FEM ANALYSIS OF THREE-DIMENSIONAL INTERACTION OF RC FRAMES SUBJECTED TO MULTI-DIRECTIONAL CYCLIC LOADING

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ABSTRACT :

Structural behavior of beam-column joints in a RC frame under seismic loadings differs from RC beam-column joints as subassemblies because neighboring members affect each other. The effects of beam's eccentricities on the seismic performances of RC beam-column joints are investigated by 3-D nonlinear FEM Analysis. The verification of experimental results is conducted using FEM analysis. It is indicated that the torsion effects of beam-column joints caused by eccentricities is restrained more, if the contact area of slabs on the joint panel is larger.

KEYWORDS: reinforced concrete, frame, beam-column joint, eccentricity, seismic performance, FEM

1. INTRODUCTION

The seismic design provisions for beam-column joints in the AIJ Guidelines are based on earlier experimental studies. However it is necessary to establish a more rational performance evaluation design for joints under two directional seismic forces. This can be accomplished by analytical study. In order to understand quantitatively progression of damages in concrete and reinforcement of a joint, accumulated absorbed strain energy of concrete and reinforcement elements is calculated from the analytical results.

2. ANALYTICAL PROGRAM

The correct analytical prediction of energy absorbed by structural elements is necessary to assure the limitation of inelastic displacement.. The target of the analytical model is to simulate the hysteretic behavior of the structural elements correctly. In this study, more realistic analysis models such as a transition hysteresis model for concrete especially in tension-compression regions, a multi-curves model for reinforcement, and a hysteresis model for shear characteristics of cracked concrete are incorporated into the 3-D nonlinear FEM analysis programs developed by the authors (**Yu and Noguchi(2004)**). The structural behavior of RC members under cyclic shear, such as the tangent stiffness for unloading and reloading, slip stiffness, residual strain and the deterioration, can be simulated more precisely. The revised FEM analytical program is useful to clarify the 3-D mechanisms of strength degradation of structural elements subjected to multi-directional cyclic shear and flexure and also investigate the effects of strength degradation of RC structural elements on the structural performance.

Each member and the other surrounding members react on each other in a building structure. As one of such an interaction effects of 3-D frames, the confining effects of slabs and lateral beams are considered to give torsional effects on the beam-column joint in the frame. It is difficult to grasp the interaction of each member by the test or analysis of a single isolated member.

As the real seismic behavior, structural frames and beam-column joints of RC buildings are subjected to arbitrary multi-directional loads. The realistic loading hysteresis like four-leaves clover-type, quadrilateral type or circular orbit-type was used for recent beam-column joint test in Japan. These loading hysteresis are more realistic than conventional one-directional or two directional loading.

In this study, two storied frame was selected for objectives of the 3-D FEM analysis, because the boundary condition of beam-column joints is close to a real building. As for the interaction effects, the effects of slabs and eccentric lateral beams on the joint shear strength were investigated. Moreover, the 3-D FEM analysis of RC solid beam-column joint subjected to multi-directional loading was carried out, and the multi-directional loading effects were investigated.

3. ANALYTICAL SPECIMENS

There are few studies where 3-D structural behavior of beam-column joints was investigated especially about the interactions between structural members. **Kawaguchi and Hayashi (2002)** carried out a cyclic loading test on a two story and two span frame, and studied on the effects of beam eccentricities on neighboring members. In this study, three-dimensional FEM analysis is conducted for three RC frames, tested by **Kawaguchi and Hayashi (2002)**, with eccentric beam-column joints using different eccentricities as a parameter. The objective of this study is to investigate the agreement between the experiment and analysis, internal stress state and structural behavior to evaluate seismic performances. The experimental parameter is the modulus of beam-eccentricity, and the beam axis of specimen has an eccentricity of 40mm from the column centre in inside or outside direction as shown in Fig. 1. Specimen N-e00 is a non-eccentric joint, Specimen I-e40 is an inside eccentric joint and Specimen O-e40 is an outside eccentric joint. The size of the specimen is 1/7 of a real size. The height of column is 400mm and the span of a beam is 850mm. The cross-section of a column is b×D=160×120mm, with four main reinforcement of D10 (SD295A) and lateral reinforcement of U5.0 (p_w=0.4%) with a space of 30mm. The cross-section of a beam is b×D=60×100mm. with four main reinforcement of SD10 (SD295A) and lateral reinforcement of φ4.3 (p_w=0.8%) with a space of 30mm. The characteristics of materials used in the experiment are shown in Table-1. The cross- section and bar arrangement of columns and beams are shown in Table-2. The loading method is shown in Fig. 2. The reversed cyclic loads were given to the loading beam using the displacement control of one cycle each of R=±1/400 and R=±1/200 and two cycles each after R=±1/100.

