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Stress Transfer from Steel Beams to Reinforced Concrete Columns

Transfert de contraintes des poutres d'acier vers les poteaux en béton armé

Kraftübertragung von Stahlriegeln auf Stahlbetonstützen

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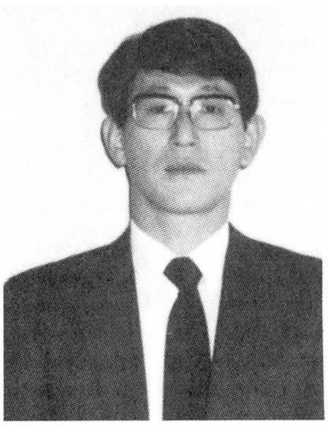

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SUMMARY

Use of structural system composed of steel beams and reinforced concrete columns has been thought to be more economical and flexible in structural design. This paper describes the mechanism of stress transfer from the steel beams to reinforced concrete columns through the joint. In this mechanism, the principle of prying action of the steel beam embedded in reinforced concrete column was applied to estimate the ultimate strength of joint, because of its simplicity and reasonable accuracy.

RÉSUMÉ

L'emploi de structures composées de poutres d'acier et de poteaux en béton armé s'est avéré nécessaire pour obtenir davantage d'économie et de flexibilité dans les projets de structures. Cet article décrit le mécanisme de transfert de contraintes au niveau des joints, des poutres d'acier vers les poteaux en béton armé. Le principe d'effet de pince à levier a été appliqué, dans ce mécanisme, sur la poutre d'acier noyée dans le béton du poteau, afin d'évaluer la résistance ultime du joint de liaison; ceci pour une raison de simplification et de précision acceptable.

ZUSAMMENFASSUNG

Tragsysteme aus Stahlriegeln und Stahlbetonstützen sind kostengünstiger und erlauben eine flexiblere Projektierung. Dieser Beitrag beschreibt die Kraftübertragung von Stahlriegeln auf die Stahlbetonstützen. Dabei wird die Spaltwirkung des im Beton eingebetteten Bewehrungsstabes zur Abschätzung der Knotentragfähigkeit herangezogen, da dies zu einer einfachen und vernünftig genauen Lösung führt.

1. INTRODUCTION

Recently in Japan, structural system composed of steel beam and reinforced concrete column is proposed. Reinforced concrete columns have excellent axial capacity and steel beams have excellent strength and ductility against bending and shear load. Therefore, it is reasonable to construct a building using reinforced concrete columns and steel beams. However, very little information is available on the stress transfer from the steel beam to the reinforced concrete column through the joint. The object of this study is to make the stress transferring mechanism of the joints clear theoretically and experimentally.

2. STRESS TRANSFERRING MECHANISM

Fig. 1 shows the mechanism of the stress transfer from the embedded steel beam to the reinforced concrete column through the interior composite beam-column joint. The mechanisms are illustrated by the free body diagrams of each members. As shown in Fig. 1, the forces acting in the steel beam consist of the bearing forces $x_b b \lambda F_c$ for below the bottom flange and above the top flange of embedded steel beam, the frictional forces $P_{rc} l/h$ and external load P_{rc}. In this paper, this force system is called the prying mechanism. On the other hand, the system of forces acting in the lower and upper reinforced concrete columns consist of the bearing force, the frictional force $P_{rc} l/h$, tensile force ${}_rT_y$ of the longitudinal bars and external load $P_{rc} l/h$ and N_{rc}. In this mechanism, the longitudinal bars in the joint act for transmitting the bearing forces to the lower and upper columns.

