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Effect of Confinement on Bond Splitting Behavior in Reinforced Concrete Beams

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ABSTRACT

It is important for reinforced concrete members to prevent bond splitting failure during earthquake. Previous experiments revealed that confinement by lateral reinforcement was effective to improve bond behavior of longitudinal bars in a reinforced concrete member. Design formulas for bond splitting strength were previously proposed based on these experiments (Orangun *et al.*, 1977; Fujii and Morita, 1983). However, the evaluation of confinement stress provided by lateral reinforcement and cover concrete have been conducted little.

In this paper, relationship between bond stress and confinement stress of lateral reinforcement was obtained from authors' experiment of beams. An analytical method was presented to evaluate confinement stress. Effect of the confinement stress on bond splitting behavior was discussed. From the analytical results, ultimate bond stress was evaluated.

KEYWORDS

Reinforced concrete; Beam; Longitudinal Bar; Bond splitting failure; Lateral reinforcement; Confinement

INTRODUCTION

It is important for reinforced concrete members with thin cover, such as beams and columns, to prevent bond splitting failure along longitudinal bars. Although the effect of confinement provided by cover concrete and lateral reinforcement on bond splitting behavior have been reported by previous research, evaluation of this confinement have been conducted little. The study of effect of the confinement is required to establish a proper design method for bond splitting failure in beams and columns.

For this purpose, simply supported beams were tested in order to gather experimental information on bond and confinement stress acting bar-to-concrete interface. An analytical study was carried out to evaluate the confinement stress. The effect of the confinement stress on bond splitting behavior was discussed. Ultimate bond stress was evaluated using the analytical results of the confinement stress.

DEFINITIONS

The resistant mechanisms of bond between a deformed bar and concrete, as already pointed out, are characterized by different stages (Gambarova *et al.*, 1989a): For small values of bond stress, bond efficiency is assured by chemical adhesion. For larger bond stress values, the chemical adhesion breaks down, then lugs of the bar induce large bearing stress in surrounding concrete. In this stage, bond force is mainly transferred by the wedging action of the lugs. The mechanism by wedging action was idealized as shown in Fig. 1. Integration of the component of bearing stress f_b, parallel to the bar axis, gives bond force ΔT. Bond stress τ_b is obtained as ΔT normalized by $(s \cdot \pi \cdot d_b)$.

$$\Delta T = \int_0^{2\pi} f_b \cdot \cos\theta\ (h / \cos\theta)(d_b /2)\ d\phi = f_b \cdot h \cdot \pi \cdot d_b \tag{1}$$

$$\tau_b = \Delta T/(s \cdot \pi \cdot d_b = f_b \cdot (h/s) \tag{2}$$

whereby, θ = angle of bearing stress to the longitudinal axis of a bar, h = lug depth, s = lug spacing, d_b = nominal diameter of bar.

Splitting force V is defined as the integration of the component of bearing stress f_b, perpendicular with respect to splitting plane (Fig. 2). If splitting stress σv was defined as splitting force V normalized by $(s \cdot d_b)$, Eq. (4) was given.

$$V = \int_0^{\pi} f_b \cdot \sin\theta\ (h/\cos\theta)(d_b/2)\ \sin\phi\ d\phi = f_b \cdot h \cdot d_b \cdot \tan\theta \tag{3}$$

$$\sigma_v = V/(s \cdot d_b) = fb \cdot (h/s) \cdot \tan\theta \tag{4}$$

Eqs. (2) and (4) give the relation of splitting stress with bond stress.

