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THREE-DIMENSINAL NONLINEAR FINITE ELEMENT ANALYSIS ON THE SHEAR STRENGTH OF RC INTERIOR BEAM-COLUMN JOINTS WITH ULTRA HIGH-STRENGTH MATERIALS

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ABSTRACT

Reinforced concrete (RC) interior beam-column joints with ultra high-strength materials were analyzed using three-dimensional (3-D) nonlinear finite element method (FEM). These specimens with concrete compressive strength of 100 MPa and the yield strength of longitudinal bars of 685 MPa were tested. The specimen OKJ3 of joint shear failure type was a plane interior joint, and the specimen I2 of beam flexural failure type was a 3-D interior joint with transverse beams.

Though the analytical initial stiffness was higher than experimental one, the analytical results gave a good agreement with the test results on the maximum story shear forces, the failure mode and the strain distributions of beam longitudinal bars.

KEYWORDS

Reinforced concrete; high-strength materials; beam-column joints; shear strength; FEM analysis.

INTRODUCTION

Interior beam-column joints in a reinforced concrete (RC) building are subjected to two-directional forces during an earthquake. In such interior beam-column joints, confined concrete in the joint results in the triaxial stress condition. It is also recognized that interior beam-column joints are confined by column axial force, joint lateral reinforcement, transverse beams and slabs. It is not desirable for the joints to neglect the severe stress conditions subjected to two-directional shear forces.

Design Guidelines for Earthquake Resistant RC Buildings Based on Ultimate Strength Concept for normal strength materials published by Architectural Institute of Japan (Architectural Institute of Japan, 1990) (AIJ Guidelines) suggest that such a 3-D interior beam-column joint should be designed for the two principal directions independently. AIJ Guidelines are based on a few test results. It is not so rational to establish the guidelines for the joints without the analytical understandings of the joint shear resistance mechanisms.

In this study, a plane RC interior beam-column joint without transverse beams and slabs, and a 3-D RC interior beam-column joint with transverse beams using ultra high-strength materials were analyzed using 3-D nonlinear finite element method (FEM) in order to clarify the shear resistance mechanisms of the joints and establish the rational design method of the joints.
Comparing the analytical results with the test results, restoring force characteristics, deformation, distributions of the beam longitudinal bars through a joint and internal stress flow along the joint were discussed.

OUTLINE OF FEM ANALYSIS

Reference Specimen for 3-D FEM Analysis

Specimens OKJ3 (Kashiwazaki *et al.*, 1991) and I2 (Lee *et al.*, 1992) were selected as the references for this study. Specimens OKJ3 and I2 were interior beam-column joints with ultra high-strength materials. As for specimen OKJ3 of the plane joint without transverse beams, joint shear failure occurred before beam flexural yielding. But as for specimen I2 of the 3-D joint with transverse beams, beam flexural failure before joint shear failure occurred in the test.

The properties of specimens OKJ3 and I2 are shown in Tables 1 and 2. The reinforcement arrangement of specimens OKJ3 and I2 are shown in Figs 1 and 2, respectively.

Table 1 Properties of specimen

Specimen		Two-Dimensional OKJ3	Three-Dimensional I2
Beam	Top Bars	10-D13	8-D16
	Bottom Bars	10-D13	8-D16
	Stirrups	2-D6 @50, p_w=0.63(%)	2-U6.4 @35, p_w=0.86(%)
Colum n	Total Bars	22-D13	16-D19
	Hoops	2-D6 @40, p_w=0.53(%)	2-U6.4 @40, p_w=0.50(%)
Joint	Hoops	4-D6×3sets @50 p_w=0.54(%)	4-ϕ6×2sets@30 p_w=0.39(%)

Table 2 Material properties

a) Concrete (unit in MPa and μ)

Specimen	Two-Dimensional OKJ3	Three-Dimensional I2
Secant Modulus	43300	39200
Compressive Strength	107	99
Strain at Comp. Strength	2860	2752
Spliting Strength	6.0	4.2

b) Reinforcement (unit in MPa and μ)