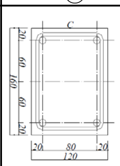
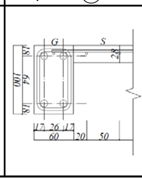
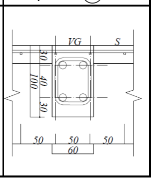
4. ANALYTICAL METHODS

As for the constitutive law, an orthogonal anisotropy model was used. This model was based on the

Table-1 Material Characteristic

Reinforcement			
Sort		Yeild Strength (N/mm^2)	Young Coefficient (N/mm^2)
Main Reinforcement		345	1.80×10^5
Hoop		1270	2.06×10^5
Stirrup		1020	1.75×10^5
Slub Bar		530	2.09×10^5
Concrete			
Specimen		Stress Strength (N/mm^2)	Young Coefficient (N/mm^2)
N-e00	Two-Story	21.2	1.67×10^4
	One-Story	23.8	1.63×10^4
	Stub	42.9	2.17×10^4
I-e40	Two-Story	22.1	1.68×10^4
	One-Story	23.4	1.68×10^4
	Stub	42.5	2.25×10^4
O-e40	Two-Story	22.9	1.69×10^4
	One-Story	23.1	1.72×10^4
	Stub	42.0	2.34×10^4

Table-2 Cross-Section and Bar Arrangement

Members	Column	Beam	orthogonal beams
Cross-Section	160×120	60×100	60×100
Main Reinforcement	4-D10	4-D10	4-D10
Tie	U5.0@30	ϕ4.3@30	ϕ4.3@30
Figure			

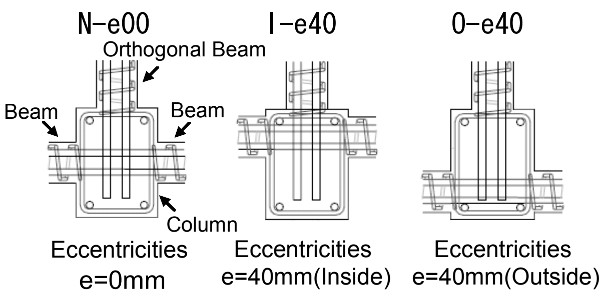


Fig.1. Experimental Parameter

equivalent uniaxial strain developed by **Darwin and Pecknold (1990)** and expanded to three-dimensional field. As for the stress-strain relationships of concrete, **Saenz (1964)** equation was used, and as for the compressive strain softening zone, the **Kent and Park (1982)** model was used. The tension stiffening effect of concrete was represented by the **Sato and Shirai (1978)** model. Reinforcement element was represented by a 2 nodes line element, and a bilinear model was used for stress-strain relationships. As for bond stress-bond slip relationships between bars and concrete, the **Morita and Kaku (1975)** model was used. In this analysis, bond-link elements were set between reinforcement and concrete to represent bond behavior. The characteristics of materials used in this analysis are the same as those of the experiment.