$$\tau_b = \sigma_v \cdot \cot\theta \tag{5}$$

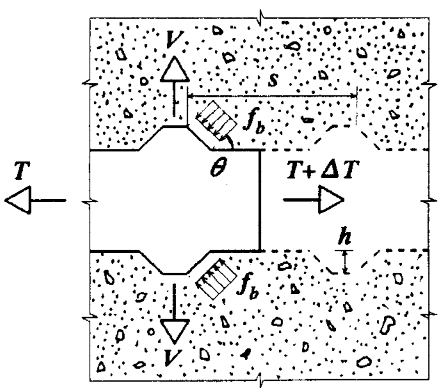


Fig. 1 Wedging action

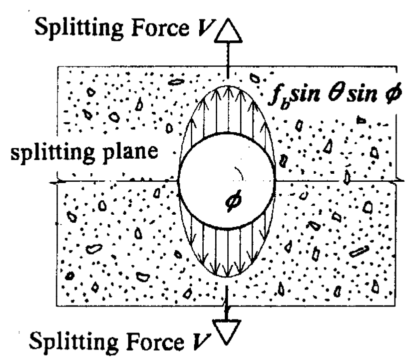


Fig. 2 Splitting Force

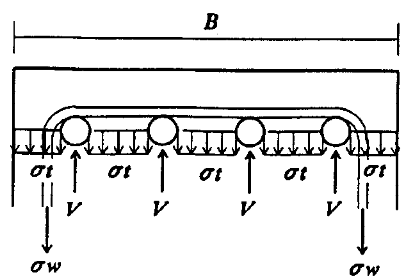


Fig. 3 Confinement Stress

The wedging action produces radial tensile stress in surrounding concrete and lateral reinforcement. Figure 3 shows confinement forces provided by tensile stress in concrete and lateral reinforcement, C_t and C_w, respectively. Following equations are obtained.

$$C_t = \sigma_t \cdot (B - N_b \cdot d_b) \cdot s \tag{6}$$

$$C_w = \sigma_w \cdot p_w \cdot B \cdot s \tag{7}$$

whereby, σ_t = average tensile stress in concrete perpendicular to splitting plane, B = beam width, N_b = number of bars in splitting plane, σ_w = average tensile stress in lateral reinforcement, $p_w = N_w \cdot A_w/(B \cdot S_w)$, N_w = the number of lateral reinforcement in one set, S_w = spacing of lateral reinforcement.

Equilibrium between splitting and confinement force gives a equation below.

$$N_b \cdot V = C_t + C_w \tag{8}$$

If confinement stresses, σ_{ct} and σ_{cw}, are defined as splitting forces normalized by ($N_b \cdot d_b \cdot s$), Eqs.(9) and (10) are obtained.

$$\sigma_{ct} = C_t / (N_b \cdot d_b \cdot s) = \sigma_t \cdot B_{si} \tag{9}$$
$$\sigma_{cw} = C_w / (N_b \cdot d_b \cdot s) = \sigma_w \cdot p_w \cdot (B_{si} + 1) \tag{10}$$

whereby, $B_{si} = (B - N_b \cdot d_b)/(N_b \cdot d_b)$

From Eqs. (5), (8), (9) and (10), relationship between confinement stresses and bond stress is given by

$$\tau_b = (\sigma_{ct} + \sigma_{cw}) \cdot \cot\theta = \sigma c \cdot \cot\theta \tag{11}$$

As a result of splitting force, splitting cracks occurs in surrounding concrete. Once splitting cracks break out the whole cover and bar spacing, bar-to-concrete bond fails if no lateral reinforcement provided. On the other hand, a sufficient amount of lateral reinforcement, such as hoops and sub-ties, would assure bond efficiency in spite of concrete splitting, because of confinement action developed by the reinforcement.

OUTLINE OF EXPERIMENT AND TEST RESULTS

Five simply supported beams were tested to gather experimental data about the effect of confinement stress on bond behavior in longitudinal bar. Sections of specimens are shown in Fig. 4. Dimensions and reinforcing details of specimens are shown in Fig. 5. The specimens were designed to fail in bond splitting (whole splitting mode) along longitudinal bars. The variables of specimens were the number and the diameter of test bars, the spacing of lateral reinforcement, and the use of sub-ties as shown in Table 1. Each specimen had four test zones. The test zones contained top or bottom bar. In the right span, every test bar was supported by a hoop or a sub-tie, and in the left span intermediate bars were unsupported. Concrete compressive and tensile strength was shown in Table 2. The mechanical properties of reinforcing bars are shown in Table 3. Refer to previous paper (Maeda *et al.*, 1991) for details.

