11 WCEE
Paper No. 486. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

ANALYTICAL STUDY ON THE SHEAR PERFORMANCE OF STEEL BEAM - R/C COLUMN CONNECTIONS IN HYBRID STRUCTURES

H. NOGUCHI and K. YONEZAWA

Department of Architecture, Faculty of Engineering, Chiba University,
1-33 Yayoi-cho, Inage-ku, Chiba-City, 263 Japan
Research Institute of Technology, Ohbayashi-gumi Corporation
4-640 Shimokiyoto, Kiyose-City, 204 Japan

ABSTRACT

The behavior of previously tested beam-column connections in hybrid structures with RC columns and S beams was simulated by the three-dimensional nonlinear finite element method. In this analysis, the slip-opening relationships between steel plates and concrete were considered by newly developed joint elements. Proposed analytical models can accurately predict the responses of specimens. It was indicated that nonlinear 3-D FEM analysis can clarify the stress resistance mechanisms of RCS connections from the observation of the internal stress condition and it can also contribute to the investigation of the shear strength of the RCS connections.

KEYWORDS

Hybrid structures; RCS connections; beam-column joints; shear strength; FEM; three-dimensional FEM analysis

INTRODUCTION

In Japan, RC column-Steel beam (RCS) moment frames have been recently used in low-rise buildings (3 to 10 story office and shopping center type buildings) with long floor span making the best use of the steel beams. The economic advantage of such systems is achieved by replacing steel columns with RC columns. The RC columns also offered increased stiffness compared to the steel frame. The shear performance of the connection is one of the most important items in the aseismic design of such systems.

The researches on the RCS connections in hybrid structures have been carried out actively by many technical research institutes of construction companies in Japan. In each institute, some reinforcement details of the connection have been proposed and investigated in the experiment to clarify the appropriateness of the details. However, as these researches have been carried out mainly based on experimental studies, the rational evaluation method of the shear strength of the connections based on the shear resistance mechanisms has not been established.

In this research, three-dimensional (3-D) nonlinear analysis was performed using FEM for previous test specimens of RCS connections in order to clarify the stress transfer mechanisms of the connections and propose the design equation for the shear strength of the connections.

ANALYTICAL PROGRAMS

In recent years, the development of the memory capacity and calculation speed of a computer have made 3-D nonlinear FEM possible by using Engineering Work Station (EWS). The number of research (Amemiya *et al.*, 1992a) using 3-D nonlinear FEM has increased. In the RCS connections of hybrid structures, the stress flow shows three-dimensional extent, because there is a large difference between a beam width and a column width. And panel concrete receives the confinement by various shapes of surrounding steel plates. Therefore, it is necessary to represent the three-dimensional extent of the stress flow caused by the details of the RCS connections using 3-D FEM analysis.

General guidelines regarding the selection of an appropriate element type and an element meshing method have not been established in the FEM analysis. In the present condition, these are decided by the restriction from the computer hardware environment. If a member has a simple form, it can be handled as the comparatively coarse element meshing with such an element that has a shape function with high order (elements of high order). For members in which details are complicated like connections in hybrid structures, a shape function with low order (elements of low order) is effective for handling and calculating. Thereupon, in order to predict the behavior of connections in hybrid structures, the authors have developed a 3-D nonlinear FEM analysis program in which low order elements and joint elements were installed based on the method developed by Uchida, *et al.* (1992b).

THE OBJECTS OF ANALYSIS

For the object of the analysis, three specimens (S-2, No.2, H-D10-5) (Sakaguchi, 1991; Kei *et al.*, 1990; Ozawa *et al.* , 1993) were selected from the previous experiments of RCS connections. All specimens had a simple through beam type connection where a steel beam was continuous through a RC column without special reinforcement. They failed in shear in the connection. For example, Fig.1 shows the shape of specimen S-2. Two cases were analyzed for the specimen S-2 in order to evaluate the influence of slip-opening between steel plates and concrete on member's behavior. In the first case, perfect bond was assumed, and in the latter case slip-opening was considered. In the experiment, all specimens were tested under reversed cyclic loading and constant axial loading.

