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SEISMIC PERFORMANCE EVALUATION OF RC ECCENTRIC BEAM-COLUMN JOINTS USING THREE-DIMENSIONAL FEM ANALYSIS

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SUMMARY

Usually, most of beam-column joints in a reinforced concrete (RC) building are concentric, as in the case when beam and column axes are in the same plane. For architectural reasons, however, it is not uncommon construction of eccentric beam-column joints in the exterior frames of RC buildings. In eccentric beam-column joints, the axis of the spandrel beams is offset from the axis of column. As for these eccentric joints subjected to earthquake loads, it was considered that additional shear forces, produced by torsion moment from beams, severely act on the joints. Moreover, brittle shear failures of eccentric joints subjected to additional shear forces were observed from the previous earthquake damages.

In order to investigate the effect of eccentricity on degradation of shear strength, stiffness and deformation capacity of beam-column joints, non-linear analyses using a three-dimensional finite element method (3-D FEM), which is very useful to get the rational solution of 3-D stress conditions, have been carried out in this study. Reference specimens for this 3-D FEM analysis were selected from the previous experimental study. Reference specimens failed in joint shear failure after beam flexural yieldings in the tests. The FEM results show a good agreement with the test results on the maximum story shear forces and the failure modes. When the beam flexural yieldings have occurred, the maximum story shear forces did not increase. Moreover, in order to understand the shear transfer mechanisms in an eccentric beam-column joint, the internal stress flows of both concentric and eccentric joints obtained from analytical results were discussed in detail. In spite of the same maximum story shear forces, it was recognized that the internal concrete stresses concentrated severely to the eccentric side in a joint.

INTRODUCTION

In Tokachi-Oki Earthquake 1968 and Hansin Awaji Earthquake 1995, it was recognized that the remarkable damages of eccentric beam-column joints in RC buildings were observed by the intensive input shear forces produced by the additional torsion moment, as it was shown in Fig. 1. Moreover, it was observed that the effective resistant area in a joint has been decreased on the beam-column joints with eccentricity of beam axis toward the column one. Regarding the eccentric beam-column joints, it was expected that the severe earthquake damages and brittle shear failure in a joint would occur because joint input shear forces have concentrated to the eccentric side in a joint.

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Therefore, it is necessary to establish the more rational shear design method for the eccentric beam-column joints subjected to seismic forces. In this study, three-dimensional FEM analysis of eccentric beam-column joint has been carried out. Compared with the FEM analytical and experimental results, the story shear force and story drift angle relation and failure modes have been discussed. Moreover, the joint shear resistance mechanisms of the eccentric beam-column joint and the deterioration of joint shear capacity have been considered by the detailed investigations of FEM analytical results.

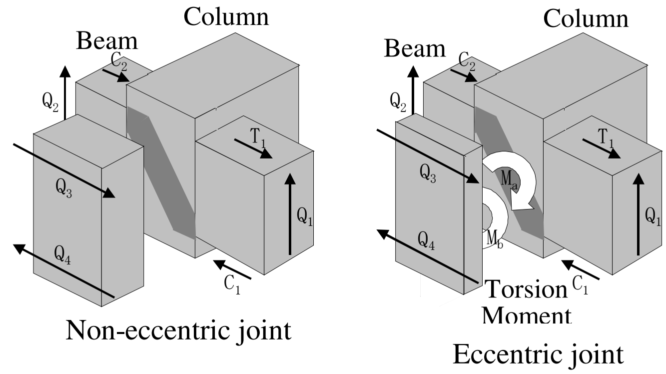


Fig. 1 Torsion moment in an eccentric joint

OUTLINE OF FEM ANALYSIS

Reference specimens

Two two-third-scale RC interior beam-column joints, specimens No.34 and No.35 have been selected as reference specimens in this study. These specimens were tested by Hayashi K., Kanoh Y. and Teraoka et al. [1] on 1991. All specimens have an interstory height of 2m and a beam span of 3.5m, as shown in Fig. 2. The dimensions of the beam and column are 50cm x 30cm and 50cm x 50cm, respectively. Specimen No.34 is a non-eccentric joint. On the other hand, the beam axis of specimen No.35 has an eccentricity of 7.5cm from the column center. During the experiment, the beam flexural yields occurred on both specimens No.34 and No.35 in the experiment. Properties of the specimens and materials are shown in Tables 1 and 2, respectively. Details of the specimens are shown in Fig. 2.