Each specimen was subjected to monotone loading. Bond stress τ_b was calculated from strain ε_s measured by a strain gauge.

$$\tau_b = \varepsilon_s \cdot E_s \cdot A_s / (\pi \cdot d_b \cdot L_b) \tag{12}$$

whereby, L_b = bond length = 24 cm.

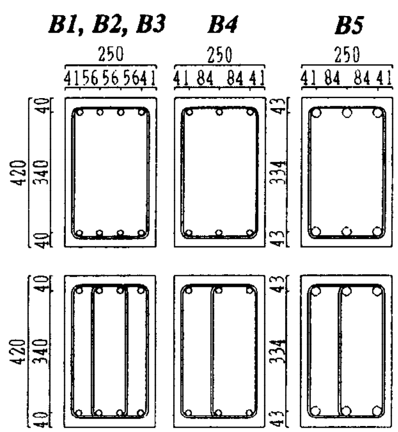


Fig. 4 Section of Specimens

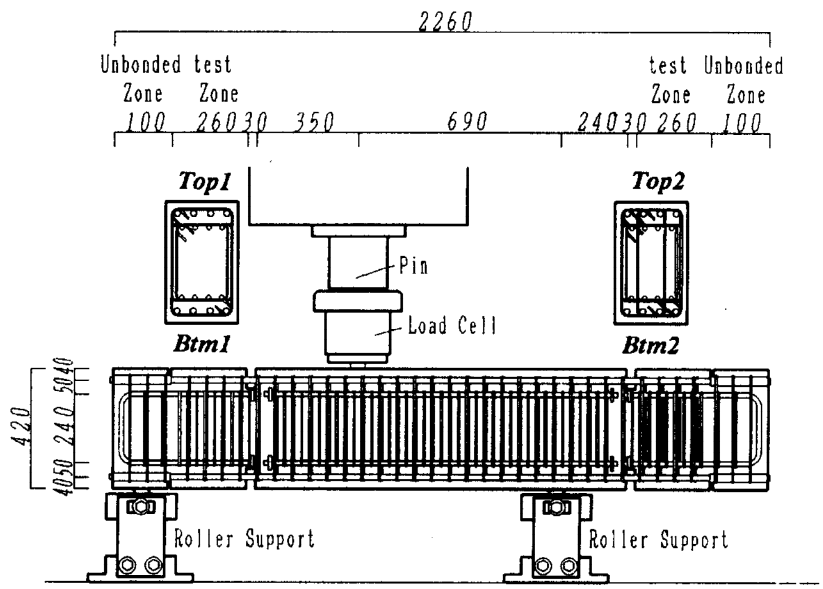


Fig. 5 Dimensions and Reinforcing Details of Specimens

Table 1 Test Variables

Specimen	Test Zone	Longitudinal Bar Top + Bottom	Lateral reinforcement Leg/ Spacing	Lateral reinforcement p_w (%)
B1	1	4-D19	2 / 120	0.19
	2		4 / 120	0.37
B2	1	4-D19	2 / 60	0.37
	2		4 / 60	0.75
B3	1	4-D19	2 / 120	0.56
	2		4 / 120	1.12
B4	1	3-D19	2 / 60	0.37
	2		3 / 60	0.56
B5	1	3-D25	2 / 60	0.37
	2		3 / 60	0.56

p_w = Lateral reinforcement ratio

Table 2 Concrete strength

	σ_B (MPa)	f_t (MPa)
B1, B2, B3	31.1	2.32
B4, B5	33.4	2.46

σ_B : compressive strength,
f_t : splitting tensile strength

Table 3 Properties of reinforcement

	d_b (mm)	A_s (cm^2)	σ_y (MPa)	E_s (10^5 MPa)
6φ	6.0	0.28	528	1.95
D19	19.1	2.87	360	1.81
D25	25.4	5.07	355	1.78