Specimen	Two-Dimensional OKJ3		Three-Dimensional I2			
	D6	D13	D16	D19	U6.4	ϕ6
Young's Modulus	182000	186000	182000	181000	186000	186000
Yield Strength	955	717	798	746	1307	356
Strain at Yielding	7340	5870				
Max. Strength	1140	766	859	806	1397	431

Specimen OKJ3 was tested by the authors. An one-third scaled specimen OKJ3 had a interstory height of 147 cm and a beam span of 270 cm. The dimensions of beams and columns were 200 x 300 mm and 300 x 300 mm, respectively. The beam was reinforced by bars of diameter 13 mm with a yielding stress of 717 MPa, and the compressive strength of concrete was 107 MPa. The joint lateral reinforcement ratio was 0.54 %. Reversed cyclic loads were applied to two beam-ends of specimen OKJ3 under each story drift angle of 1/200, 1/100, 1/50, 1/33 and 1/25 rad.. A constant axial load of 85 tons was applied to the column (axial stress $\sigma_0 = 0.1\sigma_B$, σ_B : concrete compressive strength).

Specimen I2 was tested by Lee et al. of the University of Tokyo. As shown in Fig. 2, specimen I2 had the same interstory height, beam spans and dimensions of beams and columns with specimen OKJ3. The beam was reinforced by bars of diameter 16 mm with a yielding stress of 798 MPa, and the compressive strength of concrete was 99 MPa, as shown in Tables 1 and 2. The joint lateral reinforcement ratio was 0.39 %. Three dimensional reversed cyclic loads were applied to the top of the column until the story drift angle of 1/25 rad. . A constant axial load of 32.5 tons was applied to the top of the column.

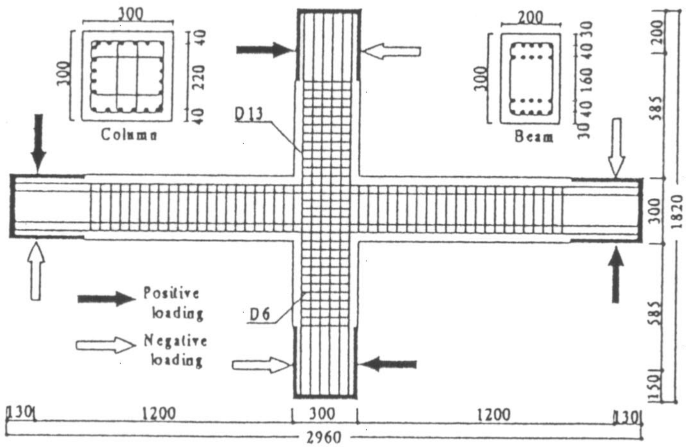

Fig. 1 Arrangement of reinforcement (OKJ3)

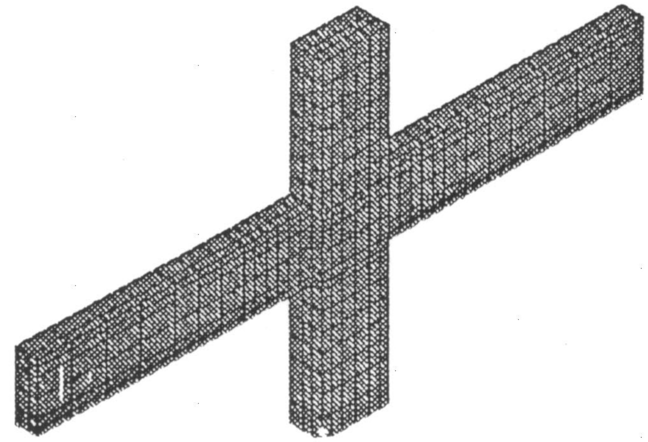

Fig. 3 Finite element idealization (OKJ3)

