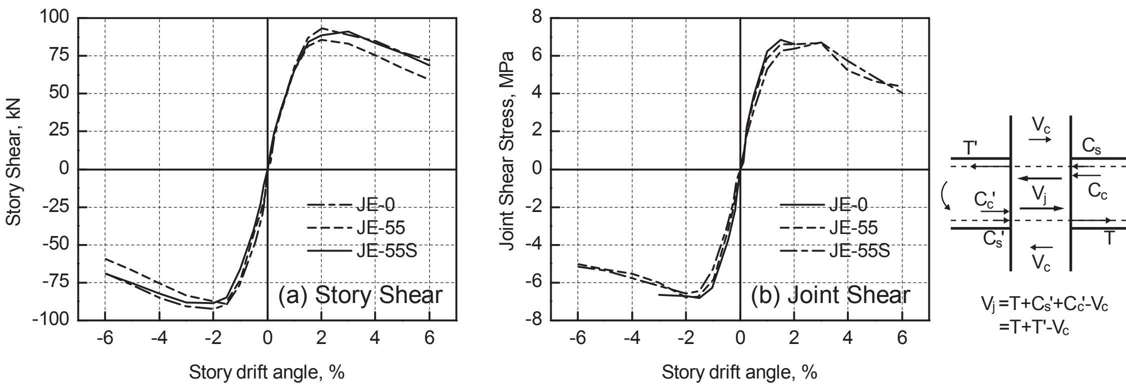

Figure 6: Comparison of story shear and joint shear

Joint Shear-Story Drift Relation

The envelope curves of joint shear-story drift relation for specimen JE-0, JE-55 and JE-55S are compared in Fig. 6(b). Joint shear was calculated with Eq.(1). The Ramberg-Osgood curve, modified by adding a linearly elastic stage and yield plateau, was used to evaluate the stress of beam longitudinal bars from the strains monitored by strain gauges.

$$V_j = T + T' - V_c = a_t f_s + a_t' f_s' - V_c \qquad (1)$$

where, V_j : joint shear force, V_c : column shear force, T and T': tensile forces in steel, a_t and a_t': sectional area of tensile reinforcement, f_s and f_s': stress in steel. Joint shear force V_j was divided by effective area of beam-column joint calculated by the rule of the AIJ Guidelines to obtain the joint shear stress.

Maximum joint shear stress was almost 25 % of the compressive strength of concrete. The joint shear was kept less than 75 % of maximum stress at the story drift of 6 % for the specimen JE-55 and JE-55S.

Predicted and Observed Story Shear

Table 3 compares the calculated and observed strengths. The story shear at flexural yield or ultimate strength of beams and columns were calculated by the flexural theory using mechanical properties of materials (See Table 1 and 2). Story shear at maximum joint shear strength was calculated assuming that the length of moment lever arm is equal to 7/8 of effective depth of beam and joint shear is equal to joint shear strength specified in the AIJ Guidelines. The observed maximum strengths are almost equal to the predicted story shear at ultimate strength of beam but a little smaller than calculated strength in the specimens with eccentricity, and which is 71% of the calculated story shear at joint failure. The first yielding of longitudinal bars in beams and columns were occurred at smaller story shear than predicted.

Table 3: Calculated and observed story shear

Specimen		JE-0	JE-55	JE-55S
Story shear at yielding of beam bars at first layer (kN)	calculated	83.2		
	observed	63.8	56.0	63.2
Observed story shear / Calculated story shear		0.77	0.67	0.77
Story shear at yielding of column bars at first layer (kN)	calculated	91.1		
	observed	82.6	77.2	74.7
Observed story shear / Calculated story shear		0.91	0.85	0.81
Calculated story shear (kN)	at ultimate strength of beam	91.9		
	at ultimate strength of column	153		
	at joint failure	129		
Calculated maximum story shear (kN)		91.9		
Observed maximum story shear (kN)		93.9	88.9	91.5
Observed story shear / Calculated story shear		1.02	0.97	0.99

Joint Shear Deformation

The joint shear strain calculated from diagonal deformation of joint panel is plotted against story drift in Fig. 7. Detail of calculation of the deformation is explained in Appendix. The increase in joint shear deformation of specimen JE-0 was accelerated after 3 % story drift. In the specimen with eccentric beams, JE-55 and JE-55S, the joint shear deformation is much larger on the east side, to which the beams shifted to, and rate of increase was accelerated after story shear drift reached 2 % at which concrete crushing also started on the east side of the joints. On the contrary, observed joint deformation on the west side was very small. There was no clear difference between the specimen JE-55 and JE-55S.