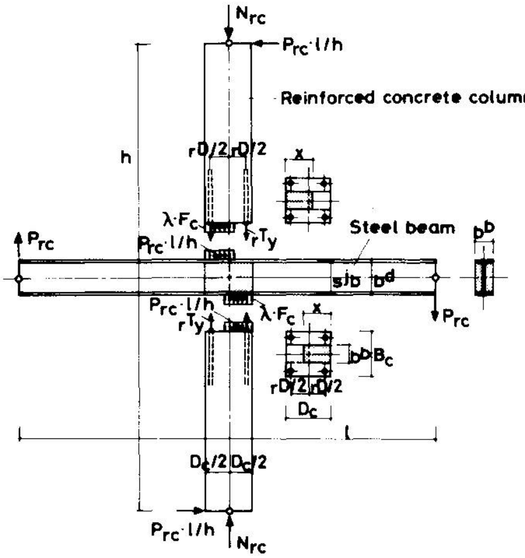


Fig. 1 Stress Transferring Mechanism.

3. ULTIMATE STRENGTH OF INTERIOR BEAM-COLUMN ASSEMBLY

The ultimate strength ${}_tm$ of interior beam-column assembly is given as,

$$ {}_tm = \min.\ ({}_mm,\ {}_pm) \qquad (1) $$

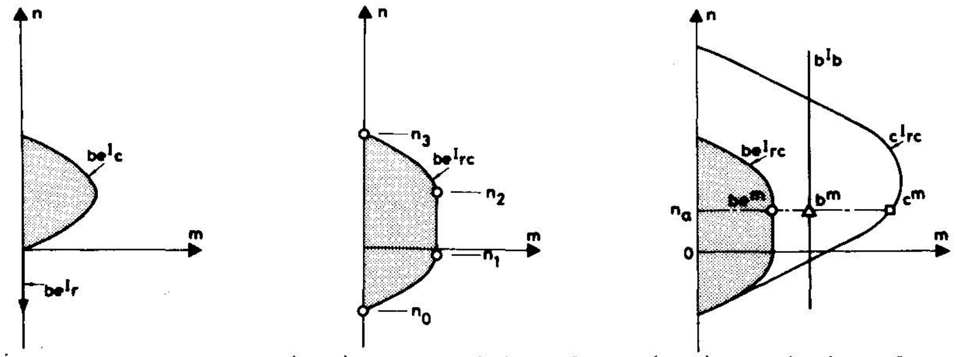
where ${}_mm$ and ${}_pm$ are the flexural capacities of the members and the shear capacity of the joint, respectively. The shear capacity of the joint is not dealt in this paper, because the object of this study is to estimate the mechanism of stress transfer from the steel beam to the reinforced concrete column through the joint.

The flexural capacities ${}_mm$ are estimated as,

$$ {}_mm = \min.\ ({}_bm,\ {}_cm,\ {}_{be}m) \qquad (2) $$

where ${}_bm$ and ${}_cm$ are the resisting moment of the beam and column, respectively. ${}_{be}m$ is the resisting moment for the prying mechanism of the embedded steel beam. ${}_bm$ and ${}_cm$ can be estimated by the superposed strength method easily. Therefore, a method for predicting the resisting moment capacity for the prying mechanism is discussed in this paper.

The steel beam is assumed to be rigid. As shown in Fig. 1, The compressive stress block on the top and bottom flanges of the embedded steel beam has a uniform stress of λF_c, where λF_c is the bearing strength of the concrete. The effective width of the concrete is assumed to be equal to the width of the



(a) Ultimate strength of each element for prying action.
(b) Superposition of ultimate strength for each element.
(c) Prediction of ultimate strength.

Fig. 2 Prediction of ultimate strength

embedded steel beam. On the base of these assumptions, the relationships between the resisting moment M and axial compression N of the concrete section at the top and bottom flanges of the embedded steel beam are given as,

$$m = n (1 - n / \lambda_1) / 2 \qquad (3)$$

where $m = M/B_cD_c{}^2F_c$, $n = N/B_cD_cF_c$, $\lambda_1 = {}_bb\lambda/B_c$. These relationships are shown as N - M interaction curve $_{be}I_c$ in Fig. 2 (a). In eq. 3, the effect of frictional strength between the steel beam and concrete is not considered.