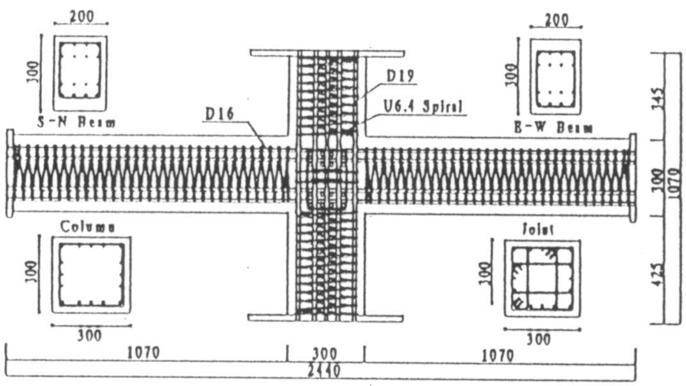

Fig. 2 Arrangement of reinforcement (I2)

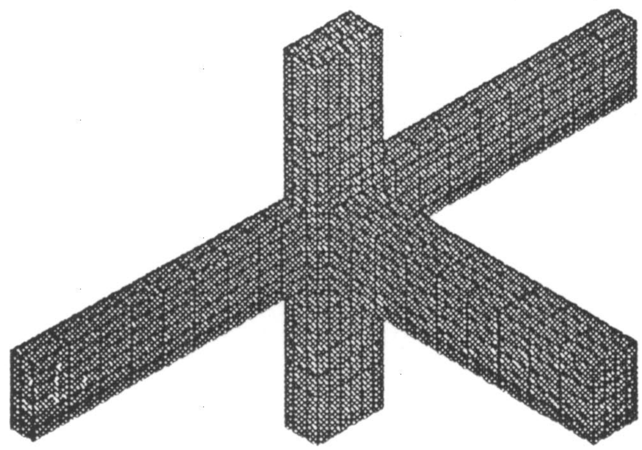

Fig. 4 Finite element idealization (I2)

Analytical Method and Material Models

This 3-D FEM analytical study was carried out using a general purpose FEM program, ABAQUS in which the user subroutine was used for installing original models for high-strength materials developed by Uchida, Amemiya and Noguchi (Uchida *et al.*, 1992), and Yonezawa and Noguchi (Yonezawa *et al.*, 1994). The 3-D FEM program was executed using the EWS.

Figures 3 and 4 show the modeling of specimens OKJ3 and I2, respectively. The half areas of specimens OKJ3 and I2 were analyzed using the symmetrical condition, as shown in Figs. 3 and 4. The boundary conditions for the top and bottom of the column and beam ends were set up according to the experiment.

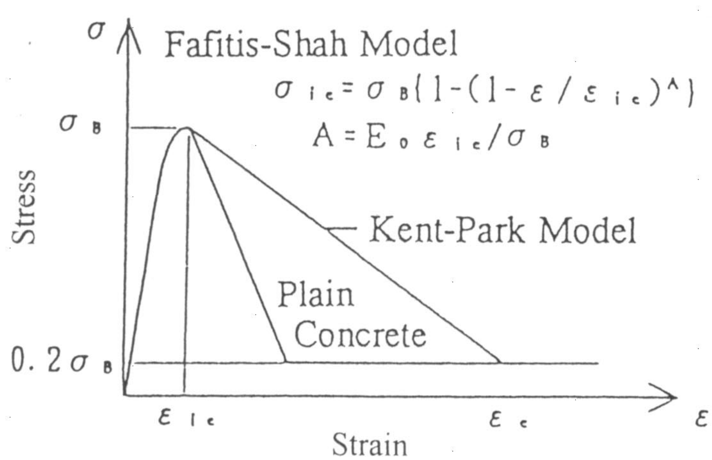

Fig. 5 Compressive stress-strain relationships of concrete

The following nonlinear constitutive models for high-strength materials were included into the 3-D FEM program.