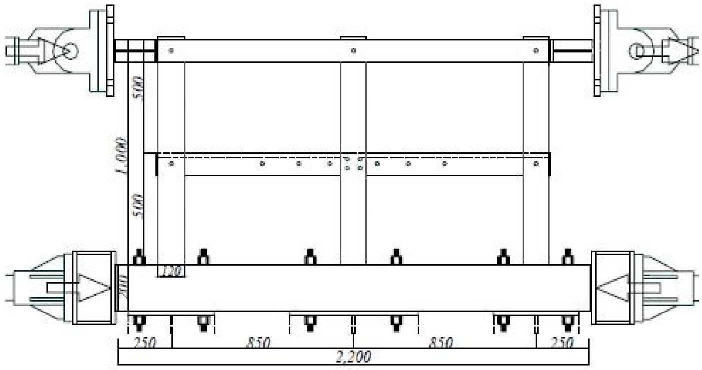


Fig.2. Pressurization Equipment

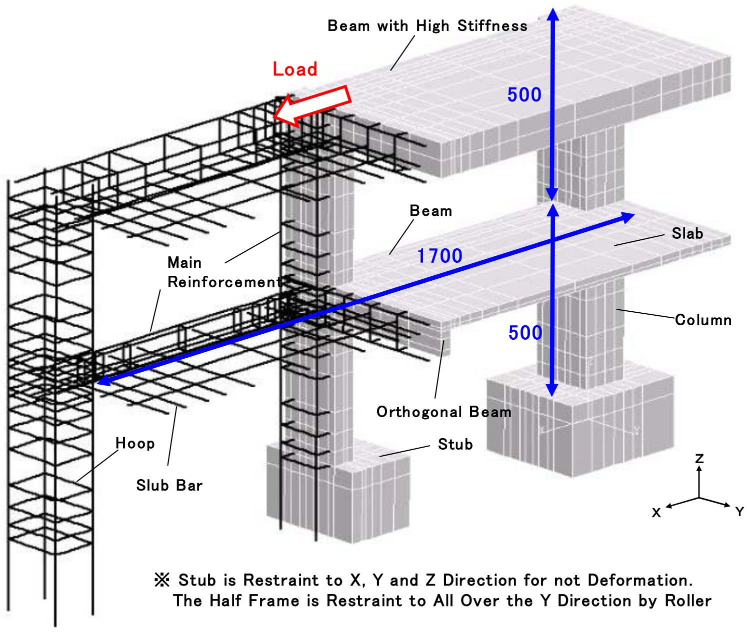


Fig.3. Boundary Condition

5. FINITE ELEMENT IDEALIZATION AND BOUNDARY CONDITION

Finite element mesh and boundary condition are shown in Fig. 3. While the frame is 2 spans and 2 stories height in the experiment, considering the symmetry, a half of the Y directional span was analyzed. A stub was restraint to X, Y and Z directions, and the half frame was restraint to the Y direction using rollers. As for the loading, horizontal forces were loaded as a displacement control in X direction at the center nodal point of a loading beam.

6. ANALYTICAL RESULTS

6.1 Relationships between Story Shear Force and Story Displacement Angle

The relationships between story shear force and story displacement angle was shown in Fig. 4. The story displacement angle was obtained from the value of the relative story displacement divided by the column height. It is indicated that the analytical strengths for three specimens are a little higher than the experimental results, but the analytical initial stiffness corresponds closely with the experimental results. The remarkable difference from the effect of modulus of eccentricity was not observed for the initial stiffness and maximum strength.

6.2 Process of Reinforcement Yielding

The minimum principal stress contour of the specimen N-e00 without the eccentricity is shown in Fig. 5