Table.1 Properties of Specimen

	S-2	NO. 2	H-D10-5
L, H	400cm, 300cm	300cm, 200cm	400cm, 180cm
S-Beam section	H-400x150 x9x19	H-350x100 x6x19	H-300x150 x6.5x9
RC Column section	45cm×45cm Main bars 12-D19 Hoop4-U6.4@50 σ_B=301kgf/cm^2	40cm×40cm Main bars 12-D19 Hoop4-8 φ @50 σ_B=303kgf/cm^2	35cm×35cm Main bars 12-D19 Hoop 2-D10@75 σ_B=278kgf/cm^2
Connection	4-D6@50 σ_B=334kgf/cm^2	2-D6@25 σ_B=303kgf/cm^2	2-D10@50 σ_B=278kgf/cm^2
Reference	[3]	[4]	[5]

L : *Span*、H : *Height*、σ_B : *Concrete strength*

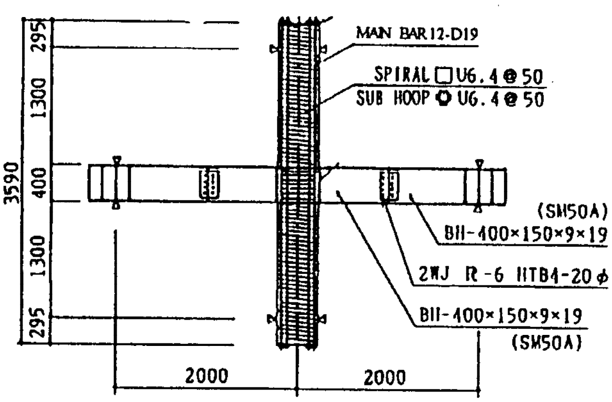


Fig.1 Shape of Specimen (S−2)

ANALYTICAL METHOD AND MATERIAL MODELS

Figure 2 shows a finite element idealization for the FEM analysis. The idealization was carried out with a half part divided by a vertical center line of the beam, due to the symmetric shape of specimens. In the analysis, all specimens were subjected to forced displacement at the both ends of the steel beam with a constant axial load on the column. To reduce the quantity of calculation, monotonic loading was assumed in the analysis. The followings are the outlines of the material models.

Concrete model

As for concrete model, the authors adopted an 8-node solid element and the equivalent uniaxial strain concept which was proposed by Darwin and Pecknold (1977) and developed for the three-dimensional analysis by Murray (Elwi *et al.*, 1979). As a failure surface, the five-parameter model (Faust *et al.*, 1974) developed by Willam and Warnke (1975) was used. The five-parameter was obtained from the panel experiments by Kupfer et al. (1973). As the basic uniaxial stress-strain relationship in the compression zone, Saenz's equation (1973) was used in the ascending zone, and Park model (1977) which considered increasing ductility by confined effect of lateral reinforcement in the connection was used for the descending curve after the maximum stress. Poisson's ratio of concrete was modeled as a function of compressive strain based on the Kupfer's experiment. After cracking, tension cut-off was assumed and the stiffness normal to a crack direction was set to be zero. No account was taken for the shear transfer behavior along the crack direction.

The characteristics of compressive strength of cracked concrete were modeled using a reduction factor λ which was assumed to be a function of the principal tensile strain across cracks. The equation for the reduction factor λ proposed by Ohkubo *et al.* (1989) was used.

Steel plate model and reinforcement model

A shell element was used as a steel plate model. The elasto-plastic model based on the von Mises yield criterion was used as the constitutive law of steel. A line element is used for a reinforcement model.

Joint model

A joint element which is applicable to the 3-D analysis were used in order to express the stress transfer mechanisms and the interaction between steel plates and concrete. The boundary between steel plates and concrete was defined as separated nodes, and a joint element was assumed to exist between the nodes. The slip and opening relationships between steel plates and concrete were obtained directly from the test. The two dimensional frictional link (Yonezawa *et al.*, 1994) was modified into a 3-dimensional model and was used as a joint element. The following shows the characteristics of the joint element.