Concrete : Concrete was represented by 8-node solid elements. Concrete was assumed as orthotropic hypoelastic model based on the equivalent uniaxial strain concept modified by Murray et al. for the 3-D FEM analysis. The failure was judged by the five parameter criterion which was added two parameters to the three parameter criterion proposed by Willam and Warnke. The five parameters were decided using the panel experiment by Kupfer.
Fafitis-Shah model (Fafitis *et al.*, 1985) was used for the ascending compressive stress-strain relationships (1), as shown in Fig. 5, because the stress-strain relationships of high-strength concrete show linear just before the compressive strength.

$$\sigma_c = \sigma_B \left[1 - \left(1 - \varepsilon_c / \varepsilon_B \right)^A \right], \quad A = E_c \cdot \varepsilon_B / \sigma_B \qquad (1)$$

σ_c : stress in concrete (kgf/cm^2)
σ_B : compressive strength of concrete (kgf/cm^2)
ε_c : strain in concrete (dimension-less)
ε_B : strain in concrete at the compressive strength (dimension-less)
E_c : initial stiffness of concrete (kgf/cm^2)

Confined effect by lateral reinforcement on the compressive descending stress-strain relationships were represented by Kent-Park model (Kent *et al.*, 1971). Poisson's ratio of concrete was modeled as a function of compressive strain proposed by Murray. Cracks in concrete elements were represented by the smeared crack model. After cracking, tension cut-off was assumed, and the stiffness normal to a crack direction was set to be zero. The reduction factor of concrete compressive strength of cracked concrete proposed by Ihzuka and Noguchi (Ihzuka *et al.*, 1992) was used. This Ihzuka-Noguchi model was derived from the test results of cracked RC panels with from normal to high strength materials.

Reinforcement : The longitudinal and lateral reinforcement in columns and beams was assumed to be a linear element. The stress-strain relationships of the longitudinal and lateral reinforcement were assumed to be bilinear and trilinear, respectively.

Bond : Bond between the longitudinal reinforcement and concrete was assumed as perfect bond. The slippage of beam longitudinal reinforcement through a joint was not considered.

Test results were used for the mechanical properties of concrete and reinforcing bars in the analysis.

ANALYTICAL RESULTS

Plane Interior Beam-Column Joint (OKJ3)

Restoring Force Characteristics. The analytical story shear force-story displacement relationships of a plane interior beam-column joint, specimen OKJ3 are shown in Fig. 6 as compared with the test results. The analytical initial stiffness was higher than the experimental one up to the story drift angle (Rs) of 1/200 rad.. As for the maximum story shear force (Ps), the analytical results (Ps = 33.5 tons) were higher than test results (Ps = 29.9 tons) about 10 percent. The yielding of beam longitudinal reinforcement did not occur in this analysis until the maximum story shear forces, and a few concrete elements in the joint reached strain softening area over concrete compressive strength at the maximum story shear force. It was recognized that the joint shear failure before beam flexural yielding (J failure) occurred in the joint of specimen OKJ3 similarly to the experiment.

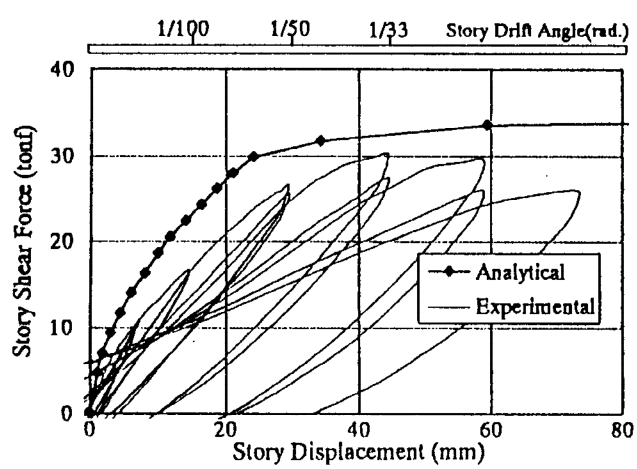

Fig. 6 Story shear force-story displacement relationships (OKJ3)

