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ANALYSIS OF SHEAR RESISTANCE MECHANISMS OF RC BEAM-COLUMN CONNECTIONS SUBJECTED TO SEISMIC FORCES

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SUMMARY

The nonlinear behaviour of RC beam-column connections under reversed cyclic loading was analyzed by the FEM with the emphasis on the shear resistance mechanisms of a connection. The applicability of the macro model was discussed by comparing the macro model calculated from the FEM analytical data with the shear distribution model and beam shear model.

INTRODUCTION

There have been many active experimental studies for beam-column connections, but it is necessary to investigate the nonlinear behavior of beam-column connections analytically in order to clarify the shear resistance mechanisms and develop a rational design method for beam-column connections. In this study, the nonlinear behaviour of beam-column connections under reversed cyclic loading was analyzed by the FEM with the emphasis on the shear resistance mechanisms of a connection (Ref. 1, 2, 3). The investigating approach in this study is shown in Fig. 1.

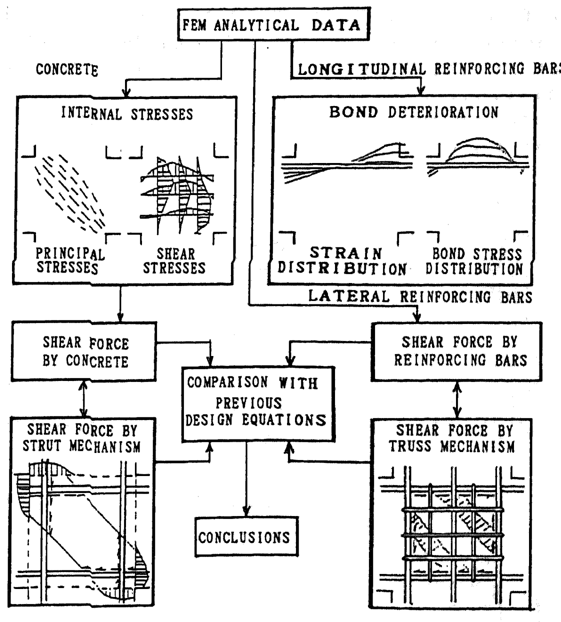


Fig.1 Investigating Approach

ANALYTICAL MODELS

The subject of analysis was limited to the connection without transverse beams, and the plane stress was assumed. In this FEM model, the rotation of principal axes and the stress-strain curves of concrete under cyclic stresses, the criterion for opening and closing of cracks and the bond stress-slip curves under cyclic stresses were considered. The development process for the analytical models was written in Ref. 2.

SPECIMEN TO BE ANALYZED

Four half-scaled interior connection specimens, J - 1, J - 1', J - 2, J - 3, were selected for the subject of analysis as shown in Table 1. Specimen J - 1 was tested by Kamimura and Hamada (Ref. 4), and specimens J - 2 and J - 3 were tested by Tada and Takeda (Ref. 5). Each specimen showed its own failure mode as shown in Table 1. The middle longitudinal reinforcing bars were set up only in the column of an imaginary specimen J - 1' to study the role of the column middle reinforcing bars in the shear resistance of the connection with good bond for beam longitudinal bars.

The detail and the finite element idealization of the specimens are shown in Figs. 2 - 3, respectively. The crack pattern was set up using link elements in accordance with the test results. In the analysis, two and half cycles of reversed deflection were applied to specimens J - 1, J - 2, J - 3 except for specimen J - 1'.

Table 1 Specimens and Material Properties

Specimen	J-1	J-1'	J-2	J-3
Failure Mode *	Joint F. Bond D.	Joint F.	Bond D. after Beam Y.	Beam Y.
Bond Situation	Poor	Good	Poor	Perfect
Concrete [kgf/cm²]	$E_c = 2.54 \times 10^5$ $f_c = 197$		$E_c = 2.20 \times 10^5$ $f_c = 290$	
Beam Bars [kgf/cm²]	$E_s = 1.94 \times 10^6$ $_s\sigma_y = 3633$		$E_s = 2.11 \times 10^6$ $_s\sigma_y = 3510$	
Joint Hoops [kgf/cm²]	$E_s = 1.98 \times 10^6$ $_s\sigma_y = 3300$		$E_s = 2.11 \times 10^6$ $_s\sigma_y = 3200$	
Bond Characteristic (Analytical)	Initial Bond Stiffness = 8000 Second Bond Stiffness = 400			
[kgf/cm³] **	$\sigma_{B1} = 24$ $\sigma_{B2} = 50$	$\sigma_{B1} = 60$ $\sigma_{B2} = 120$	$\sigma_{B1} = 28$ $\sigma_{B2} = 60$	$\sigma_{B1} = 84$ $\sigma_{B2} = 180$
Beam Bars Stirrups	3-D22 2-9φ	9-D13 2-9φ	3-D16 2-9φ	3-D16 2-9φ
Column Bars Hoops	8-D22 2-9φ	10-D22 2-9φ	8-D16 2-9φ	8-D16 2-9φ
Joint Hoops Pw(%)	2-9φ 3set@6.0 0.58	2-9φ 3set@6.0 0.58	2-9φ 5set@4.0 0.98	2-9φ 5set@4.0 0.98