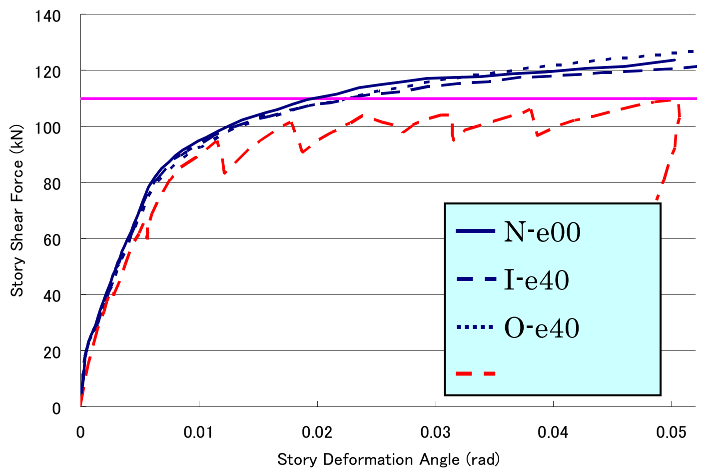


Fig.4. Relationship between Story Deformation Angle and Story Shear Force

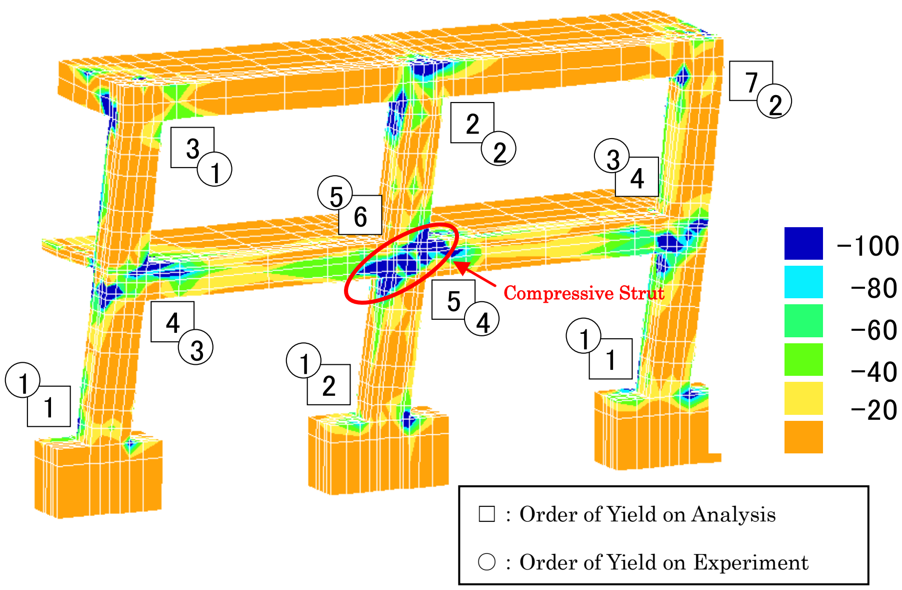


Fig.5. Minimum Principal Stress of the Cruciform Joint at N-e00 and Order of Yield

together with the story deformation and the yielding process of reinforcement. The minimum principal stress contour of the whole frame specimen was shown in Fig. 6 together with the story deformation. Fig. 5 shows the minimum principal stress contour at the time of yielding of top and bottom beam reinforcement in the joint specimen N-e00. In the analysis, the yield of the column main reinforcement at the top was a little delayed, but the analytical yielding process was almost similar to the experimental process.

6.3 Strain in Beam Main Reinforcement at the Critical Section

The strain in beam main reinforcement at the critical section of the internal beam-column joint is shown in Fig. 7. The analytical strain of the specimens N-e00 without the eccentricity and I-e40 with inside eccentricity showed a good agreement with the experimental results, but the analytic strain of the specimen O-e00 with outside eccentricity showed earlier increase as compared with the experimental strain. For the specimen O–e00, the analytical story displacement angle was also smaller than the experimental one. The existence of slabs seems to influence on the yielding of the beam main reinforcement, because in the beam main reinforcement near the lateral beam, the bottom reinforcement yielded before the yielding of top reinforcement.

6.4 Torsional Deformation of Beam-Column Joint

The principal minimum strain distribution and torsional deformation are shown in Fig. 8, and the story shear force-torsional deformation is shown in Fig. 9. Out of plane torsional characteristics affected by the difference of beam eccentricities are compared. In Fig. 8, the arrow indicates the direction of the rotation. In Fig. 9, the torsional angle was derived by dividing the relative displacement at two points of central upper and lower edge in the critical section of the joint by the distance of the two point. The direction of the torsion was assumed to a positive at anti-clockwise from the view of a positive direction of X axis and Z axis. On the C1-J and C2-J sides of the specimen N-e00 without eccentricity, there is scarecely torsion because the direction of the rotation is equal although the rotation was caused. The torsion did not occur even in the beam. The torsion in the specimen I-e40 with inside eccetricity was larger than that in the specimen O-e40 with outside eccentricity, and the torsion in the column increased in proportion to the increase of the shear force. On the other hand, a remarkable increase of torsion like the specimen I-e00 with inside eccentricity was not seen in the specimen O-e40 with outside eccentricity. It is considered that this is because the slab had a role of control over the torsion in the column by increase of slab connection area in the column.

6.5 Principal Minimum strain Distribution of Joint Concrete

The principal minimum strain distribution of joint concrete is shown in Fig. 10. In all specimens, the diagonal compressive stress strut can be observed, and the compressive stress transfer can be confirmed. The minimum principal strain of joint concrete of the specimen N-e00 without the eccentricity concrete joint is almost uniformly distributed and smaller than those of other specimens with the inside or outside eccentricity.