Interaction straight line $_{be}I_r$ for the longitudinal bars is given as,

$$n = - 2 ({}_rp_t \cdot {}_r\sigma_y / F_c) = - 2 \cdot {}_r\mu_t \qquad (4)$$

where $_rp_t$ and $_r\sigma_y$ are the tension reinforcement ratio and the yield stress of longitudinal bars, respectively. Interaction line $_{be}I_r$ is shown in Fig. 2 (a).

N - M interaction curve $_{be}I_{rc}$ for the prying action can be obtained from using superposed method of interaction line $_{be}I_r$ on the interaction curve $_{be}I_c$. Accordingly, as shown in Fig. 2 (b), the resisting moment capacity is given by the following expressions :

$$n_0 \leqq n \leqq n_1, \quad m = (n + 2 \cdot {}_r\mu_t)\{ 1 - (n + 2{}_r\mu_t) / \lambda_1 \} / 2 \qquad (5)$$

$$n_1 \leqq n \leqq n_2, \quad m = \lambda_1 / 8 \qquad (6)$$

$$n_2 \leqq n \leqq n_3, \quad m = n (1 - n / \lambda_1) / 2 \qquad (7)$$

where, $n_0 = - 2 \cdot {}_r\mu_t$, $n_1 = \lambda_1 / 2 - 2 \cdot {}_r\mu_t$, $n_2 = \lambda_1 / 2$, $n_3 = \lambda_1$.

As shown in Fig. 2 (c), using interaction curve $_{be}I_{rc}$, the resisting moment for prying action of embedded steel beam under axial compression n_a is obtained as $_{be}m$. In Fig. 2 (c), $_bI_b$ and $_cI_{rc}$ denote the interaction curves of the beam and column, respectively. Using these interaction curves, the resisting moment of the beam and the column under axial compression n_a is given as $_bm$ and $_cm$, respectively.

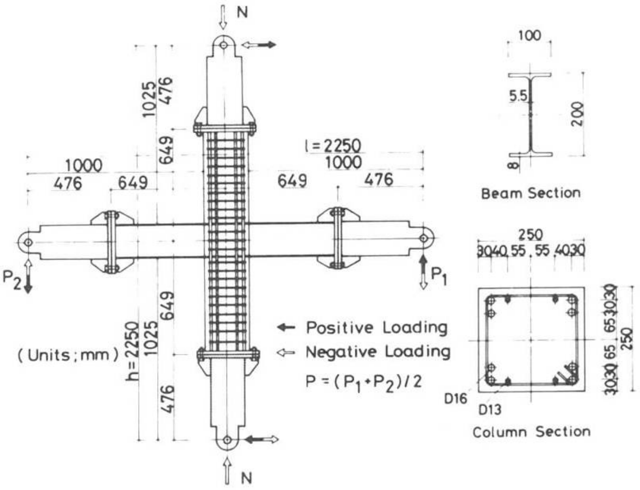
4. TEST PROGRAM AND TEST RESULTS

Table 2 Test and theoretical results

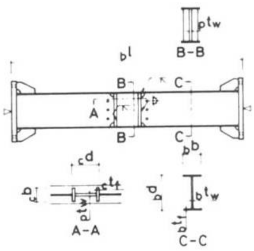
Specimen	Applied Axial Load N(kN)	Flexural Cracking Load P_{fl}(kN)		Diagonal Tension Cracking Load P_{cr}(kN)		Maximum Load $P_{max.}$(kN)		Theoretical Values		
		P.L.	N.L.	P.L.	N.L.	P.L.	N.L.	$P_{theo.}$(kN) P.L.	N.L.	$P_{max.}/P_{theo.}$
ION	0	18.8	21.2	26.7	14.6	41.4	39.5	32.8	1.26	1.20
I2N	514	32.4	42.0	32.4	45.5	50.5	48.4	32.8	1.54	1.48

P.L. : Positive Loading. N.L. : Negative Loading.