In the test, reversed cyclic loads were applied to two beam-ends of both specimens No.34 and No.35, with constant axial stress of 8MPa on the top of the column in both specimens. The beam flexural yields before joint shear failure were observed both in Specimens No.34 and No.35 at the maximum story shear forces in the test.

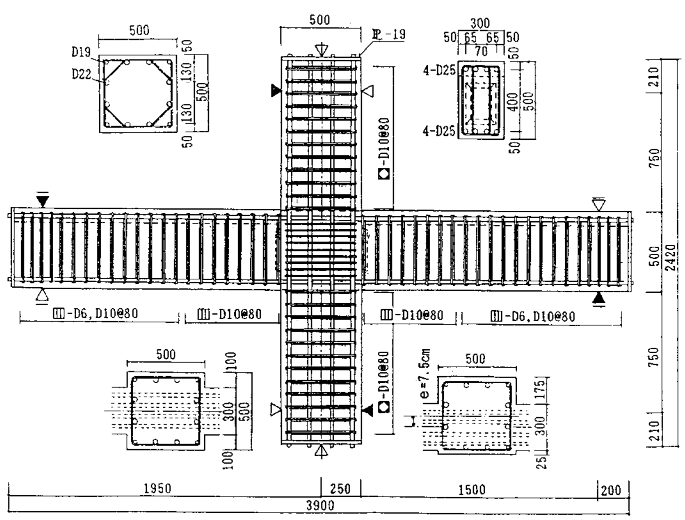


Fig. 2 Details of the specimens

Table 1 Properties of specimens

Specimen		No.34	No.35
Eccentricity		0cm	7.5cm
Column	Section	50cm x 50cm	
	Main bars	4-D19 + 8-D22	
	Lateral reinforcement	4-D10@80, 0.71%	
Beam	Section	50cm x 30cm	
	Main bars	Upper: 4-D25 Bottom: 4-D25	
	Lateral reinforcement	4-D10@65, 0.71%	
Joint	Lateral reinforcement	2-D10@40, 0.71%	

Table 2 Material properties

a) Concrete

Member	Comp. strength	Secant stiffness	Split strength
Column	32.9MPa	2.31GPa	3.1MPa
Beam	35.5MPa	2.53GPa	2.6MPa
Joint	39.4MPa	2.65GPa	3.2MPa