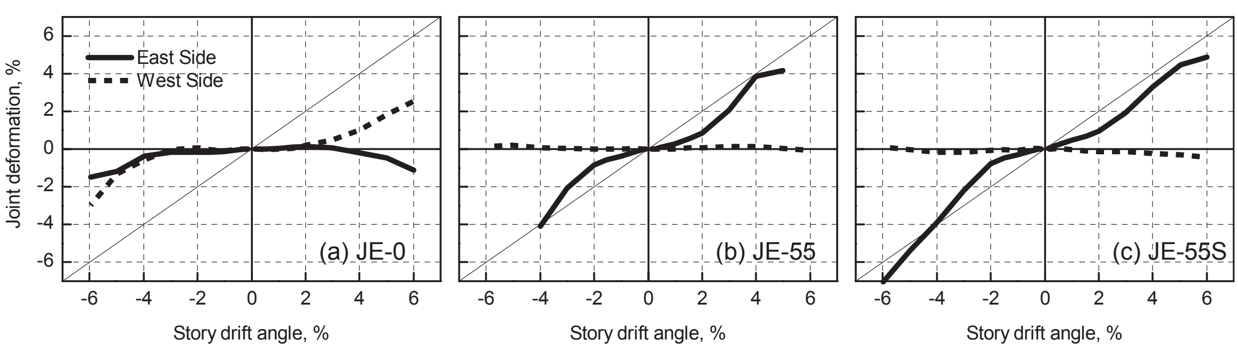

Figure 7: Joint shear deformation on East and West side

Torsional rotations of joint and beams

Figure 8 shows the observed torsional rotations of the joints and beams caused by torsional moment. Detail of calculating the deformation is explained in Appendix. In the specimens with eccentricity, JE-55 and JE-55S, the torsional rotation in joints rapidly increased after story drift of 1.5 %. And the difference of the shear deformation on the east and the west side may be attributed to the torsional rotation. The observed torsional rotation of beams increased after story drift of 2.0 %.