*) F. : Failure D. : Deteriolation Y. : Yielding
**) σ_{B1} : Bond Deteriolation Stress σ_{B2} : Maximum Bond Stress

RESTORING FORCE CHARACTERISTICS

The analytical load-story displacement relationships are compared with the test results in Fig. 4. For J - 1 and J - 2, the analytical results gave a good agreement with the experimental shape of hysteresis loops. The analytical restoring force characteristics adopted the pinching-shape with poor energy dissipation capacity, as cracking and bond deterioration of beam longitudinal bars in the connection progressed under the subsequent cyclic loading. For specimen J - 3, the analytical restoring force characteristics showed the stable spindle-shape hysteresis loops and almost the same tendency as the test results. For specimen J - 1' with good bond for beam longitudinal bars, the analytical maximum strength was

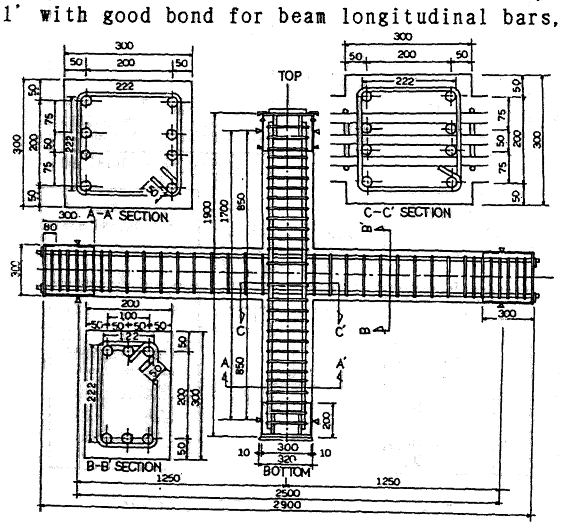


Fig. 2 Detail of Specimen

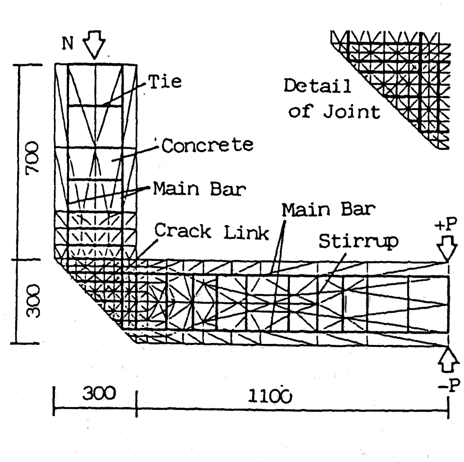
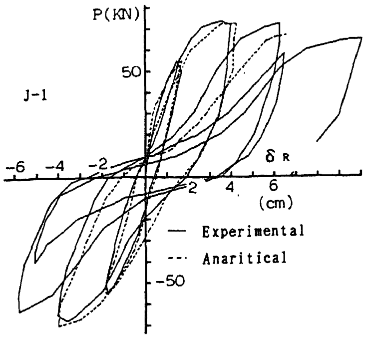
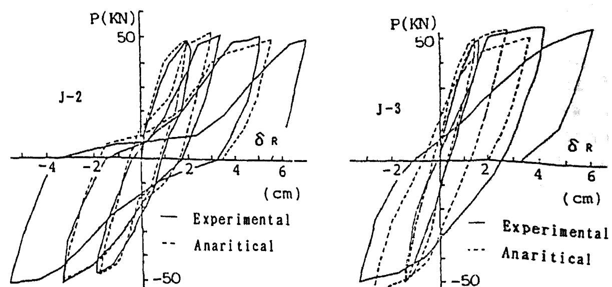