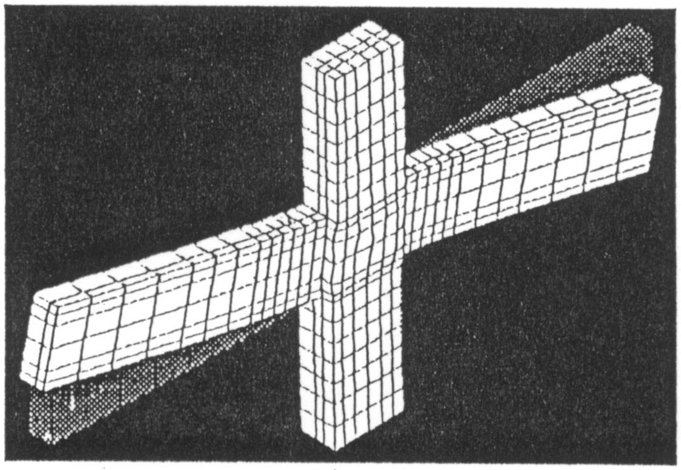

Fig. 7 Deformations (OKJ3)

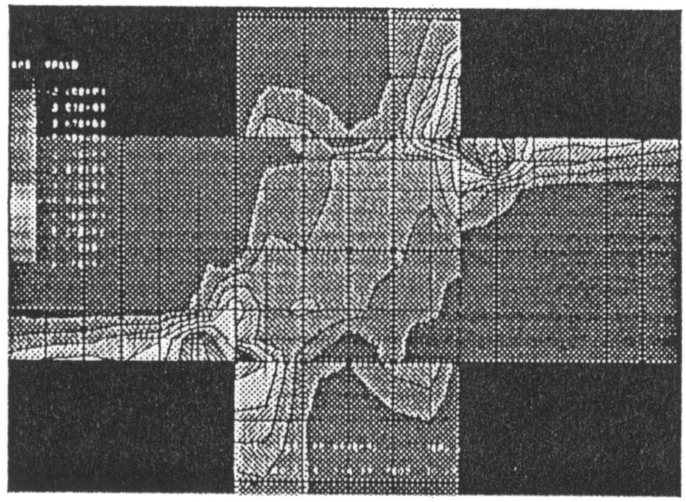

Fig. 8 Stress contour of concrete (OKJ3)