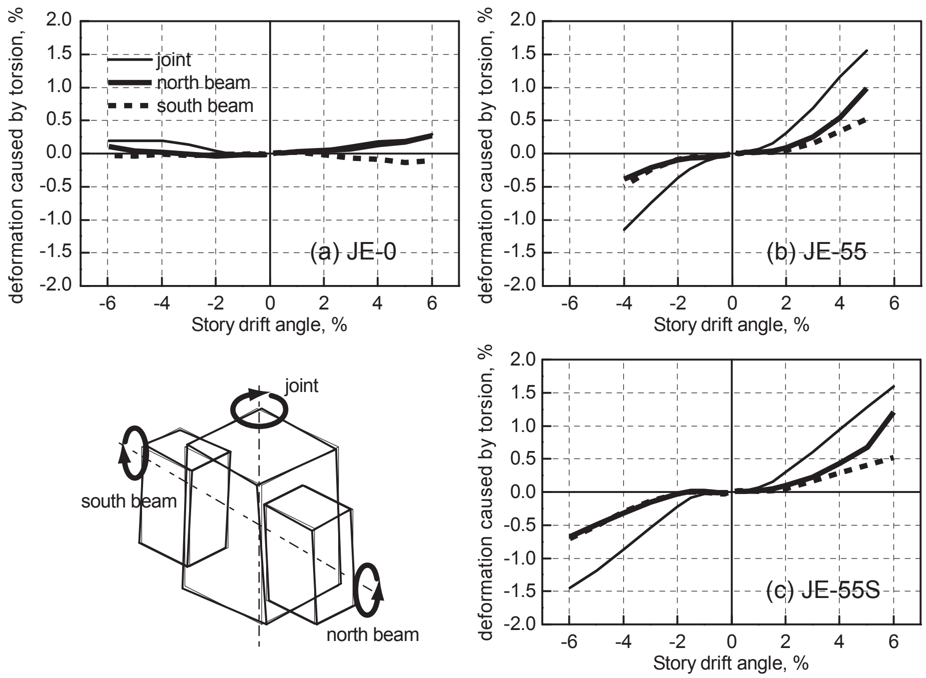

Figure 8: Torsional rotation of joint and beams

Stress in the beam reinforcement and anchorage capacity

The stress distribution in the longitudinal bars of beams is shown in Fig. 9. The stress was calculated from the strains measured by strain gauges. The degradation of anchorage resistance in beam bars passing the joint occurred in all specimens as story deformation increased. Thus, the compressive stress in compressive reinforcement bars decreased and changed to tension. In the specimen JE-55 and JE-55S, the stress of tensile reinforcement on the west side is larger than that of the east side. In other words, the stress of tensile reinforcement in eccentric beams is smaller on the side to which the beams shifted. The stress in compressive bars changed to tension earlier on the west side, which is the far side from the face the beams shifted to. On the east side of the joints with eccentric beams, the stress at the column face decreased after 3 % story drift.

Figure 10 shows attained maximum bond stress in the beam longitudinal bars passing the joint. The bond stress was calculated from the axial stress in bars at the both faces of the column. The average of observed maximum bond stress in cases of that the stress was tension at north side and cases of tension at the south side is plotted. The attained bond stress in second layer was within 40 to 70 % of in first layer in all specimens. In the bars at corner; the both side of first layer, the bond capacity was smaller than that at the middle of beam width. And furthermore, the bond capacity was smaller at the side the beams sifted to in the specimens with eccentric beams.