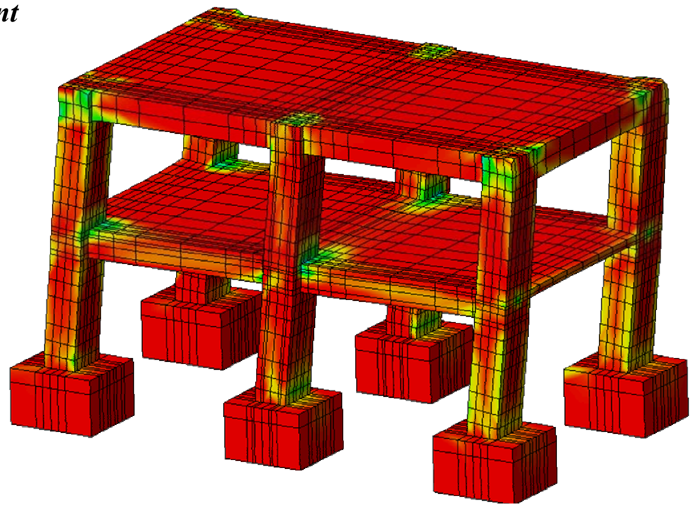


Fig.6. All Frame Specimens and Their Stress Contour

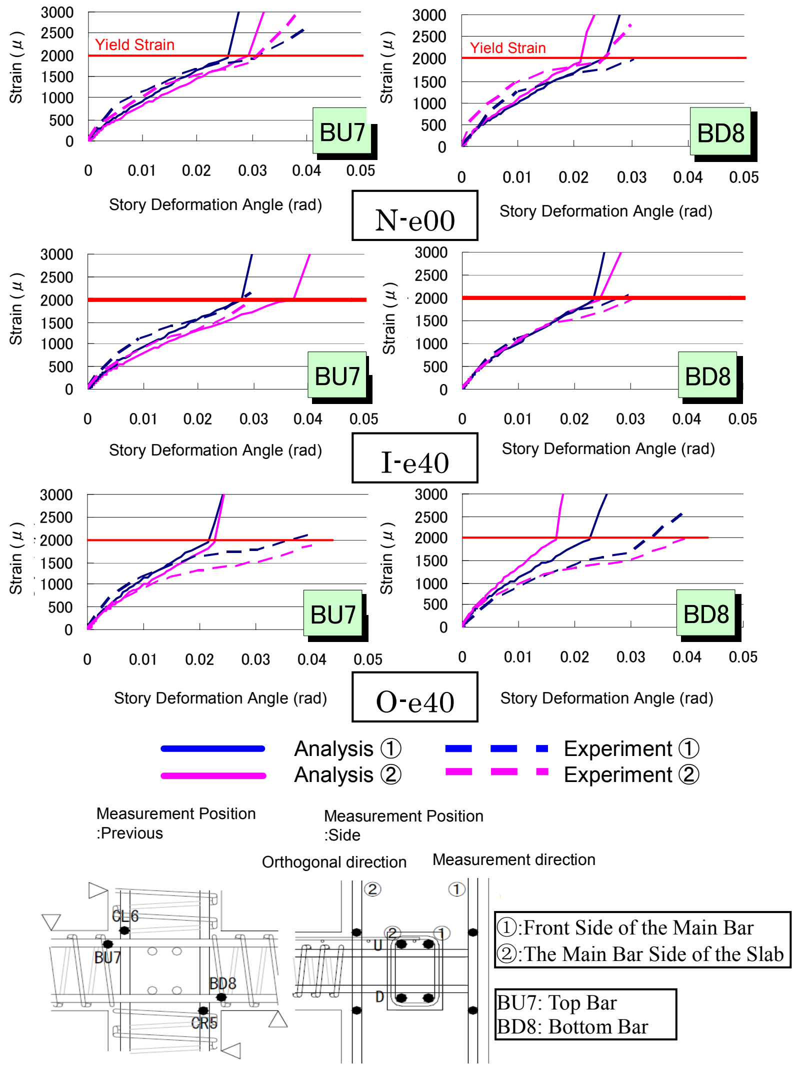


Fig.7. The Situation of the Strain of Beam Main Reinforcement which is in the Position of the Cruciform Joint's Left and Right Critical Section