Fig. 3 Finite Element Idealization



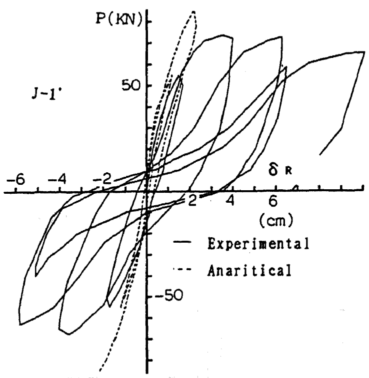
a) Shear and Bond Deterioration



b) Bond Deterioration after Beam Flexural Yielding

c) Beam Flexural Yielding

Fig.4 Load-Story Displacement Relationships

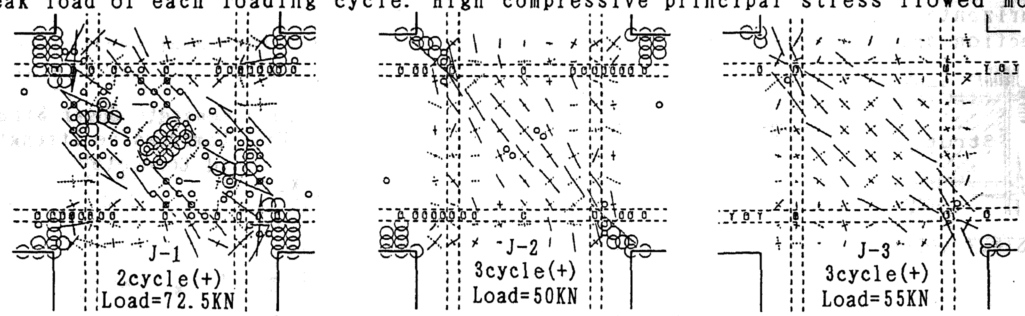


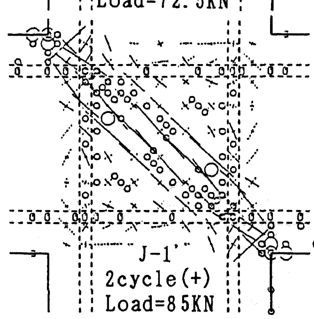
d) Shear Deterioration

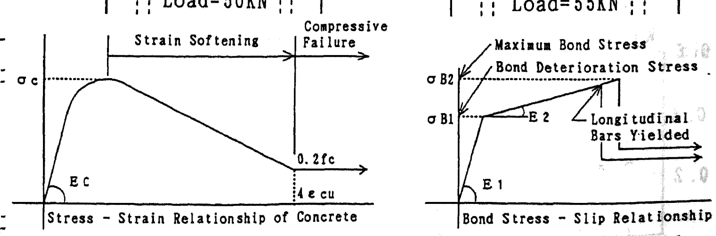
higher than the experimental strength for specimen J - 1 with poor bond. For J - 1, J - 2, J - 3, the analytical results also gave a good agreement with the test results for crack propagation, progress of failure, connection behaviour and bond slip of beam longitudinal bars through the connection. The accuracy of the analytical results was considered to be sufficient to simulate the internal stresses in the connection.

PRINCIPAL STRESS DISTRIBUTION

Fig. 5 shows principal stress distribution of the connection concrete at the maximum strength for specimens J - 1, J - 1', and at the peak load during the last loading cycle for specimens J - 2, J - 3. It is one of the most advantageous points in FEM analysis that internal stress flow is visible. The compressive strut, where the compressive principal stress was dominant, was formed along the diagonal line of the connection near the peak load of each loading cycle. High compressive principal stress flowed more







o:Strain Softening ○:Compressive Failure 0:Bond Failure

Fig.5 Principal Stresses

widely in the connection for good bond specimen, J - 3, than in the connection for bond deterioration type specimen, J - 2. The compressive strut was formed clearly along the diagonal line for J - 1'. The stress-strain relationship of concrete after peak stress is represented by descendant slope called strain-softening which shows the behaviour between ductile and brittle state. Strain-softening was remarkable along the diagonal line on the connection of J - 1', but the compression failure was less remarkable in specimen J - 1' than in J - 1. The analytical failure mode gave a good agreement with the test results for specimens, J - 1, J - 2 and J - 3.

SHEAR STRESSES CONTRIBUTED BY COMPRESSIVE STRUT MECHANISM

The macro model for the shear resistance mechanisms proposed by Park and Paulay (Ref. 6) was shown in Fig. 6. In the proposed macro model, the contribution of the concrete and connection reinforcing bars to the connection shear resistance were represented by the compressive strut mechanism and the truss mechanism, respectively. The horizontal connection shear force, Vch, provided by the compressive strut mechanism was calculated from the corresponding analytical data by FEM as follows,

$$Vch = {}_BC_c + \Delta_B T_c - Vcol \tag{1}$$

in which ${}_BC_c$ = concrete compressive force from the beam, $\Delta_B T_c$ = part of the total beam bar bond force contributing to the strut mechanism and Vcol = horizontal shear force across the column (See Fig. 6). In the shear stress distribution model, the shear force contributed by compressive strut were obtained by integrating concrete shear stress over the central horizontal section in the connection and subtracting the