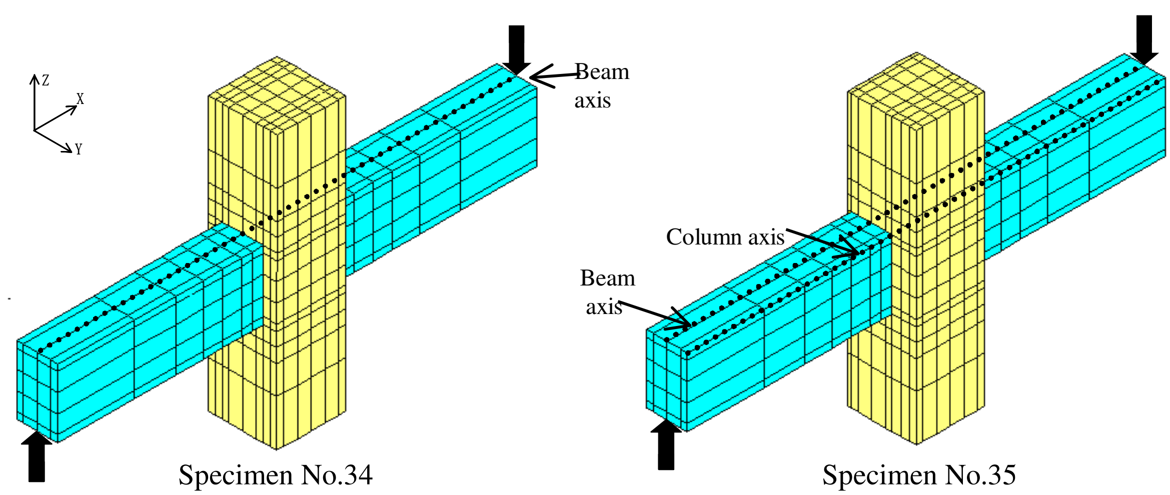
b) Reinforcement

Bar size	Yield stress	Maximum stress	Young's Modulus
D10	339MPa	493MPa	18.5GPa
D19	442MPa	621MPa	19.5GPa
D22	427MPa	601MPa	19.2GPa
D25	429MPa	620MPa	18.5GPa

Analytical method and materials models

This analysis was carried out by using a three-dimensional nonlinear FEM program developed by Uchida K. and Noguchi H. [2]. Figure 3 shows the modeling of specimens No.34 and No.35, respectively. The boundary conditions for the top and bottom of the column and beam ends were set up according to the experiment. In the analysis, monotonic loads were applied to the ends of beams in specimens. The following materials models were introduced into this FEM program.

Concrete was represented by 8-node solid elements. It was modeled as orthotropic material, based on the hypoelastic formulation, using the equivalent uniaxial strain concept proposed by Darwin-Pecknold [3], modified by Murray et al. for the three-dimensional 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 et al. [4]. Saenz model [5] was used for the ascending compressive stress-strain relationships of concrete, as shown in Fig. 4. Confined effect by lateral reinforcement on the compressive descending stress-strain relationships were



Specimen No.34 Specimen No.35

Fig. 3 Finite element idealization

represented by Kent-Park model [6]. 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-stiffening model proposed by Shirai et al. [7] was assumed. The reduction factor of compressive strength of cracked concrete proposed by Ihzuka and Noguchi [8] was used.

The longitudinal and lateral reinforcement in columns and beams was modeled by linear elements. The stress-strain relationships of the longitudinal and lateral reinforcement were assumed to be bilinear and trilinear, respectively.

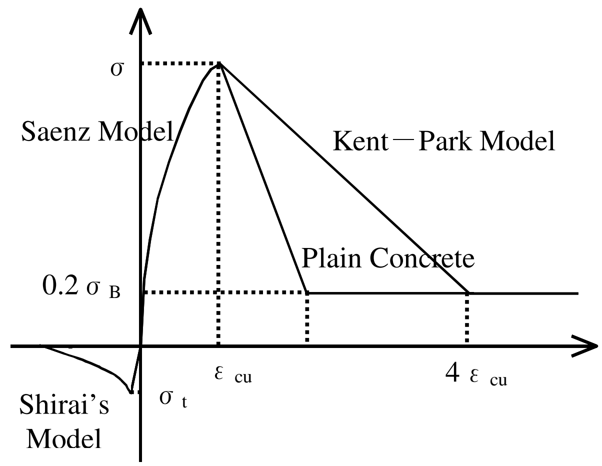


Fig. 4 Concrete model

The bond between the longitudinal reinforcement and concrete was assumed as perfect. The slippage of beam longitudinal reinforcement through a joint was not considered. Test results were used for the properties of concrete and reinforcing bars in the analysis.