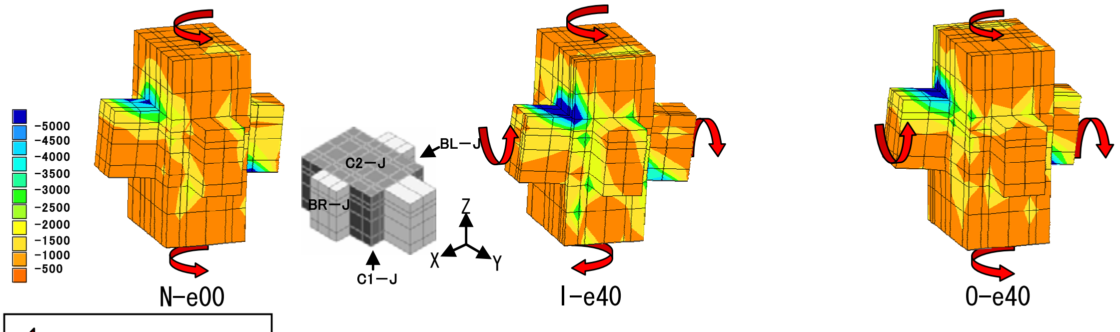


Fig.8. Minimum Strain Distribution and Twist

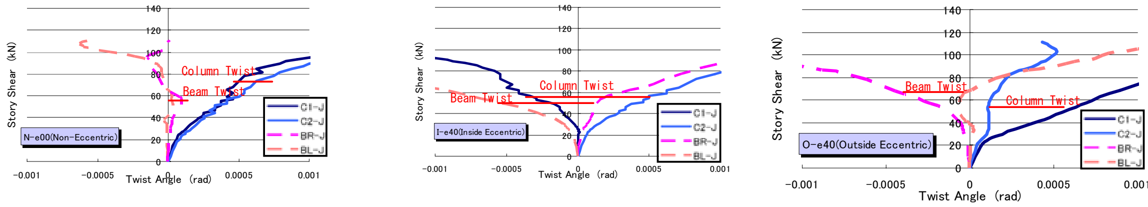


Fig.9. Story Shear Force-Twist Angle

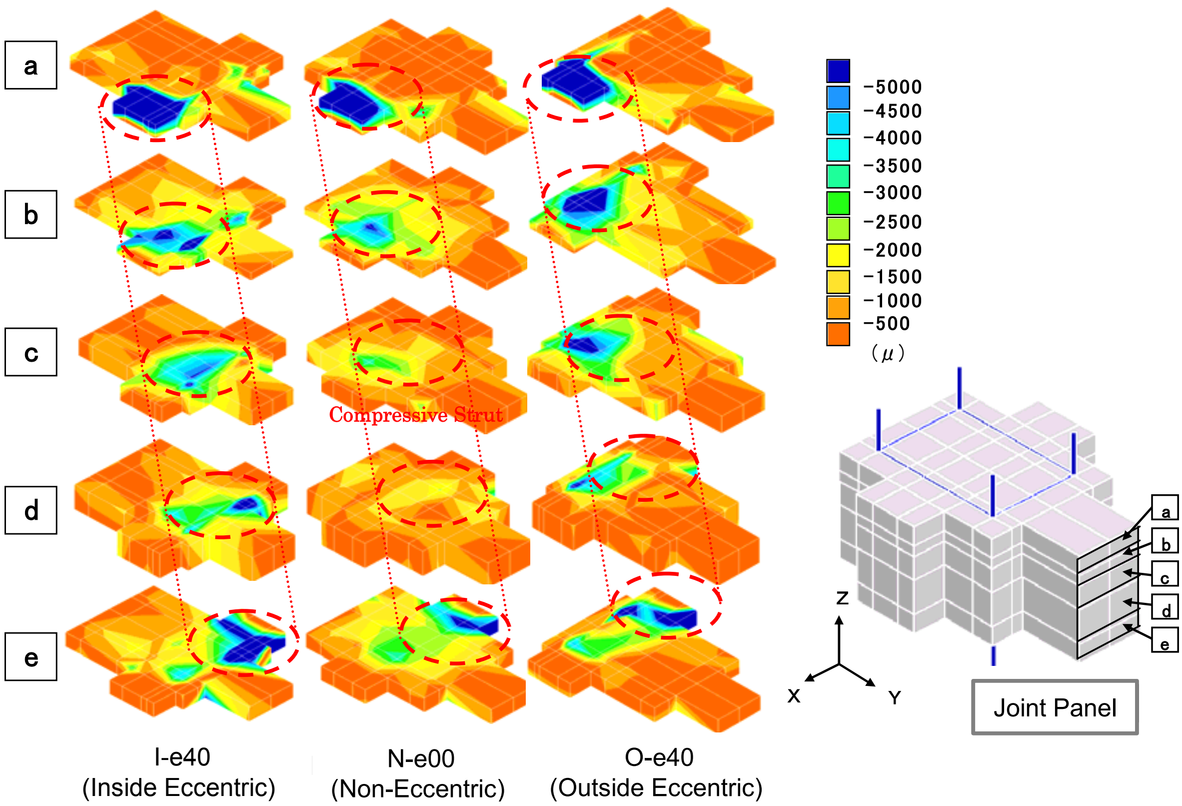


Fig.10. Minimum Strain Distribution of the Concrete in RC Beam-Column Joints

7. FEM ANALYSIS OF RC SOLID BEAM-COLUM JOINT SUBJECTED TO MULTI-DIRECTIONAL CYCLIC LOADING

7.1 Analytical Specimen and Outline of FEM analyses

The Specimen GBS4 is a beam-column joint with lateral beams and a slab which was tested by **Fujii and**

Morita(1987). The cross-sections and bar arrangement of columns and beams are shown in Table-3. The characteristics of materials used in the experiment are shown in Table-4. The finite element idealization is shown in Fig. 11. In the test, reversed cyclic loads were applied to two beam-ends of the specimen, with a constant axial force of 98kN applied to the top of the column. The multi-directional cyclic loading methods and boundary conditions are shown in Fig. 12.