1. The opening between steel plates and concrete in the direction normal to steel plates (σ_t-S_t):
When σ_t was a tensile stress, it was assumed that the stress increased linearly before σ_t=0.04Fc and equal to zero after σ_t=0.04Fc. When σ_t was a compressive stress, it was assumed that the stiffness was infinite and the stress increased linearly.

2. Stress -slip relationship in direction parallel to steel plates (σ_h-S_h) :
A linear increase was assumed before σ_h=0.04Fc. When σ_t was a compressive stress, the frictional factor was 0.65. For σ_h>0.65σ_t, it was assumed that σ_h=0.65σ_t, and the excess stress was released. When σ_t was a tensile stress, it was assumed that σ_h=0 and the excess stress was released.

The frictional factor and the cohesion strength were obtained from the push-out strength tests of H-shaped steel (Japan Concrete Institute, 1983). Table 2 shows characteristics of materials of the joint element. (refer to Figs. 3 and 5 for σ_t,S_t, σ_h, and S_h, Fc : concrete strength)

DEFINITION OF JOINT ELEMENTS

Referring to the joint element proposed by Yamada *et al.*, (1979), joint elements using a shape function of normal solid elements were developed. The interaction between steel plates and concrete was expressed

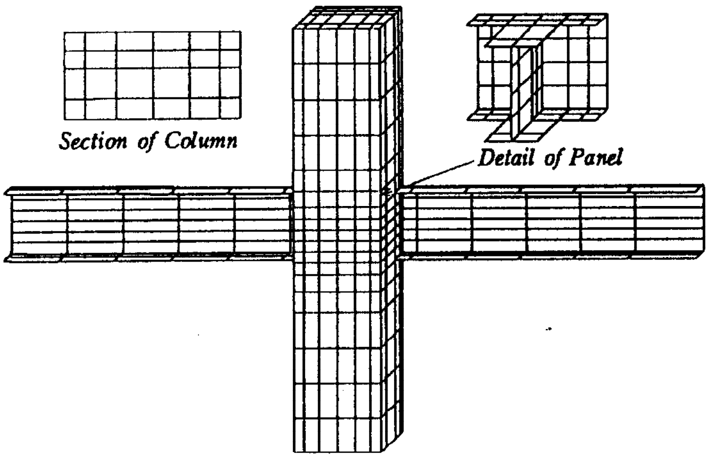


Fig.2 Finite Element Idealization

Table.2 Characteristics of Joint Element

	S-2	NO. 2	H-D10-5
Stiffness G_h*1 (kgf/cm^2)	24.0	24.0	24.0
Frictional factor	0.65	0.65	0.65
Cohesion strength*2 (kgf/cm^2)	12.0	12.0	12.0
Thickness	h=0.01cm	h=0.01cm	h=0.01cm

**1 A joint element was expressed as a shear stiffness parallel to a boundary face*
**2 0.04 × Fc*

by the joint element. In an ordinary solid element, the stresses of six components acting at any positions consist of three stresses normal to the surface ($\sigma_{xy}, \sigma_{yz}, \sigma_{zx}$) and three shear stresses parallel to the surface ($\tau_{xy}, \tau_{yz}, \tau_{zx}$). The six-components describe the constitutive equations expressing the material characteristics of the element. As the joint element inserted into a boundary surface was very thin, it was simple to evaluate the stiffness and stresses by three components that consist of two shear stresses (σ_{h1}, σ_{h2}) and the normal stress to the boundary face (σ_t). Figure 3 shows the concept of the joint element used in this analysis. As shown in Fig. 3, in normalized coordinates system(ξ, η, ζ), X'-axis was taken as the tangent of ξ -axis, Y'-axis was taken as the tangent of η -axis in any positions of the element. Z'-axis was taken in vertical direction to X'-axis and Y'-axis.

A constitutive law ({D}matrix) was assumed to be given by stress-strain relationships between a stress matrix $\{\sigma\}$ and a strain matrix {S} on each axis of local coordinate system (Eq.(2)). As for the equation of "nodal displacement-strain relationships of the element", ({B}matrix), the shape function and the cosine-matrix between the whole and local coordinate system were used. Then, as the thickness of the joint element is extremely small, attention was paid only to the displacement slope of Z' direction (Eq.(1)).