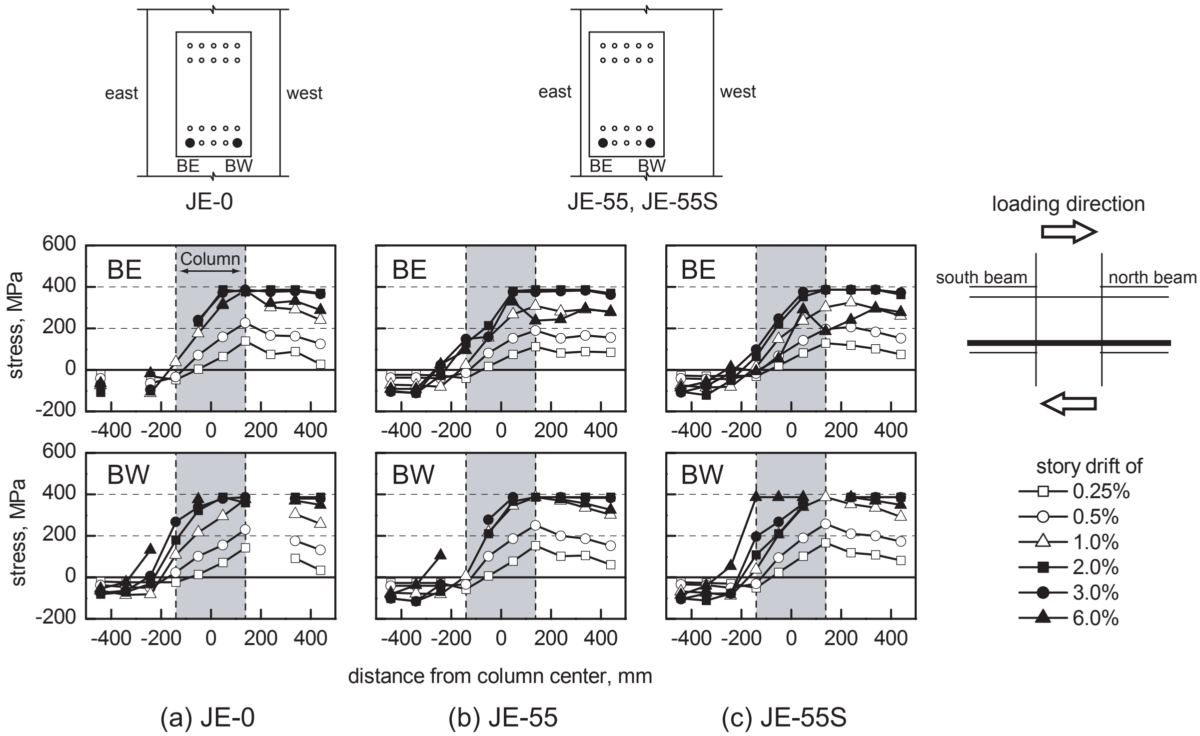

Figure 9: Stress distribution in beam bars

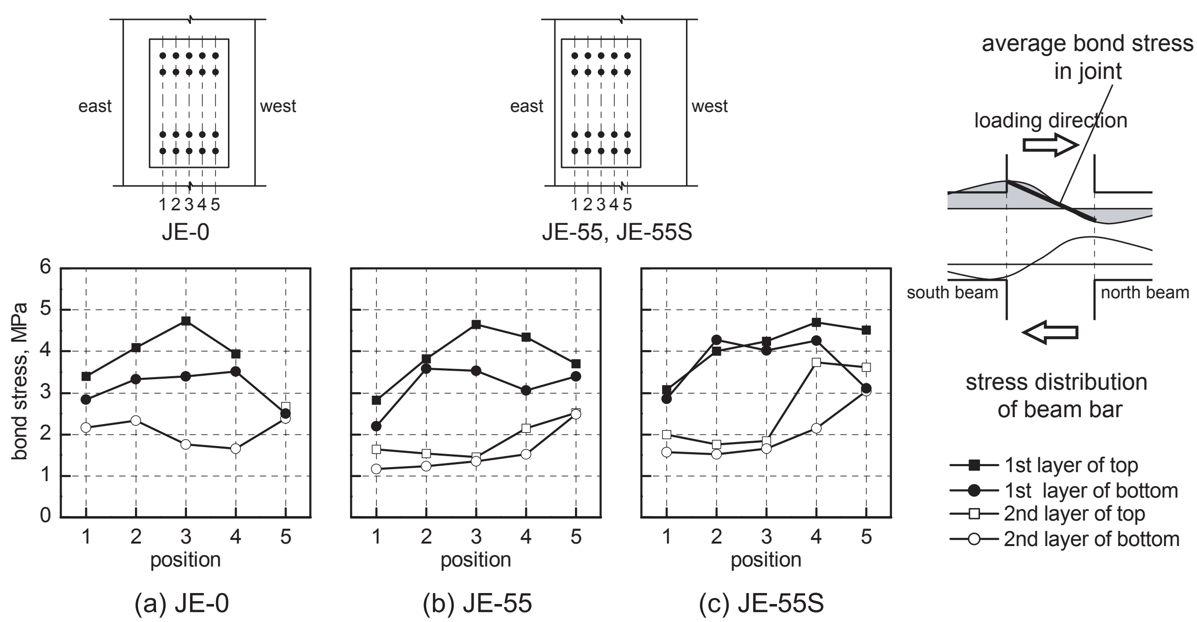

Figure 10: Maximum bond stress in beam bars passing the joint

Strain in the column reinforcement

The strains measured by strain gauges in column longitudinal bars at beam face are shown in Fig. 11. The eccentricity influenced a lot. In other words, in the specimen with eccentric beams, JE-55 and JE-55S, the strains in bars on the side to which the beam shifted were larger than on the opposite and yielding occurred earlier. In the joints with eccentric beams, joint deformation was larger on the side beams shifted to and it caused large stress on that side even in columns.