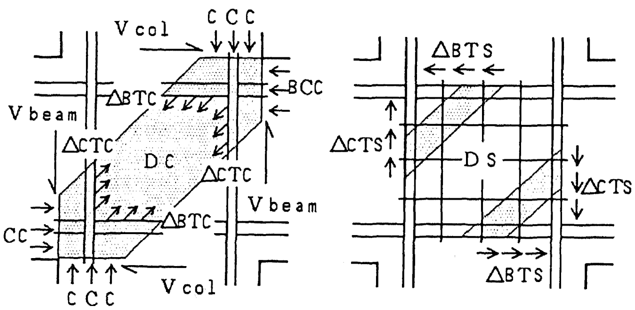
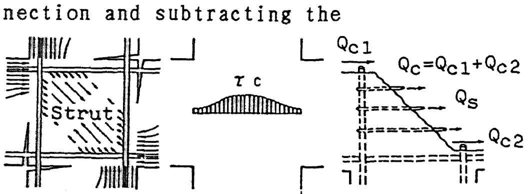


Fig. 6 Macro Model for Shear Resistance Mechanisms Proposed by Park and Paulay



STRUT MODEL SHEAR DISTRIBUTION MODEL BEAM SHEAR MODEL

K1 = τc/Fc τc : Concrete Shear Stress
Fc : Compressive Strength of Concrete

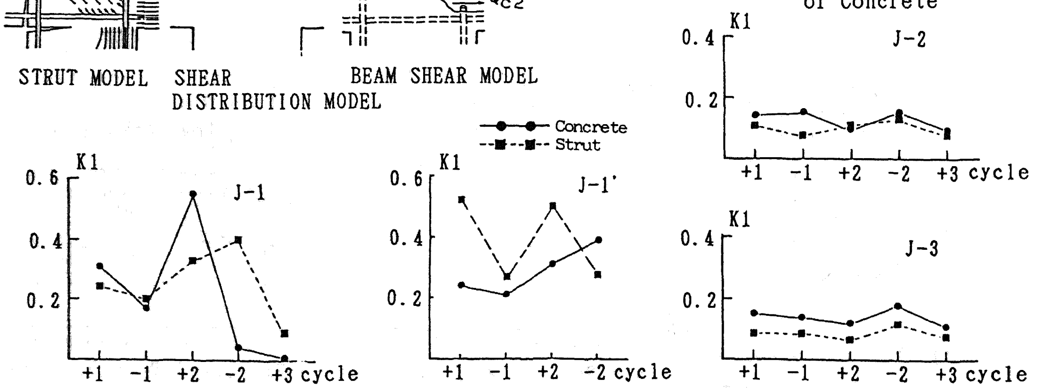


Fig. 7 Concrete Shear Stresses Calculated by Strut Mechanism and Shear Distribution Models

component of the diagonal reaction forces, which were produced in connection concrete by the truss mechanism of connection reinforcing bars. The shear forces, Vch, calculated by Eq. 1 are compared in Fig. 7 for the peak load in each cycle with the shear forces obtained by the shear stress distribution model. The strut mechanism model gave a good agreement with the shear stress distribution model for all four specimens. It was shown that the shear stress contributed by concrete could be estimated by the compressive strut mechanism.

SHEAR STRESSES CONTRIBUTED BY TRUSS MECHANISM

The horizontal shear forces, Vsh, contributed by the truss mechanism was calculated from the analytical data by FEM as follows,

$$Vsh = \triangle_B T_S \tag{2}$$

in which $\triangle_B T_S$ = shear forces introduced at the boundaries of the connection core by beam bar bond forces in the outer concrete of the compressive strut (See Fig. 6). The shear forces, Vsh, calculated by Eq. 2 were compared for the peak load in each cycle with the shear forces obtained by the strain in the connection reinforcing bars in Fig. 8. The truss model was not in agreement with the contribution of connection reinforcing bars for J - 1, J - 2, J - 3. It was considered that this was because these three specimens had no middle longitudinal bars in the column, and the beam bar bond forces, $\triangle T$, in the connection were separated into the following two kinds; one is $\triangle_B T_C$ inside the compressive strut, and the other is $\triangle_B T_S$ outside the strut. In Paulay and Park's truss mechanism model, the horizontal and vertical compression forces which need to be applied to the core concrete at the boundaries of the connection, to sustain the diagonal compression field , Ds in Fig. 6, can originate from distributed horizontal (connection shear reinforcing bars) and vertical tension reinforcement (column middle bars). For J - 1' with the column middle bars, the truss model gave a better agreement with the contribution of the connection reinforcing bars. It is considered that the further investigation is needed for the role of the column middle bars and the bond forces of the beam and column bars inside and outside of the compressive strut in the truss mechanism.