To verify this proposed mechanism of stress transfer and the method capable of predicting the ultimate strength of the joint, two interior steel beam-reinforced concrete column assemblies were tested under reversed cyclic loading. Details of test specimens are shown in Fig. 3. The dimension of specimen and cross sections are identical for each specimen. Experimental variable was the applied axial load. The applied axial load was 0 and 20 % of the ultimate compressive strength N_0 of the column. The mechanical properties of materials are listed in Table 1.



(a) Overall dimensions, loading and cross sections.



(b) Detail of steel beam.

Fig. 3 Details of test specimens.

Fig. 4 shows a hysteresis loop for each specimen. The ordinate represents the applied load at end of beam. The abscissa gives the deflection of the beam relative to the column at the point of application of load. $_bP$ denotes the calculated ultimate flexural strength of steel beam. For each specimen, the hysteresis loop shows the reversed S-shape with very small energy dissipation. After the attainment of the maximum load, the strength reduction due to reversed load for specimen I2N is remarkable. The strength reduction was caused by the crushing of concrete on the top and bottom flanges of the embedded steel beam as shown in Fig. 5. The above situation of concrete failure is similar to failure of concrete block that is tested to investigate the bearing strength.

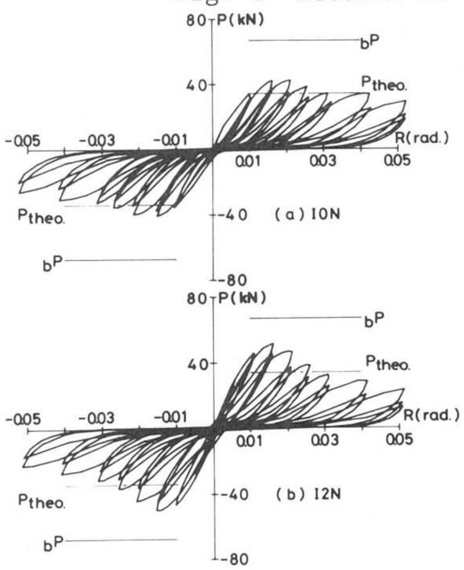


Fig. 4 Hysteresis loops.

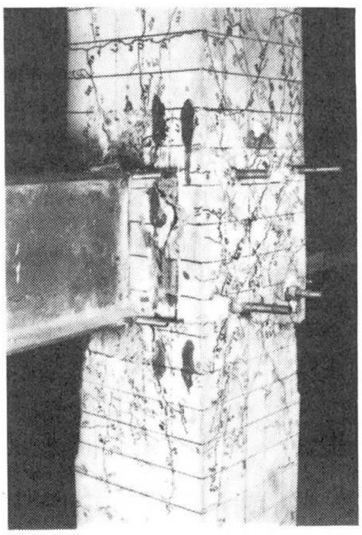


Fig. 5 Failure mode. for Specimen I0N.

5. PREDICTION OF TEST RESULTS

N - M interaction curves according to the present analysis are shown in Fig. 6. The ordinate and abscissa present the axial load n and resisting moment m, respectively. $_{be}I_{rc}$, $_bI_b$ and $_cI_{rc}$ denote the interaction curves for prying mechanism of embedded steel beam, steel beam

Table 1 Properties of materials.

	Steel				Reinforcing Bar			Concrete	
	σ_y	$\sigma_{max.}$	ε_u		σ_y	$\sigma_{max.}$	ε_u	F_c	F_t
	(N/mm^2)				(N/mm^2)			(N/mm^2)	
PL 5.5	367	443	0.201	6φ	181	288	0.290		
PL 8	319	424	0.259	D13	360	525	0.148	28.6	2.68
PL 16	264	434	0.304	D16	378	554	0.189		

F_c : Compressive Strength. F_t : Splitting Strength
σ_y : Yield Stress. $\sigma_{max.}$: Maximum Stress. ε_u : Maximum Elongation