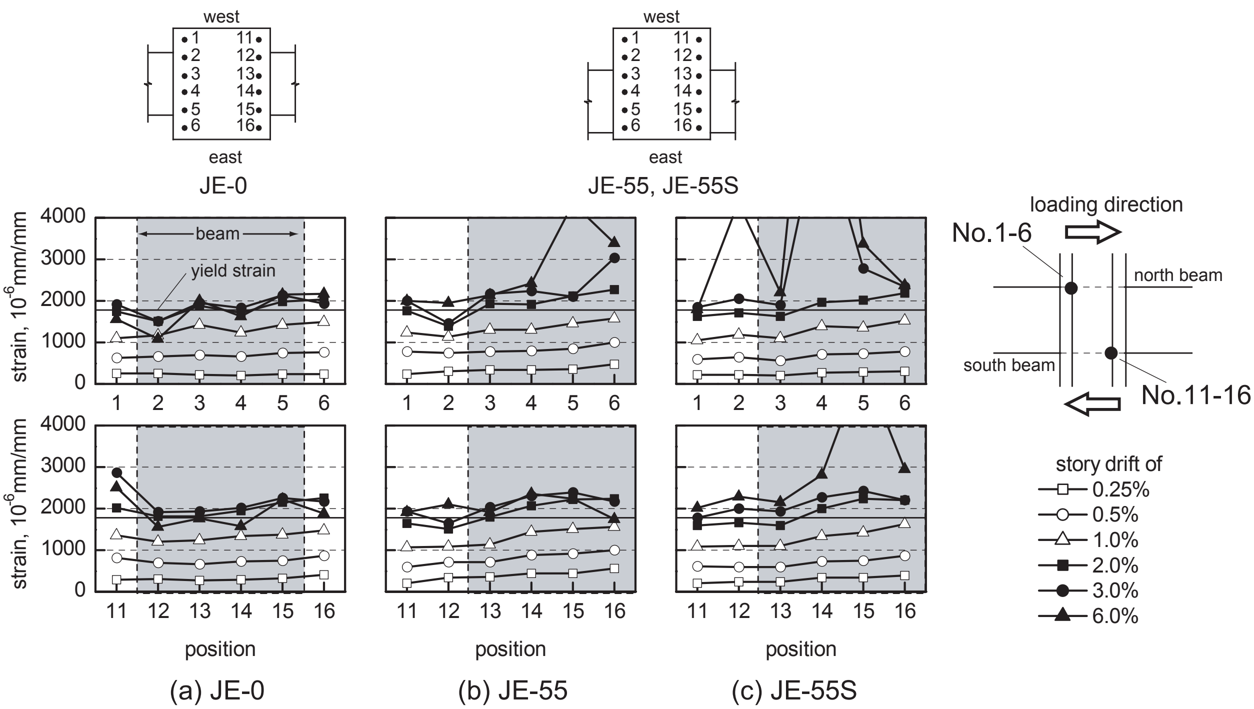

Figure 11: Strain in column bars at the beam face

Strain in the joint shear reinforcement

The strains in joint shear reinforcements are shown in Fig. 12. The strains were measured by strain gauges at all of the three sets of hoops and four sets of C shaped additional reinforcement bars in the specimen JE-55S. The plotted values are their averages. In the specimen JE-0, without eccentricity, the strains were large on the east and west side and reached yield strain at the story drift of 3 %.

In the specimen JE-55, the joints with eccentricity and without additional reinforcement in joint, the strains in hoops started to increase on the east and west side after diagonal cracks observed at the story drift 0.5 %. After the cracks due to the torsional forces observed on north and the south side at 1.5 % of story drift, the strains rapidly increased on the west, north and south side, while strains started to decrease on the east side. This means that internal force in concrete due to the torsional forces was taken over by hoops after cracks observed. The hoops yielded first on the west side and next on the north and south side at the loading cycle to 2.0 % of story drift. In the specimen JE-55S, the strains were smaller than in JE-55 except for on the west side, on which reinforcement was not increased, due to the additional reinforcement. The strains in the additional reinforcement in the specimen JE-55S were not large and did not reach yield strain.