7.2 Relationship between Story Shear Force and Story Displacement Angle

The relationship between story shear force and story displacement angle is shown in Fig. 13. The analytical results correspond well with the test results for the maximum strength. The hysteresis curve in the analysis at the cyclic loads is different from the curve of the experiment which is the reversed slip type from the result of EW direction. The main reason is considered that the bond between the longitudinal reinforcement and concrete was assumed to be perfect.

7.3 Accumulated Absorbed Strain Energy of Concrete

In this study, imaginary specimen GBO4 which is a beam-column joint with a transverse beam without the slab was made and analyzed. The accumulated absorbed strain

Table-3 Cross-Sections and Bar Arrangement

Member		Main Beam (NS direction)	Transverse Beams (EW direction)	Column
Longitudinal Reinforcement	top re-bars	4-D13 2-D10	3-D13	12-D13
	bottom re-bars	4-D13	3-D13	
Stirrups and Hoops		2-D6 @50	2-D6 @50	2-D6 @75
b×D(mm)		175×250	160×250	220×250
Section				

Table-4 Material Characteristics

	Sort	D13	D10	D6
Reinforcing Bar	Yeild Strength(N/mm^2)	368	385	367
	Young Strength(N/mm^2)	1.99×10^5	1.95×10^5	1.82×10^5
Concrete	Compressive Strength (N/mm^2)	38.4		