ANALYTICAL RESULTS

Story shear force-story drift angle relationships

The analytical story shear force-story drift angle relationships of both specimens No.34 and No.35 are shown as compared with the test results in Figs. 5 and 6, respectively. The analytical initial stiffness was higher than the experimental one. It is considered that this was due to the local flexural crack on the critical section of the beam and the bond-slippage behavior between beam longitudinal bars and concrete in a joint, which were not taken into account in the model. The analytical maximum story shear force of 471kN of specimen No.34 was higher than the test results of 451kN about 4%. On the other hand, as for specimen No.35, the analytical maximum story shear force of 468kN exceeded the test results of 457kN about 2%. From the analytical results, the yielding of beam longitudinal reinforcement was observed at the maximum story shear force in both specimens No.34 and No.35. It was recognized that the beam flexural failure occurred in both specimens No.34 and No.35 similarly to the experiment. It was reported by Hayashi K. et al. [1] that the deterioration of maximum story shear force was not obvious because of the small eccentricity of 7.5cm between beam axis toward the column center and the beam flexural yielding before joint shear failure. In this analysis, it was recognized that the deterioration of maximum story shear force was not remarkable in case of the beam flexural yielding occurred before shear failure in a joint.

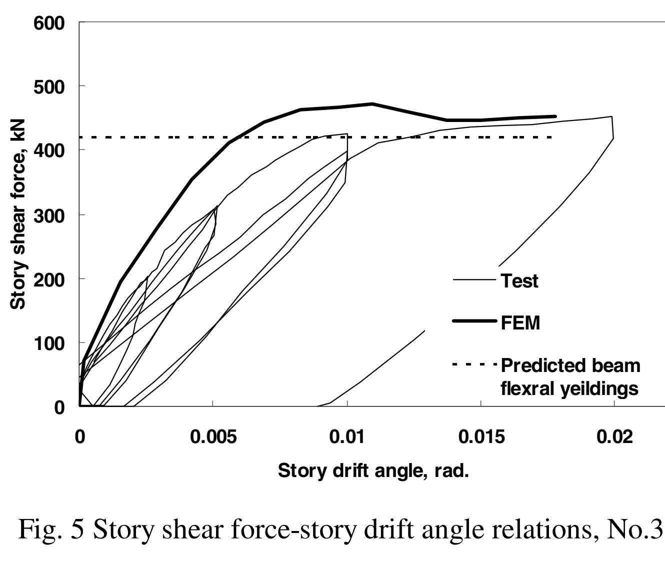


Fig. 5 Story shear force-story drift angle relations, No.34

Analytical results of specimens No.34 and No.35 are shown as compared with the predicted maximum story shear force, proposed by Architectural Institute of Japan [9] in Fig. 7. In case of calculation for maximum story shear force of specimen No.35 with eccentricity of 7.5cm, the effective width in a joint was assumed by the following Eq. (1).

$$Bj = 0.5 \times (Bc + Bb) - e \quad \text{Equation (1)}$$

Bj: Effective width in a joint
Bc: Column width
Bb: Beam width
e: Eccentricity in a joint

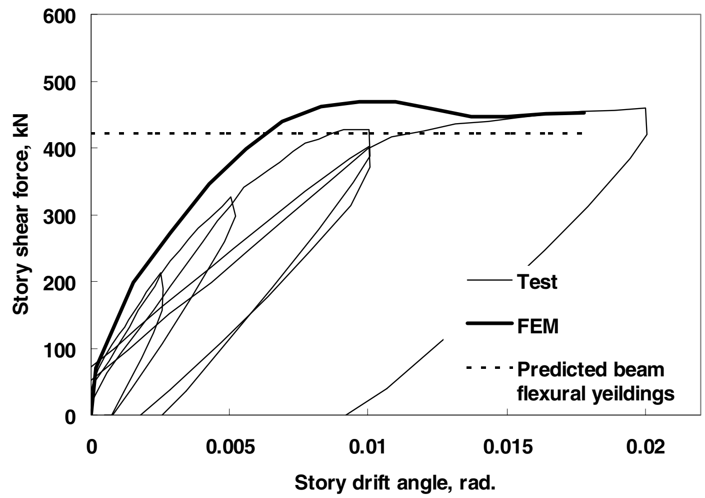


Fig. 6 Story shear force-story drift angle relations, No.35

Deterioration of predicted maximum story shear force by eccentricity of specimen No.35 was 20% of the one for specimen No.34. Because analytical maximum story shear force of specimen No.35 with eccentricity of 7.5cm was the same as for specimen No.34, similarly to the experiment, it was recognized that the deterioration of maximum story shear force by Eq. (1) were overestimated in case when beam flexural yield has occurred before shear failure in a joint.