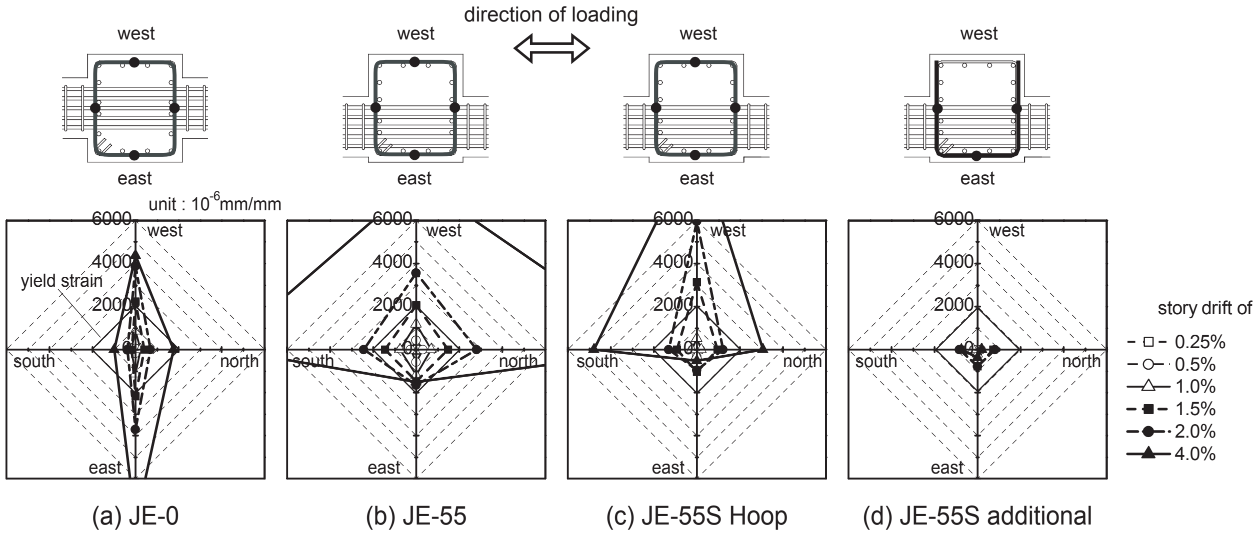

Figure 12: Strain in joint shear reinforcement

Deflection of beams to out-of-plane direction

Large deflection of beams to out-of-plane direction was observed in the specimens with eccentric beams, JE-55 and JE-55S. Displacement to out-of-plane direction of the north and south beams and the lower column relative to the east side of the upper column was measured. For the north and south beam the deformation angle of deflection to out-of-plane direction and story drift relations are plotted in Fig. 13. The definition of the deformation is shown in Fig. 13. The deformation of the joints in horizontal plane is also plotted. In the specimen JE-0 without eccentricity, the deformation was quite small. On the contrary in the specimens with eccentric beam, JE-55 and JE-55S, the rate of increase in deflection of beams was larger.

The difference between specimen JE-55 and JE-55S were observed in the joint deformation. In the specimen JE-55, the direction of joint deformation at the small story drift stage was that led the beams deformed to the west side. It means the crack width on the east side of the joint increased while the crack width on the other side is small. After the story drift reached 3 %, the direction of deformation changed to opposite due to the beginning of concrete crushing on the east side. In the specimen JE-55S with increased reinforcement in the joint, that deformation at the small story drift stage was not observed as a consequence the increasing reinforcement reduced the crack width on the east side.

Hence, if the eccentric beam-column joint has a slab which restricts the deflection of the beams to the out-of-plane direction, large compressive stress would not be generated in the concrete on the side to which beams shifted to and it may reduce the damage in concrete. It may also decrease strain in the joint hoops on the side to which beams shifted to. It also would lead to the smaller stress in longitudinal bars in beams on the side to which beams shifted to. Therefore it may conclude that slab is effective to mitigate the damage of eccentric beam-column joints.