Because the thickness, h was included in the denominator of the stiffness, the stiffness of the element grew large infinitely with a decrease of the thickness, h. Therefore, in the previous research[16], it was noted that a large error would happen, when the nodal-displacement was solved. Yamada had devised a method to make a transformation matrix in order to avoid this problem. However, as the transformation matrix became complicated in the three-dimensional analysis, it was difficult to apply Yamada's method. A pilot analysis was carried out to confirm the appropriate limit value of the thickness by which the error could be prevented. From the pilot analytical result, it was confirmed that the solution was convergent and stabilize with a value greater than 0.1 mm. From the result, the thickness of the joint element was defined as 0.1mm in this analysis.

As for the joint element, it was assumed that the three-directional springs were distributed continuously to the boundary surface. Compared to the bond link in which the spring is set up directly at each node, the joint element forms a continuous stress distribution along the boundary surface independent of an element meshing method. The joint element is considered to be suitable to represent an interaction between surfaces in the three-dimensional FEM analysis.

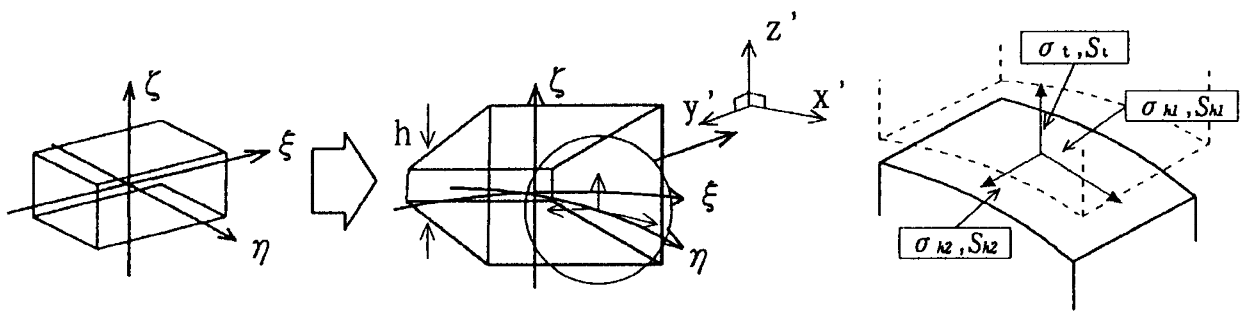


Fig.3 Concept of a Joint Element

$$\begin{bmatrix} S_{h1} \\ S_{h2} \\ S_t \end{bmatrix} = \begin{bmatrix} \dfrac{\partial u_{h1}}{\partial Z'} \\ \dfrac{\partial u_{h2}}{\partial Z'} \\ \dfrac{\partial u_t}{\partial Z'} \end{bmatrix}_{3\times 1} = \begin{bmatrix} B \\ 3 \times 3n \end{bmatrix} \begin{bmatrix} u_1 \\ v_1 \\ w_1 \\ \vdots \\ u_n \\ v_n \\ w_n \end{bmatrix}_{3n \times 1} \quad \boxed{\text{---Eq.(1)}}$$

$$\begin{bmatrix} \sigma_{h1} \\ \sigma_{h2} \\ \sigma_t \end{bmatrix} = \underbrace{\begin{bmatrix} G_{h1} & 0 & 0 \\ 0 & G_{h2} & 0 \\ 0 & 0 & G_t \end{bmatrix}}_{[D]} \begin{bmatrix} S_{h1} \\ S_{h2} \\ S_t \end{bmatrix} \quad \boxed{\text{---Eq.(2)}}$$

u_n, v_n, w_n :Increment nodal displacements of the whole coordinate system

u_{h1}, v_{h2}, w_t :Increment displacements of a local coodinate system at an optional position