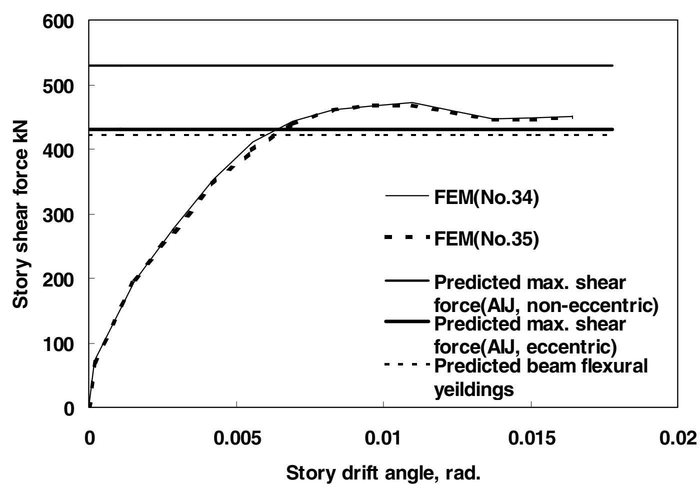


Fig. 7 Story shear force-story drift angle relations

Distributions of shear stress and shear force in a joint

Distributions of joint shear stress at the maximum story shear force obtained from FEM analytical results of specimens No.34 and No.35 are shown in Fig. 8. The locations of estimated elements in a joint are shown at the top of Fig. 8. As shown in this figure, the elements from C to F and from B to E are within a beam width of specimens No.34 and No.35, respectively. It was recognized that the shear stresses on elements from C to F in specimen No.34 have concentrated to the center of a column. The shear stress of specimen No.34 showed the asymmetric distributions in a joint. On the other hand, the distributions of shear stresses in specimen No.35 with eccentricity of 7.5cm concentrated to the eccentric side in a joint.

The shear forces calculated by accumulation of shear stress in some elements were shown in the same figure. The total shear forces within and outside a beam width in specimen No.34 were 695kN and 418kN, respectively. The shear forces within a beam width were 66% higher than that outside a beam width. On the other hand, as for specimen No.35 with eccentricity, the total shear forces within and outside a beam width were 705kN and 375kN, respectively. The shear forces within a beam width were

88% higher than that outside a beam width. From these analytical results, it was recognized that the concentrated shear force was applied to the eccentric side in a joint.

CONCLUSIONS

In order to investigate the effect of the eccentricity of beam axis toward column center on the deterioration of maximum story shear force and formation of shear resistant mechanisms of the joint, three-dimensional FEM analysis of eccentric beam-column joint was carried out.