TOTAL SHEAR FORCES CONTRIBUTED BY CONCRETE AND SHEAR REINFORCING BARS

The total of shear forces contributed by concrete and connection reinforcing bars was calculated by the three methods shown in Fig. 7 for specimen J - 1 as

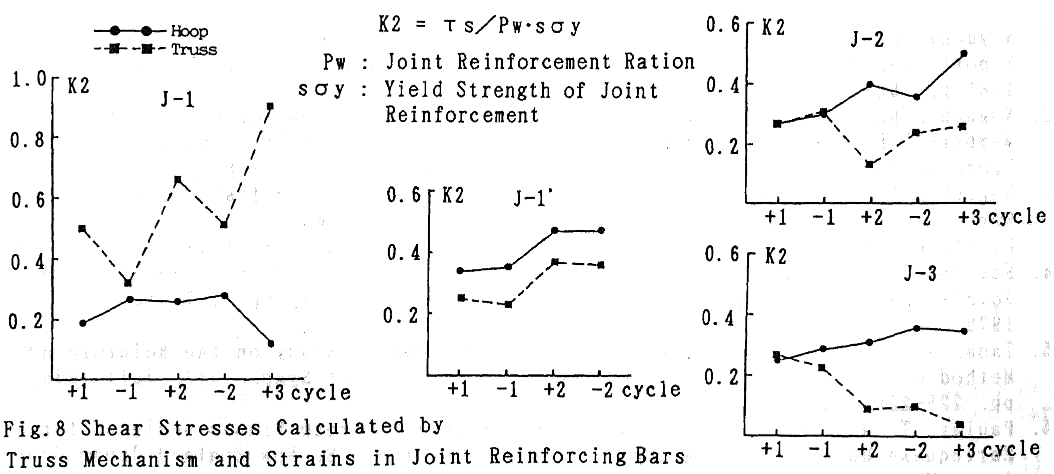


Fig. 8 Shear Stresses Calculated by Truss Mechanism and Strains in Joint Reinforcing Bars

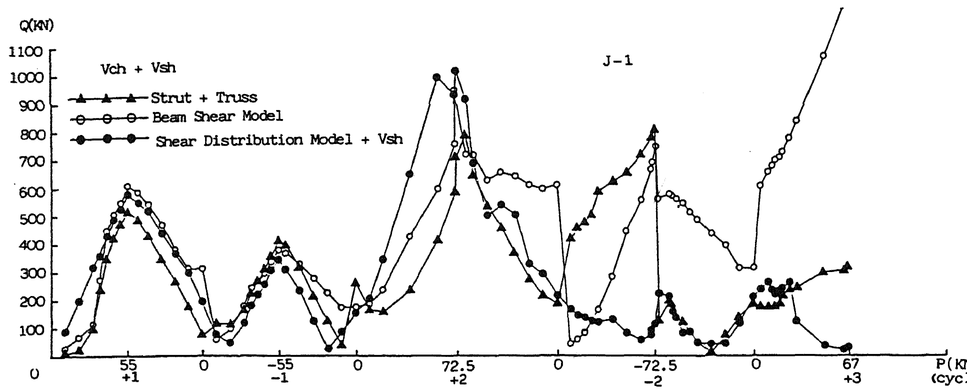


Fig.9 Shear Forces Contributed by Concrete
and Joint Shear Reinforcing Bars

shown in Fig. 9. The two mechanisms (strut and truss) model gave a good agreement with the shear stress distribution model and the beam shear model for J - 1, which was of connection failure and bond deterioration type. But it should be noted that the errors in the strut and truss mechanisms were compensated each other in the two mechanism model.

After the positive peak load in the second cycle, the good correspondence with the other two models could not be observed because of the local compression failure of connection concrete.

CONCLUSIONS

The nonlinear behaviour of reinforced concrete beam-column connections under reversed cyclic loading was analyzed by FEM with the emphasis on the shear resistance mechanisms of the connection.

The shear force contributed by connection concrete could be estimated by the compressive strut mechanism model proposed by Park and Paulay considerably well.

The truss model proposed by Park and Paulay was not in agreement with the contribution of connection reinforcing bars for the specimens without the middle longitudinal bars in the column. The further investigation is needed for the role of each component of the truss model.

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