A_s : nominal area,
σ_y : yielding stress,
E_s : young's modulus

Table 4 Test results (MPa)

Test Zone	Maximum Bond Stress $\tau_{bu.c}$	Maximum Bond Stress $\tau_{bu.i}$	Stress in hoops and sub-ties $\sigma_{wu.c}$	Stress in hoops and sub-ties $\sigma_{wu.i}$
B1-Top1	2.75	2.56	155	155
B1-Top2	3.31	3.43	164	143
B2-Top1	3.74	2.89	212	100
B2-Top2	4.88	4.99	184	177
B3-Top1	4.27	3.16	215	183
B3-Top2	5.88	6.24	187	211
B4-Top1	5.07	4.62	282	271
B4-Top2	5.59	5.45	212	220
B5-Top1	4.85	3.10	316	274
B5-Top2	4.76	5.02	245	271

$\tau_{bu.c}$: maximum bond stress in corner bars
$\tau_{bu.i}$: maximum bond stress in intermediate bars
$\sigma_{wu.c}$: average stress in hoops and sub-ties when the corner bar reached to the maximum bond stress
$\sigma_{wu.i}$: average stress in hoops and sub-ties when the intermediate bar reached to the maximum bond stress

Test results of top bars were summarized in Table 4. After occurrence of initial splitting crack, bond slip started to increase and bond stresses rose with gradual propagation of splitting cracks. Finally, splitting cracks broke off the whole cover and at the same time bond stresses reached to their peak. Tensile stress in hoops or sub-ties σ_w increased until τ_b reached to its peak. After bond stresses τ_b started declining, σ_w were constant at their peak level (about 200 MPa) in all test zones.

Relations between bond stress τ_b and confinement stress σ_{cw} was shown in Fig. 6. Although specimen B2-Top1 had the same quantity of lateral reinforcement ratio, p_w, as specimen B1-Top2, maximum bond stresses in intermediate bars, unsupported by sub-ties, were lower than B1-TOP2. By the use of sub-ties, maximum bond stresses in bars of B2-TOP2 were improved in comparison with B2-TOP1 . The confinement stress was nearly zero until initial splitting crack occurred and bond stress level was around τ_{co}. τ_{co} indicates bond strength in case no lateral reinforcement provided calculated by Fujii - Morita's formula (1983). It is important and interesting that after occurrence of initial splitting crack the increase of bond stress (τ_{bu} - τ_{co}) was proportional to the confinement stress, σ_{cw}. This result suggest bond stress is governed by the confinement stress. Comparison of the increase of bond stress (τ_{bu} - τ_{co}) with σ_{cwu} (confinement stress when bond stress reached to the maximum value) was shown in Fig. 7. Coefficient α were, in an average, 0.444 and 0.683 for the bars unsupported and supported by hoops or sub-ties, respectively.