n : Number of node in a elemet

[D]: A constitutive equation expressing material characteristics of a element

G_{h1} :A stiffness at X'direction G_{h2} :A stiffness at X'direction

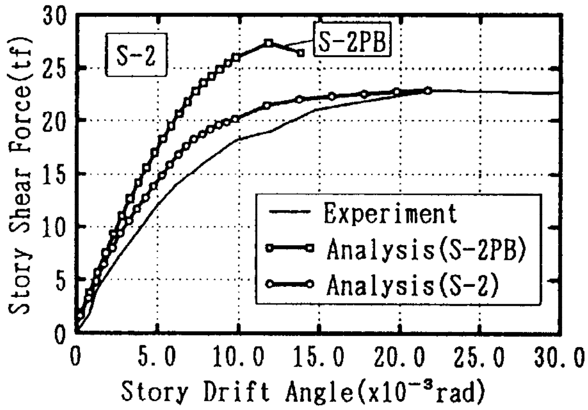
G_t :A stiffness at X'direction

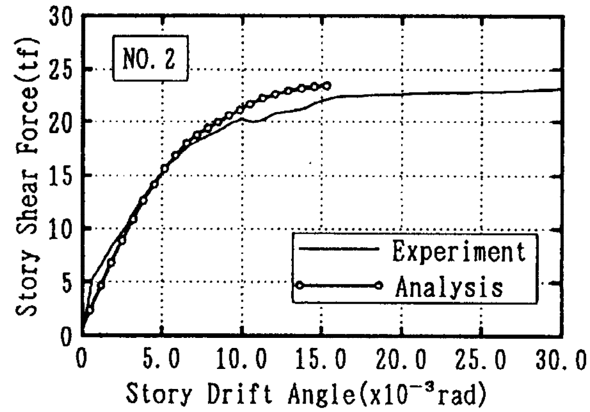
ANALYTICAL RESULTS

Figure 4 shows the relationships between the story shear force-story drift angle obtained from the analytical and experimental results. The analytical results are shown in Table.3. As an example, Figure 5 shows the deformation mode obtained from the analysis of specimen S-2. As for the analytical results of specimens S-2 and H-D-10-5, the predicted stiffness was a little larger than the experimental results. The predicted maximum strength showed a good agreement with the experimental results. As for the analytical results of specimen No. 2, the predicted strength was a little larger than the experimental result, but the predicted stiffness showed a good agreement with the experimental result. In the analysis of specimen S-2PB with perfect bond, the stiffness and the maximum strength were significantly overestimated. From this point, it was recognized that the slip and opening between steel plates and concrete influenced greatly on the analytical results. As for specimens S-2, H-D10-5, the element meshing of a column was coarse, because the memory capacity of a computer was restricted. This is a reason why the analysis overestimated the stiffness in comparison with the experimental results.

In three specimens, the steel web in the connection yielded before the maximum load. From the deformation mode, the deflection of the connection was larger than beams and columns. In the analysis, specimens failed by crushing of concrete in the connection after yielding of the web in the connection. The predicted failure mode agreed with the experimental results. It was considered that this analysis could predict the responses accurately by considering the slip-opening relationships between steel plates and concrete.

Page 6





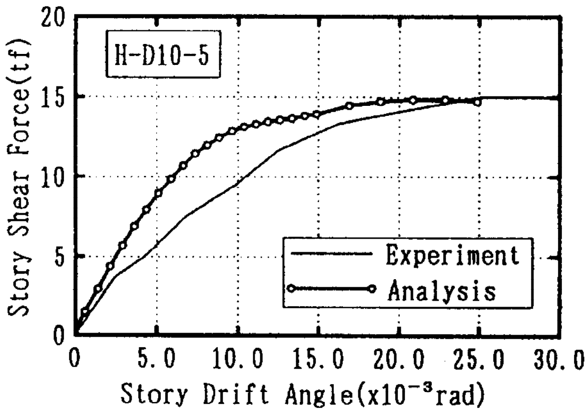


Fig.4 Story Shear Force – Story Drift Angle

Table.3 Analytical Results

	P_w	P_h	Maximum load		
			Test	Analysis	Analysis / Test
S-2	17.6	19.5	23.0	22.5	0.98
NO. 2	21.1	22.2	22.4	23.4	1.04
H-D10-5	11.4	14.8	15.0	14.8	0.98