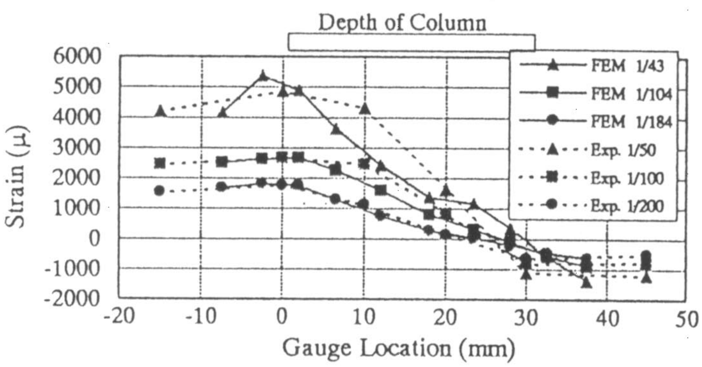

Fig. 9 Strain distributions of beam longitudinal reinforcement

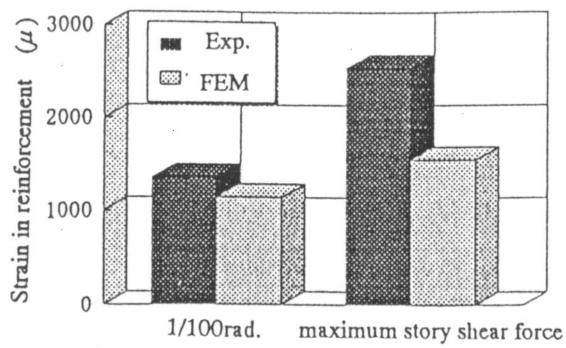

Fig.10 Strain in joint lateral reinforcement

Deformations and Internal Stress Flow. Figures 7 and 8 show the analytical deformations and stress contours of concrete in the joint of specimen OKJ3, respectively. In Fig. 7, the beam flexural deformation caused by loading to the beam ends and joint shear distortion were so remarkable. It was also recognized that the expansion of the joint panel which was not obtained by two-dimensional FEM analysis were so considerable. This expansion was caused by the volume expansion of the diagonal compressive strut of panel concrete. The arch mechanisms of beams and columns and the diagonal compressive strut mechanism along a joint were obtained from the stress contours of concrete, as shown in Fig. 8. Stress in the concrete strut of a joint were from 36 to 52 MPa. These stresses were about 40 percent of the concrete compressive strength.

Strain Distributions of Beam Longitudinal Bars. Strain distributions of beam longitudinal reinforcement (the first layer of top bars) through the joint at each story drift of specimen OKJ3 are shown in Fig. 9. The excessive bond deterioration of beam longitudinal reinforcement through the joint did not occur during the experiment. In spite of assuming perfect bond for beam longitudinal reinforcement, the analytical results gave a good agreement with the test results. Figure 10 shows the analytical strains in the joint lateral reinforcement (sub ties) of specimen OKJ3 of joint shear failure type. The analytical results were about 84 and 60 percent, at Rs of 1/100 rad. and at the maximum story shear force, respectively, compared with the test results. It was recognized that the analytical strains were smaller than the experimental one.

Three-dimensional Interior Beam-Column Joint (I2)

Restoring Force Characteristics. Figure 11 shows the analytical story shear force-story displacement relationships of the 3-D interior beam-column joint, specimen I2 with transverse beams. The P-δ effect caused by loading to the top of column was considered in these analysis and experiment. Similar to the analytical results of specimen OKJ3 without transverse beams, the analytical initial stiffness of specimen I2 with transverse beams was higher than the experimental one. The analytical maximum story shear force (Ps = 38.3 tons) was reduced about 4 percent from the experimental one (Ps = 40 tons). Because the calculated story shear force at the beam flexural yielding were 40.7 tons, the analytical results gave a good agreement for the maximum story shear force.

The failure mode of specimen I2 was beam flexural failure before joint shear failure similar to the experiment, because the beam longitudinal reinforcement yielded at the maximum story shear force (Ps = 38.3 tons) in this analysis.

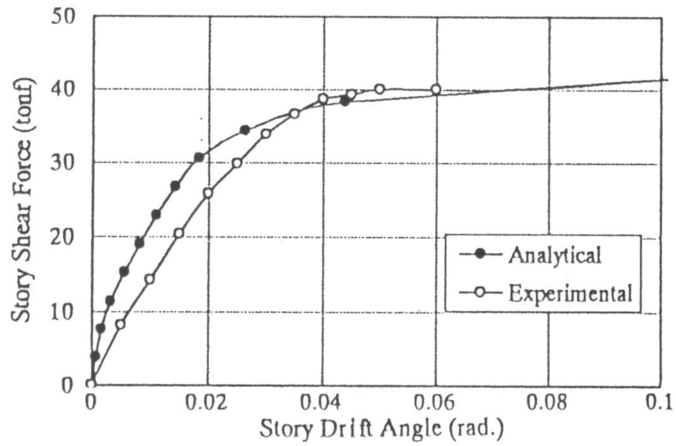

Fig. 11 Story shear force-story displacement relationships (I2)