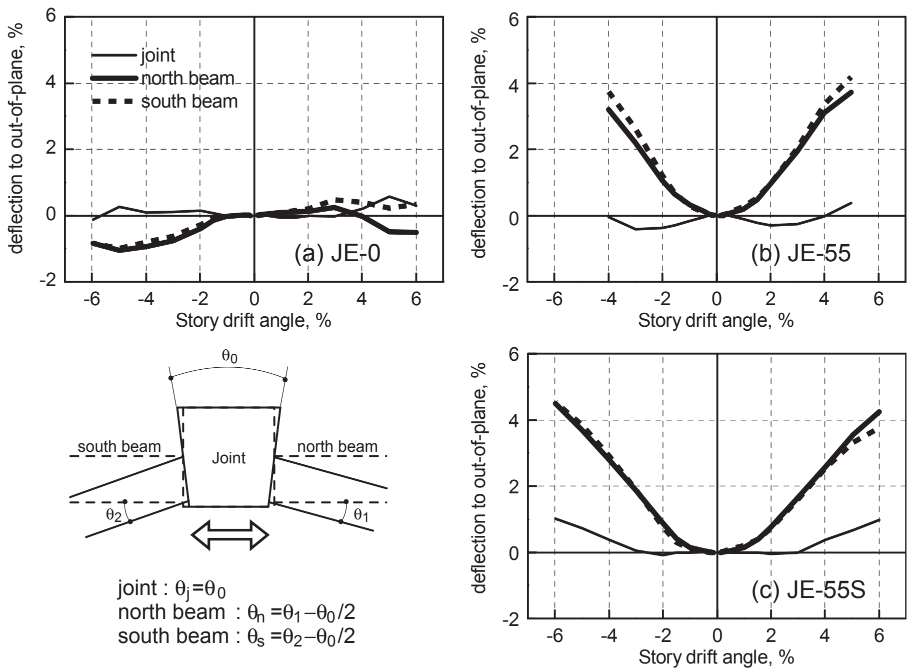

Figure 13: Deflection of beams to out-of-plane direction

CONCLUSIONS

A test of reinforced concrete interior beam-column joints was carried out in order to identify the effect of the eccentricity in beam-column joints, including three dimensional deformation of beam-column joint. The test results indicated that the eccentricity in beams led to (1) decreasing story shear capacity to 94 % of that of the joint without eccentricity in beam, (2) severer concrete damage in the joint on the side to which the center line of beam shifted to, while the other side had little damage except minor cracks and (3) large strain in the joint hoops on the side perpendicular to the direction of applied load. Increasing the joint shear reinforcement with additional bars (4) improved story shear capacity of the joint with eccentric beams to 97 % of that of the joint without eccentricity in beam and (5) was not effective to mitigate the concentration of concrete damage at large displacement reversals, however it was effective to reduced the crack width at the loading stages before beams yield. In addition to that, (6) test of an eccentric beam-column joint without slabs may cause larger deflection to out-of-plane direction which causes severer concrete damage in joint than that without slab.

REFERENCES

1. Architectural Institute of Japan, "Design Guidelines for Earthquake Resistant Reinforced Concrete Buildings Based on Inelastic Displacement Concept", 1997 , (in Japanese).
2. American Concrete Institute, "Building Code Requirements for Structural Concrete (ACI 318-02) and Commentary (ACI 318R-02)", 2002
3. Susanto Teng and Hua Zhou, "Eccentric Reinforced Concrete Beam -Column joints Subjected to Cyclic Loading", ACI Structural Journal, March-April 2003, pp.139-147

APPENDIX: MEASURMMENT OF DEFORMATION IN JOINTS

The system measuring joint deformation is shown in Fig. A1. The displacements were measured by displacement transducers of type CDP. Notations for deformations are in Fig. A2

Joint shear deformation, γ

Join shear strain was calculated as follows with observed displacement d_9, d_{10}, d_{13} and d_{14}.

on the east side : $$\gamma_e = \frac{\sqrt{a^2+b^2}}{2ab}\left(\Delta d_{10} - \Delta d_9\right)$$

on the west side: $$\gamma_w = \frac{\sqrt{a^2+b^2}}{2ab}\left(\Delta d_{14} - \Delta d_{13}\right)$$

Torsional rotation, θ_T

Torsional rotation at beams and columns caused by torsional moment were calculated as follows with observed displacement d_1, d_2, d_3, d_4, d_5 and d_6. The reference point of deformation is the center of the joint on the east side.

at the column: $$\theta_{Tc} = \left(\frac{\Delta d_4 - \Delta d_3}{L_3}\right)\Big/2$$

at the north beam: $$\theta_{Tnb} = \frac{\Delta d_5 - \Delta d_6}{D_c} - \frac{\left(\Delta d_3 + \Delta d_4\right)/2}{L_3}$$

at the south beam: $$\theta_{Tsb} = \frac{\Delta d_1 - \Delta d_2}{D_c} + \frac{\left(\Delta d_3 + \Delta d_4\right)/2}{L_3}$$

Deflection to out-of-plane direction

Deflection of beams to out-of-plane direction was calculated as follows with observed displacement d_1, d_2, d_3, d_4, d_5 and d_6. The reference point of deformation is the center of the joint on the east side. The deformation in horizontal plane of the joint is also calculated.