P_w : Yielding of web in the connection *(Unit : tf)*
P_h : Yielding of hoop in the connection
**All values are story shear force.*

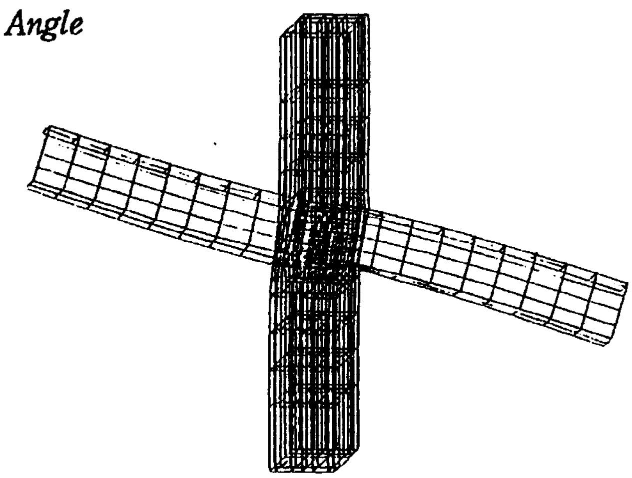


Fig.5 Deformation mode (S-2)

STRESS TRANSFER MECHANISMS

Figure 6 shows the principal stress distributions of column concrete at the maximum load for specimen S-2 in each section. The crushing of concrete was defined by black circles in this figure. At the section in the beam flange (Fig. 6, A-A' section), the crushing of concrete occurred at the column concrete close to the beam flange in the connection from the bearing by a leverage of the beam flange. The lateral beam web separated the panel concrete into two pieces, because the slip occurred between concrete and the lateral beam web in the connection. Inside of each concrete piece, the intensity of the principal compressive stress was very high in diagonal direction, and the crushing occurred at the corner of the concrete pieces.

At C-C' section (Fig. 6) at the outside of the beam flange, the principal compressive stress level was lower than that at A-A' section in the middle of the column width. In the analysis, the specimen failed in shear at the connection, and it was recognized that the damage of the bearing resistance mechanism was large. In other specimens, the principal compressive stress level was about the same. Estimating from crushing points in the Fig. 6, it was recognized that the stress was transferred from the steel beam to the column by bearing between the beam flange and the lateral beam web (Fig. 7). The shear force was transmitted by the diagonal strut in two concrete pieces (Fig. 8), and the beam web in the panel. Thus, without lateral beams, the concrete strut angle in the connection would change, and it was considered that the lateral beam influenced the shear strength of connections.