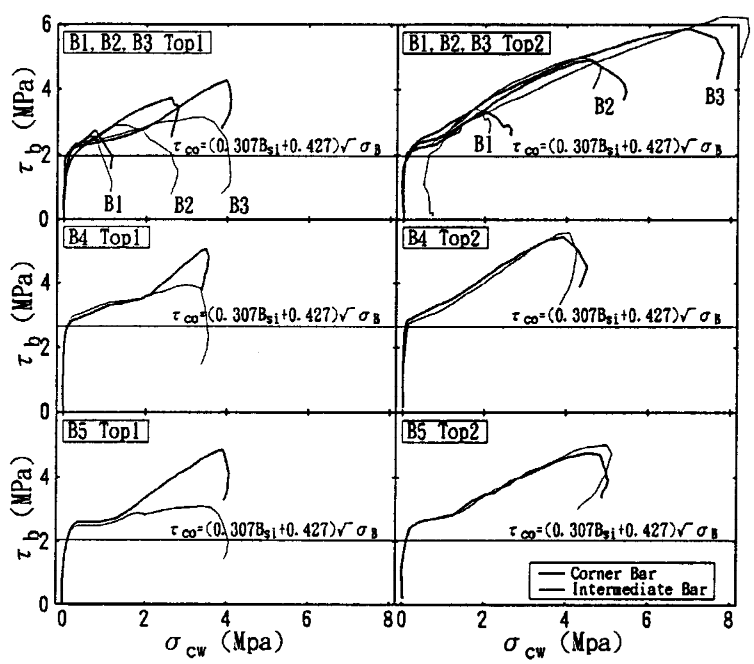


Fig. 6 τ_b - σ_{cw} relationship

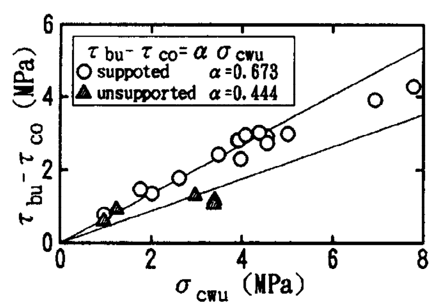


Fig. 7 (τ_{bu} - τ_{co}) vs. σ_{cwu}

Analytical Method

Analytical Model

To evaluate the confinement stresses acting on splitting plane, a simple analytical model was introduced as shown in Fig. 8. This analytical model consists of three components: (1) beam which represents cover concrete; (2) steel columns connected to the beam with pin connection, which represent hoops and sub-ties; (3) crack springs which represent tensile force and crack opening of concrete in the splitting plane. Splitting force V was assumed to be acting at the center of each bar.

Definitions

Crack opening and forces are defined in Fig. 8(c). Crack openings are summation of flexural deformation of the beam, δ_{fi}, and crack opening of ***crack spring 0***, δ_0, namely,

$$\delta_i = \delta_{fi} + \delta_0 \tag{13}$$
$$\delta_{ti} = \delta_{fti} + \delta_0 \tag{14}$$
$$\delta_{wi} = \delta_{fwi} + \delta_0 \tag{15}$$

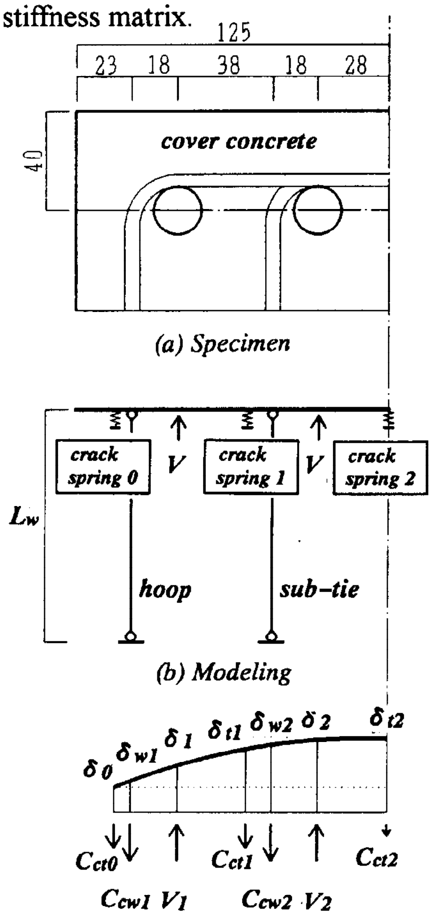
The force vector and flexural deformation vector are defined as

$$\{V\} = \{ V_1 , V_2 , C_{ct1} , C_{ct2} , C_{cw1} , C_{cw2} \}^t \tag{16}$$
$$\{\delta\} = \{ \delta_{f1} , \delta_{f2} , \delta_{ft1} , \delta_{ft2} , \delta_{fw1} , \delta_{fw2} \}^t \tag{17}$$

The constitutive equation of the beam is

$$\{ V \} = [K] \{ \delta \} \tag{18}$$

whereby, $[K]$ = stiffness matrix.