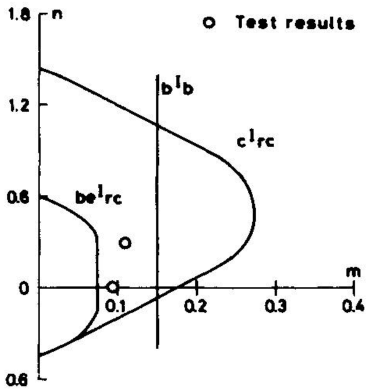
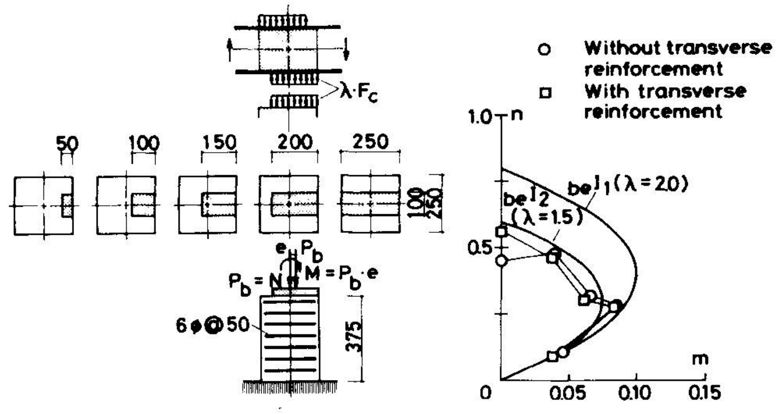


Fig. 6 Predictions of test results.



(a) Details of test specimens. (b) Bearing strength.
Fig. 7 Bearing test.

and reinforced concrete column, respectively. The open circle shows experimental values. The coefficient λ of 1.5 was adopted, based on tests to simulate the bearing zone under a steel beam as shown in Fig. 7. The comparisons of predictions with test results are listed in Table 2. The predictions are good agreement with the test results.

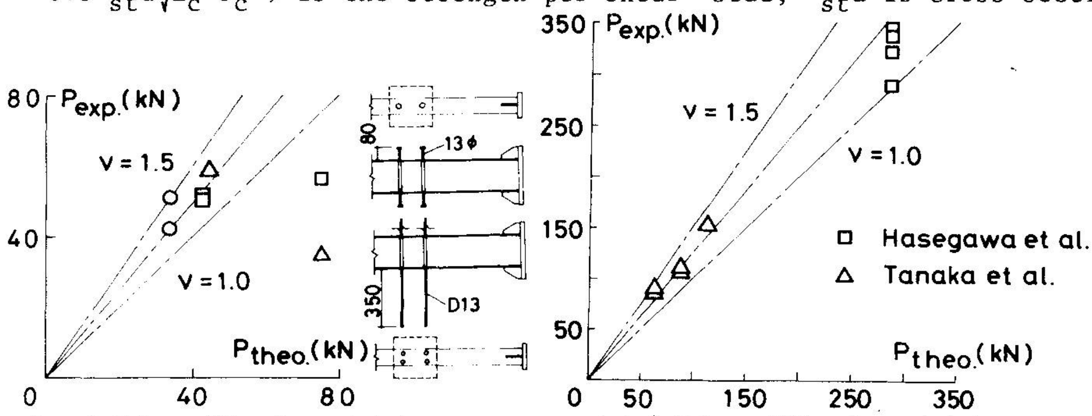
6. APPLICATION TO JOINTS WITH ADDITIONAL REINFORCEMENT

This proposed method was applied to estimate the ultimate strength of steel beam - reinforced concrete column joints containing additional reinforcement ; shear studs and reinforcing bars welded to the outside faces of the embedded steel beam, and steel beam - composite column joints. In predicting the ultimate strength of joints with additional reinforcement, the ultimate strength $P_{theo.}$ of the joints was given as,

$$P_{theo.} = P_u + \Delta P_u \qquad (8)$$

where P_u is the ultimate strength obtained by eq. 5 - eq. 7. ΔP_u is an additional strength provided by additional reinforcement.