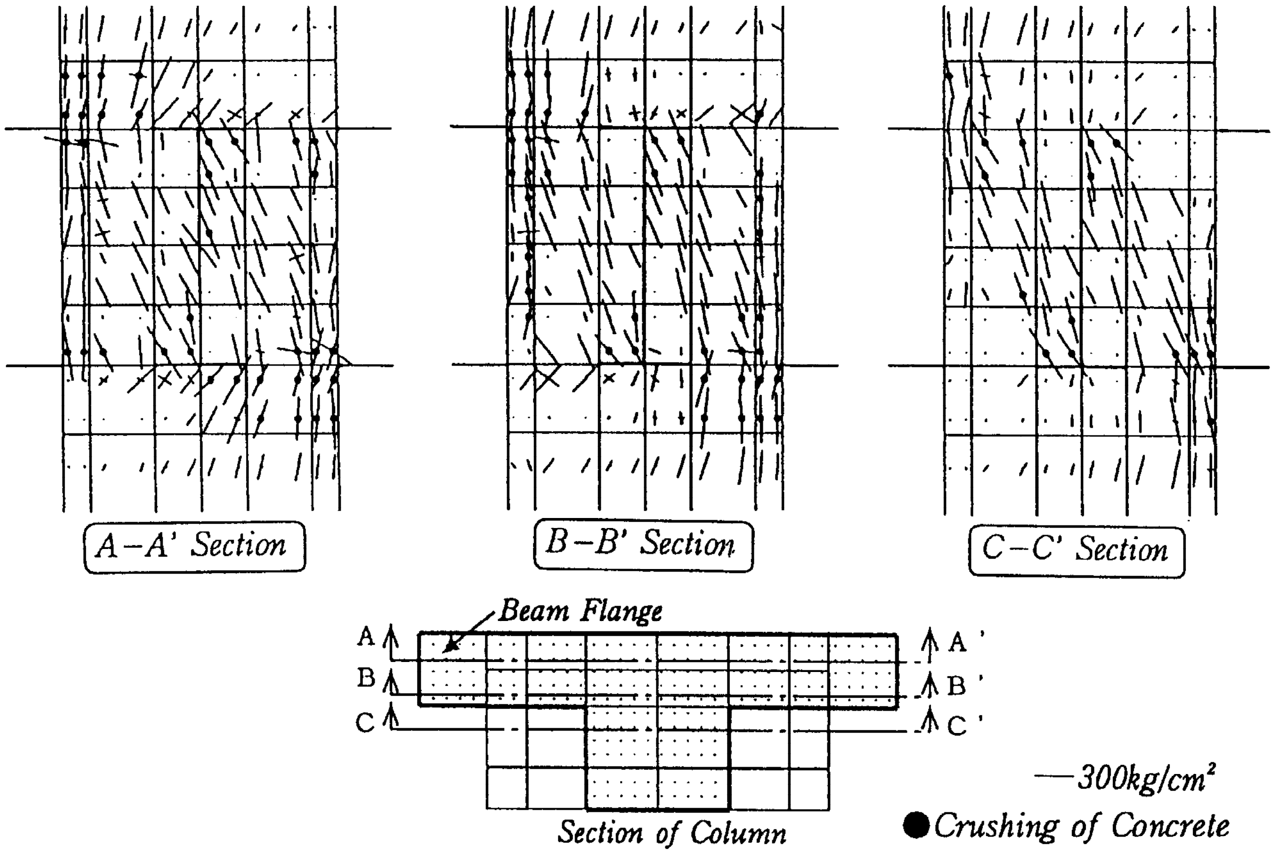


Fig.–6 The Principal Stress Distribution

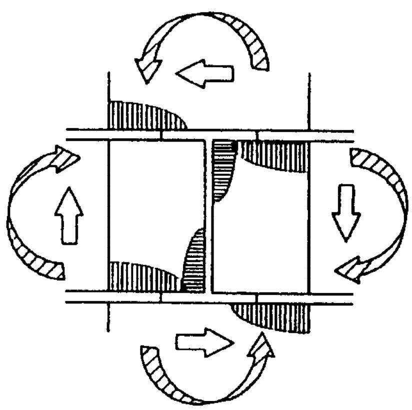


Fig.–7 Bearing Resistance Mechanism

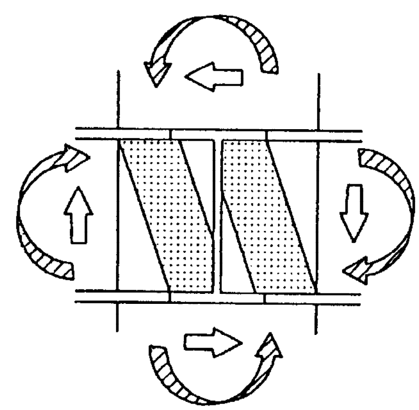


Fig.–8 Shear Resistance Mechanism

CONCLUSIONS

1. Proposed analytical models can accurately predict the responses of specimens by considering the slip-opening relationships between steel plates and concrete.
2. The slip-opening relationships between steel plates and concrete gave a large effect on the shear behavior of members.
3.Nonlinear 3-D FEM analysis can clarify the stress resistance mechanisms of RCS connections from the observation of the internal stress condition and contributed to the investigation of the shear strength of the RCS connections.

ACKNOWLEDGMENTS

The works reported in this paper are related to the research regarding US-Japan cooperation research on hybrid structure (Chairman : Prof. H. Aoyama, Nihon University). And this research has been discussed by RCS Sub-Committee (Chairman : Prof. H. Noguchi, Chiba University). The authors deeply acknowledge to the members of this sub-committee, and also to Mr. Uchida of Fujita Corporation, and Dr. Naganuma of Obayashi Corporation, for their valuable suggestions and comments on this works.