(a) Specimen

(b) Modeling

(c) Definition of forces and deformetion

Fig. 8 Analytical Model

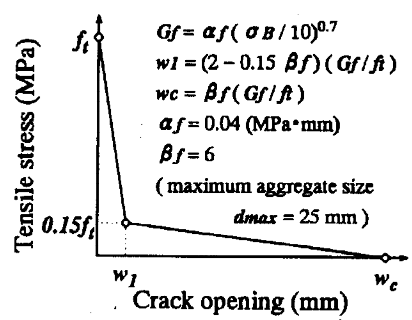


Fig. 9 Diagram of concrete at stress crack opening

The constitutive equation of hoops and sub-ties is

$$C_{wi} = (E_s \cdot A_w / L_w)\, \delta_{wi} \tag{19}$$

whereby, L_w = effective length = j_t / 2.

Equilibrium of forces is

$$\Sigma V_i = \Sigma C_{ti} + \Sigma C_{wi} \tag{20}$$

Assumptions

Crack spring is assumed as a pin connection until its force C_{ti} reached to cracking force. Once C_{ti} reaches to the cracking force, CF_i, crack spring is assumed to elongate. The relation of elongation with tensile force C_{ti} was given as shown in Fig. 9 on the basis of tension softening model of concrete (CEB, 1991), namely,

$$\begin{array}{ll} \text{for } \delta_{ti} \le w_1 & C_{ti} = CF_i - 0.85CF_i\,(\delta_{ti} / w_1) \\ \text{for } w_1 < \delta_{ti} \le w_c & C_{ti} = 0.15CF_i\,(w_c - \delta_{ti}) / (w_c - w_1) \\ \text{for } w_c < \delta_{ti} & C_{ti} = 0 \end{array} \tag{21}$$

whereby, CF_i = cracking force = $f_t \cdot b_{ci} \cdot s$, b_{ci} = width of concrete represented by a crack spring.

Splitting force of the corner bar, V_1, was assumed to be equal to that of the intermediate bar, V_2, namely

$$V_1 = V_2 \tag{22}$$

Flexural stiffness of the beam, EI, was assumed as

$$EI = k \cdot E_c \cdot I_c \tag{23}$$

whereby, k = reduction factor due to cracking, I_c = inertia moment = $s \cdot d_c^3 / 12$, d_c = top cover depth, E_c = young's modulus of concrete = $2.1 \times 10^5 \times (\sigma_B / 20)^{0.5}$ (MPa).

Calculation was carried out by solving Eqs. (18), (19), (20), (21) and (22), controlled by incremental crack opening of the intermediate bar, δ_2. In the analysis, three cases were considered : *Case 1*; stiffness of the beam was considered to be elastic (stiffness reduction factor k = 1 was assumed in Eq. (23)). *Case 2;* stiffness reduction factor k = 1/2 was adopted in Eq. (23) (the Stiffness was assumed to be declined because of cracking). *Case 3*; stiffness reduction factor k = 1/4 was adopted in Eq. (23).

Analytical Results and Discussions

Contribution of concrete and lateral reinforcement

Relationships between confinement stress σ_c and crack opening of the intermediate bar δ_{c2} of specimen B2-Top1 was shown in Fig. 10. In Fig. 10, the contribution of concrete to confinement stress was divided into two components. Contribution of ***crack spring 0*** (concrete in side cover) is obtained from Eq. (9), namely,

$$\sigma_{ct0} = C_{t0} / (N_b \cdot d_b \cdot s) \tag{24}$$

Similarly, the contribution of ***crack spring 1*** and ***2*** (concrete between bars) is

$$\sigma_{ct1} + \sigma_{ct2} = (C_{t1} + C_{t2}) / (N_b \cdot d_b \cdot s) \tag{25}$$