in the joint: $$\theta_j = \theta_0 = \frac{\left(\Delta d_{11} + \Delta d_{12}\right)/2 - \left(\Delta d_7 + \Delta d_8\right)/2}{b_c}$$

in the north beam: $$\theta_{nb} = \theta_1 - \frac{\theta_0}{2} = \frac{-\left(\left(\Delta d_5 + \Delta d_6\right)/2 - \frac{\left(\Delta d_3 + \Delta d_4\right)/2}{2}\right) + \theta_{Tc}\frac{L_1}{2}}{L_2} - \frac{\theta_j}{2}$$

in the south beam: $$\theta_{sb} = \theta_2 - \frac{\theta_0}{2} = \frac{-\left(\left(\Delta d_1 + \Delta d_2\right)/2 - \frac{\left(\Delta d_3 + \Delta d_4\right)/2}{2}\right) - \theta_{Tc}\frac{L_1}{2}}{L_2} - \frac{\theta_j}{2}$$

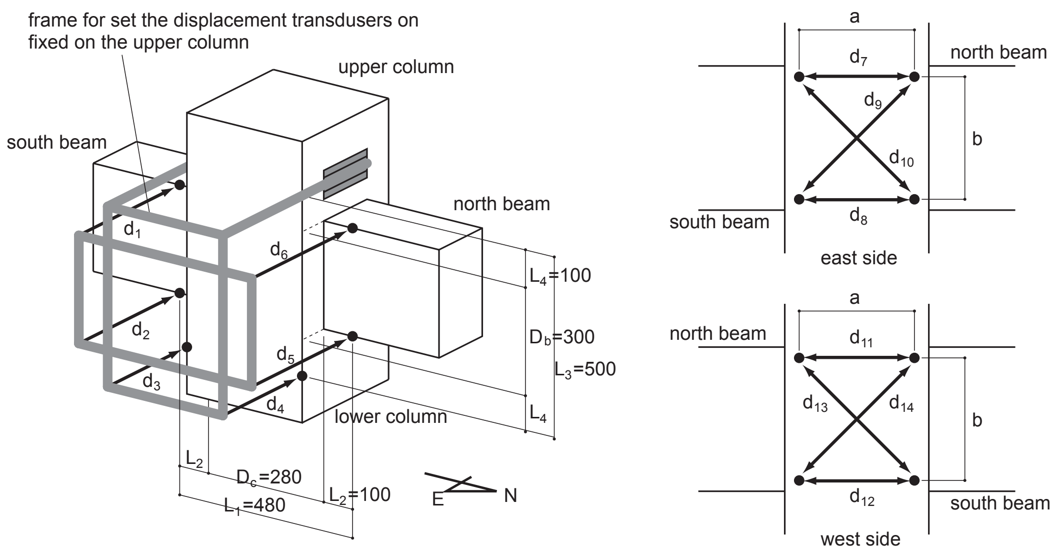

Figure A1: Instrumentation for joint deformation

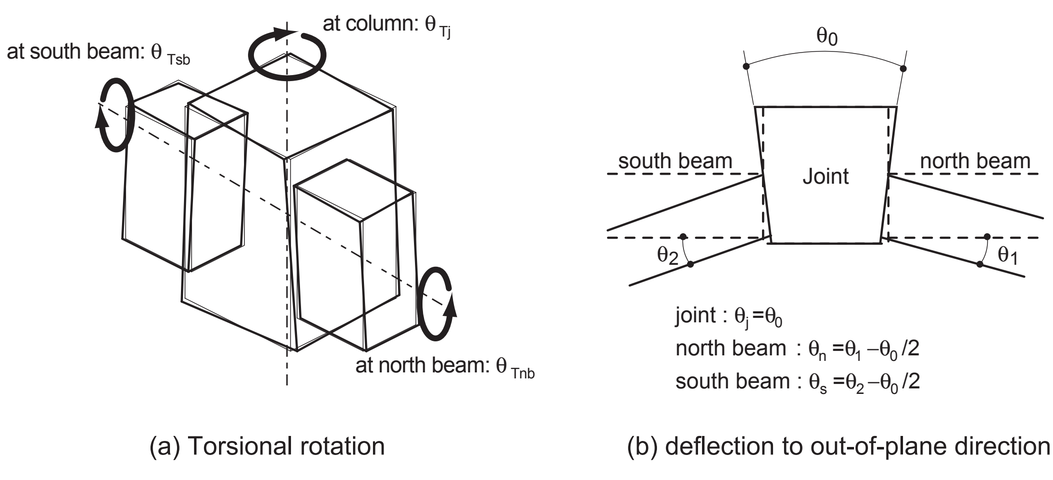

Figure A2: Notations for joint deformation