REFERENCES

Amemiya, A., K. Uchida and H. Noguchi (1992a). Three-Dimensional Nonlinear Finite Element Analysis for Reinforced Concrete Members. *Summaries of Technical Papers of Annual Meeting AIJ*, 1061-1064.

Amemiya, A., K. Uchida and H. Noguchi (1992b). The Development of 3-Dimensional Non-linear Finite Element Method Program for The Reinforced Concrete Member. *Proceeding of JCI*, **Vol.14, No. 2,** 21-26.

Darwin, D. and D. A. Pecknold (1977). Nonlinear Biaxial Law for Concrete. *Journal of the Engineering Mechanics Division, ASCE,* **Vol. 103, No. EM2,** Proc.Paper 12839, 229-241.

Elwi, Alaa, A. and David, W. Murray (1979). A 3D Hypoelastic Concrete Constitutive Relationship. *Journal of the Mechanics Division, ASCE,* **Vol. 105, No. EM4,** Proc. Paper 14746, 623-641.

Faust, J. H. G., J. Szimmat, E.P.Warnke and K. J. William (1974). Recent Developments in the Finite Element Analysis of Prestressed Concrete Reactor. *Nucl. Eng. Des.*, **28**, 42-75.

Japan Concrete Institute (1983). Committee Report on Mixed Structure System. 115-130. Kei, T., Y. Higashibata, Y. Sugiyama, K. Hujimura, H. Itou and Y. Honma (1990). An Experimental Study on RC Columns-Steel Beams Joints (Part 1-2). *Summaries of Technical Papers of Annual Meeting AIJ,* 1183-1186.

Kupfer, H. B. and K. H. Gerstle (1973). Behavior of Concrete under Biaxial Stresses. *Journal of the Engineering Mechanics Division, ASCE,* **Vol. 99, No. EM4,** Proc. Paper 9917, 853-866.

Ohkubo, M., S. Hamada and H. Noguchi (1989). Basic Experiments on the Degradation of Cracked Concrete under Seismic Forces. *Proc. of JCI Colloquium on Analytical Study on Shear Design of RC Structures*, 17-22.

Ozawa, J., T. Yamamoto, T. Iwakura, and M. Suda (1993). Steel Beam-Reinforced Concrete Column Joints of Mixed Frame Structures. *Tokyu Construction Technical Reports*, **19**, 79-86.

Park, R. and P. D. Leslie (1977). Curvature Ductility of Circular Reinforced Concrete Columns Confined by ACI Spirals. *Proc. of 6th Australian Conference on the Mechanics of Structures and Materials,* **1,** Technical Papers, Christchurch, New Zealand, 342-349.

Saenz, L. P. (1964). Discussion of Equation for the Stress-Strain Curve of Concrete, by P. Desayi and S. Krishnan, *America Concrete Institute Journal,* **61**, 1229-1235.

Sakaguchi, N. (1991). Shear Capacity of Beam-Column Connection Between Steel Beams and Reinforced Concrete Columns. *Journal of Structural and Construction Engineering, AIJ,* **428**, 69-78 .

Willam, K. J. and E. P. Warnke (1975). Constitutive Model for the Triaxial Behavior of Concrete. *International Association for Bridge and Structural Engineering Proceeding,* **19.**

Yonezawa, K. , H. Yoshikawa, T. Ohya and H. Noguchi (1994). Study on Shear Strength of Crossed Section Columns of a New Reinforced Concrete System with Steel Plates by FEM Analysis. *Journal of Structural and Construction Engineering, AIJ,* **Vol.15, No. 2**, 179-189.

Yamada, Y. , Y. Ezawa, I. Nishiguchi and M. Okabe (1979). Handy Incorporation of Bond and Singularity Elements in the Finite Element Solution Routine. *SEIKEN TECHNICAL REPORTS*, **31-6**, 519-524.

Yamada, Y. (1980). Matrix Methods in the Material Mechanics, Baifukan Inc.