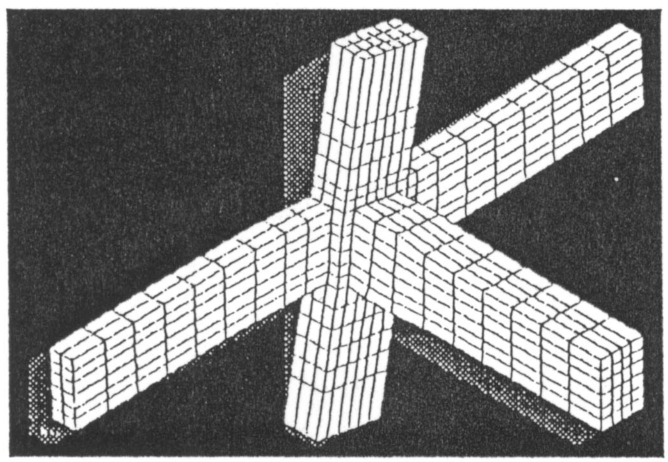

Fig. 12 Deformations (I2)

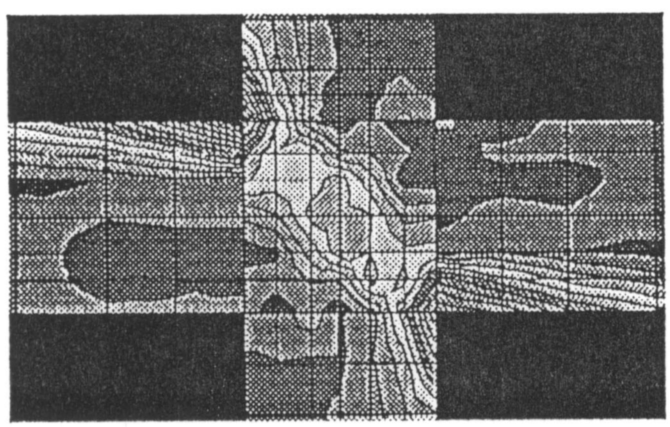

Fig. 13 Stress contour of concrete (I2)

Deformations and Internal Stress Flow. The analytical deformations and the stress contours of concrete in the 3-D joint with transverse beams, specimen I2 at the maximum story shear force were shown in Figs. 12 and 13, respectively. It was recognized that the horizontal displacement of the top of the column and both beam ends, and beam flexural deflections were so large. From Fig. 13, it was recognized that the diagonal compressive strut of concrete transferred from the flexural compressive zones of beams and columns were formed in the joint panel. The stress concentrated zone in the center of the joint, which was not observed also in the plane joint without transverse beams (Fig. 8), was observed in the analysis of the 3-D joint with transverse beams. It was considered that the stress concentrated zone was caused by the confinement effect of transverse beams on the joint panel. Concrete stresses in the center and the circumference of the concentrated zone were from 42 to 51 MPa and from 33 to 42 MPa, respectively. These stresses were about 47 and 38 percent of the concrete uniaxial compressive strength.

CONCLUSIONS

In order to understand the shear resistance mechanisms and the shear capacity of RC interior beam-column joints with ultra high-strength materials, two specimens of a plane joint with the joint shear failure type and a 3-D joint with the beam flexural failure type were analyzed using a nonlinear 3-D FEM analysis. From the detailed investigations of the FEM analytical results in comparison with the test results, the following conclusions were obtained.

Though the analytical initial stiffness of restoring force was higher than experimental one, the analytical results gave a good agreement with the test results on the maximum story shear forces, the failure mode and the strain distributions of the beam longitudinal bars.

Concrete stresses in the main diagonal strut of a joint panel was about 40 percent of the concrete uniaxial compressive strength in both cases of the plane and the 3-D joint. In the case of the plane joint, joint shear failure before beam flexural yielding occurred. On the other hand, in the case of the 3-D joint, joint shear failure did not occur. Accordingly, it is considered that the joint shear strength is increased by the joint confinement effect of transverse beams.

In the future, in order to develop the rational design method of joints, it is necessary to investigate the joint shear resistance mechanisms using the results of the parametric 3-D FEM analysis including the variations of the concrete compressive strength, joint lateral reinforcement, column axial load, transverse beams and floor slabs.

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