Figs. 8 (a) compares predictions with the test results of specimens with shear studs or reinforcing bars conducted by author [2]. In this test, shear studs were intended to increase the frictional strength between the steel beam and concrete. On the other hand, reinforcing bars were intended to increase the resisting moment capacity for prying action. In case of these specimens with shear studs, additional strength ΔP_u was given as $n \cdot Q_{st} \cdot {}_b d / l$, where n is the number of the shear stud at the above or bottom flange of embedded steel beam, Q_{st} ($= 0.5 \cdot {}_{st}a \sqrt{E_c \cdot F_c}$) is the strength per shear stud, ${}_{st}a$ is cross-sectional



(a) S beam-RC column joints with additional reinforcement.
(b) S beam-SRC column joints.
Fig. 8 Application of proposed method

Table 3 Comparison of predictions with test results

Reference	Specimen	Experimental Value	Theoretical Value			
		$P_{exp.}$(kN)	$P_{theo.}$(kN)*)	P_u(kN)	ΔP_u(kN)	$P_{exp.}/P_{theo.}$
	WS0002N	49.1	41.8	32.8	9.01	1.18
2	WS0000N	50.0	41.8	32.8	9.01	1.20
	WH0002N	58.2	43.2	32.8	10.5	1.35
	N0-Ms10	86.3	62.3	43.3	18.9	1.38
	N0-Ms25	110.8	86.7	43.3	43.3	1.28
3	N40-Ms10	91.2	62.3	43.3	18.9	1.46
	N40-Ms25	105.9	86.7	43.3	43.3	1.22
	N0-Ms50	152.0	111.8	43.3	68.2	1.36
	A-01	314.8	285.4**)	-	-	1.10
4	A-01R	337.3	285.4	-	-	1.18
	A-04	329.5	285.4	-	-	1.15
	A-001	282.4	285.4	-	-	0.989

*) $P_{theo.} = P_u + \Delta P_u$
P_u : Ultimate strength for prying mechanism of embedded steel beam.
ΔP_u : Additional strength obtained by additional reinforcement.
**) Flexural strength of steel beam.

area , E_c and F_c is elastic modulus and compressive strength of concrete, respectively. On the other hand, ΔP_u of specimens with reinforcing bars was given as $2 \cdot {}_{re}a \cdot {}_{re}\sigma_y \cdot {}_{r}d \,/\, l$, where ${}_{re}a$ is cross-sectional area of tension reinforcing bars welded at the above or bottom flange of embedded steel beam, ${}_{re}\sigma_y$ is the yield stress of the reinforcing bar. Figs. 8 (b) compares predictions with the test results of interior steel beam - composite column joints [3, 4]. In this case, N - M interaction curve ${}_{be}I_{src}$ for the prying mechanism of embedded steel beam was obtained by means of superposition of the interaction curve ${}_{c}I_{s}$ for the steel column section on the interaction curve ${}_{be}I_{rc}$ obtained by eq. 5 - eq. 7. In these figures, the ordinate and abscissa represent the test results and predictions, respectively. The comparisons of predictions with test results are listed in Table 3. The predictions were shown to be in good agreement with the test results.

7. CONCLUDING REMARKS

The following remarks can be drawn from the discussion presented above.

1) The mechanism of stress transfer from the steel beam to reinforced concrete column was clarified experimentally and theoretically. In this mechanism, the principle of prying action of the steel beam embedded in reinforced concrete column was applied.

2) On the basis of this mechanism, a method capable of predicting the ultimate strength of joint was developed. The predictions were in good agreement with the test results.

3) This proposed method could be applied to estimate the ultimate strength of steel beam-reinforced concrete column joints containing additional reinforcement and steel beam-composite column joints.

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