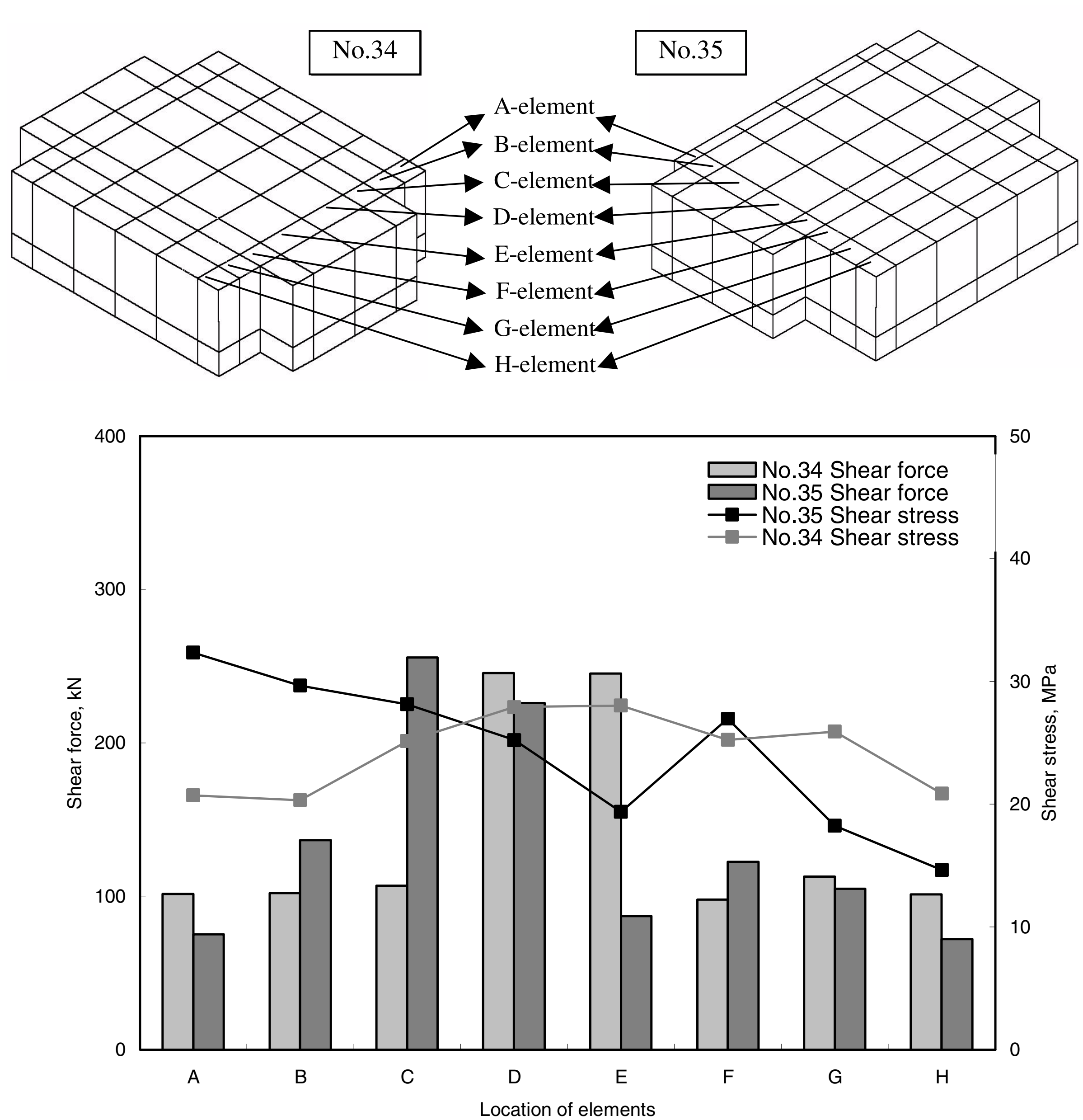


Fig. 8 Distributions of shear stress and shear force in a joint

From detailed investigations of analytical results, the following conclusions can be made:

(1) The deterioration of maximum story shear force of eccentric beam-column joints by the additional torsion moment was not observed in case when the beam flexural yields occurred without the joint shear failure and the eccentricity of beam axis toward the column center was relatively small as of 7.5cm.
(2) It was recognized that the shear stresses of eccentric beam-column joint concentrated to the eccentric side in a joint compared with the non-eccentric beam-column joint. The concentrations of shear stress in eccentric beam-column joints must be considered at the shear design of beam-column joints.
(3) In order to understand quantitatively the effect of eccentricity in a joint on the deterioration of maximum story shear force, it is necessary to analyze the beam-column joints with excessive eccentricity and brittle shear failure.

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