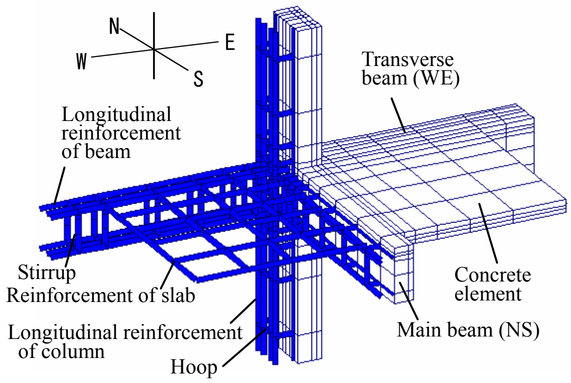


Fig.11. Finite Element Idealization

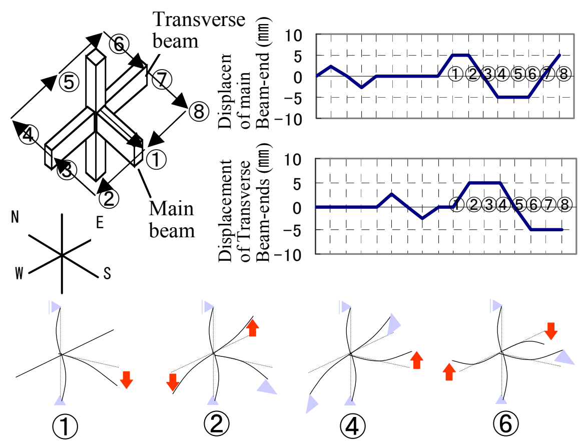


Fig.12. Loading Methods and Boundary Conditions

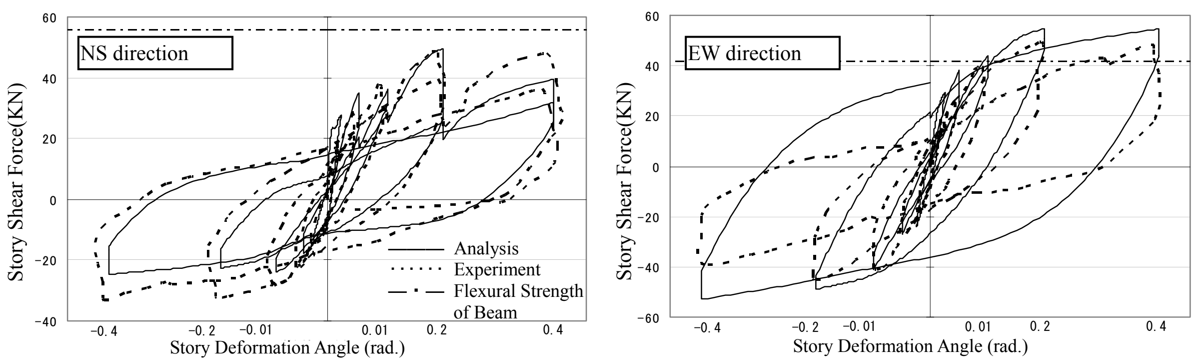


Fig.13. Relationship between Story Deformation Angle and Story Shear Force

energy and deformation for the specimen GBO4 when the story deformation angle was R=1/25 are shown in Fig. 14. It is understood that the accumulated absorbed strain energy increased greatly in the plastic hinge region in the main beam and the transverse beam.

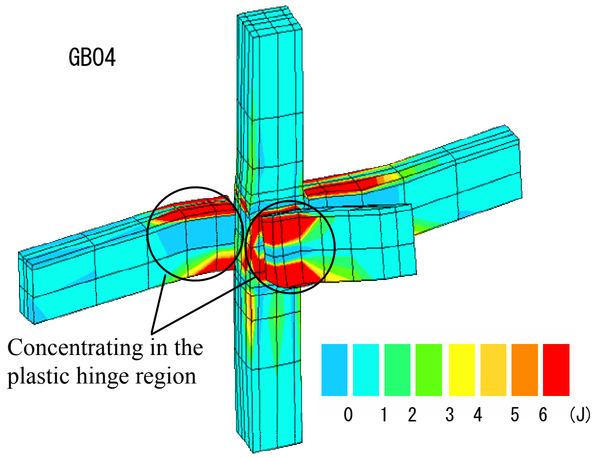


Fig.14. Accumulated Absorbed Strain Energy Contour
(R=1/25, Deformation for 10 times)

8. CONCLUSIONS

The three-dimensional FEM analysis of RC frames with beam-column joints in different beam eccentricity was carried out, and the following conclusions were obtained from the verification of the experimental results and investigation of the seismic performances.

1. Though the analytical maximum strength showed a little higher results as compared with the experimental ones, but the analytical initial stiffness and the formation process of yielding mechanisms showed a good agreement with the experimental ones.
2. The existence of slabs seems to influence on the yielding of the beam main reinforcement, because in the beam main reinforcement near the lateral beam, the bottom reinforcement yielded before the yielding of top reinforcement.
3. It is considered that this is because the slab had a role of control over the torsion in the column by increase of slab connection area in the column.
4. In the beam-column joint subjected to the multi-directional cyclic loading, it was indicated than the accumulated absorbed strain energy increased greatly in the plastic hinge region of the main beam and the transverse beam.

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REFERENCES

1. Kawaguchi, M. Shinoda, S. Katori, K. Hayashi, S. (2002) : Seismic Performance of RC Frame Consisting of Eccentric Beam-Column Joints (Part 1, 2), Summaries of Technical Papers of Annual Meeting C-2, pp.527-530.
2. Darwin, D., and Pecknold, D.A.W. (1974) : Inelastic Model for Cyclic Biaxial Loading of Reinforced Concrete, A Report on A Research Project Sponsored by the NSF, University of Illinois, July 1974.
3. Yu, Y. Kashiwazaki, T. Noguchi, H. (2004) : Development of FEM Analytical Program on RC Structural Elements Subjected to 3 Dimensional Cyclic Loads (Part 1, 2), Summaries of Technical Papers of Annual Meeting, C-2, pp.67-70.
4. Saenz, L. P (1964) : Discussion of ‘Equation for the Stress-Strain Curve of Concrete’, by P. Desayi and S. Krishnan, Journal of the American Concrete Institute, Vol.9, pp.1229-1235.
5. Park, R., Priestley, M.J.N. and, Gill, W.D. (1982) : Ductility of Square-Confined Concrete Columns, Journal of the Structural Division, Proceeding of ASCE, ST4, pp.930-950.
6. Sato, T. Shirai, N. (1978) : Elasto-Plastic Behavior of RC Shear Walls, Summaries of Technical Papers of Annual Meeting, C-2, pp.1615-1618.
7. Morita, S. Kaku, T. (1975) : Bond-Slip Relationship Under Repeated Loading, Transactions of the Architectural Institute of Japan, No.299, pp.15-24,.
8. Fujii, S. Morita, S. (1987) : Behavior of R/C Exterior Beam-Column Joint under Bi-directional Loading, Proc. of JCI Annual Convention, Oct. 1987, pp181-186