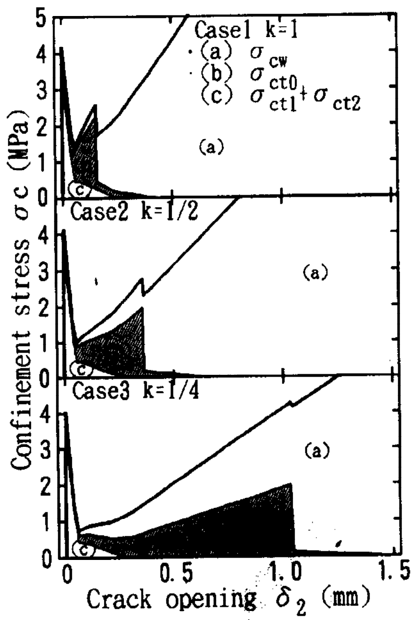


Fig. 10 Crack opening - σ_c relationships

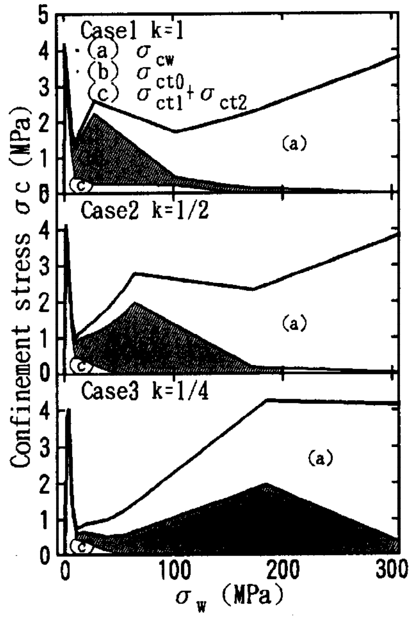


Fig. 11 σ_w - σ_c relationships

The contribution of hoops and sub-ties σ_{cw} can be obtained by Eq. (8). From Fig. 10, it is observed that, in any case, most part of the confinement stress σ_c is provided by the concrete between bars until splitting cracks occur between bars (crack opening is nearly zero). After crack occurring between bars, there is a rapid drop of confinement stress σc due to decline of σ_{ct1} $+\sigma_{ct2}$. On the other hand, the contribution of the side cover concrete and lateral reinforcement increase, and most part of the confinement stress σ_c is provided by σ_{ct0} and σ_{cw}. Stiffness reduction factor k affects the crack opening when crack occurs in the side cover concrete (whole splitting). Relationship between confinement stress σ_c and average stress in hoops and sub-ties σ_w was shown in Fig. 11. The stiffness reduction factor k affects σ_w when splitting crack run across the whole cover. As mentioned in test results above, bond stress reached its maximum value at the same time crack completely cut across the whole cover. Considering σ_w was about 200 MPa at the maximum bond stress, case3 (k = 1/4) is agreeable to the test results. Therefore k = 1/4 was assumed in discussion below.

Bond stress - Confinement Stress

Bond stress τ_b was predicted from the analytical results of confinement stress σ_c. In calculation, two cases were considered: *Case 4*; The relation of τ_b with σ_c is defined by Eq. (11). Coefficient α, obtained from experiment, was adopted as $\cot\theta$ in Eq. (11). *Case 5*; Experimental equation by Gambarova (1989b) was used as the relation of τ_b with σ_c, namely,

$$\tau_b = \tau_0 + (2/\pi)\, K_t \cdot \sigma_c \tag{26}$$
$$\tau_0 = 0.042 - 0.288\ (\delta_i / d_b) \tag{27}$$
$$K_t = 0.258/(\delta_i / d_b + 0.11) - 1.018 \tag{28}$$

Relationship between predicted bond stress τ_b and confinement stress provided by hoops and sub-ties σ_{cw} was shown in Fig. 12. In any cases, the analytical bond stresses when splitting initial cracks occur are twice as high as the experimental or more. After occurrence of cracks between bars, analytical results of case 5 agree with test results. In case of without sub-ties, difference of analytical bond stresses between in the corner bars and the intermediate bars were large in comparison with case of with sub-ties. This tendency agrees with test results. Analytical bond stresses when whole splitting are assumed as ultimate bond stress τ_{bcal}. Comparison between τ_{bcal} in case 5 and experimental maximum bond stress τ_{bu} was shown in Fig. 13. The analytical ultimate bond stress τ_{bcal} agree experimental test results.

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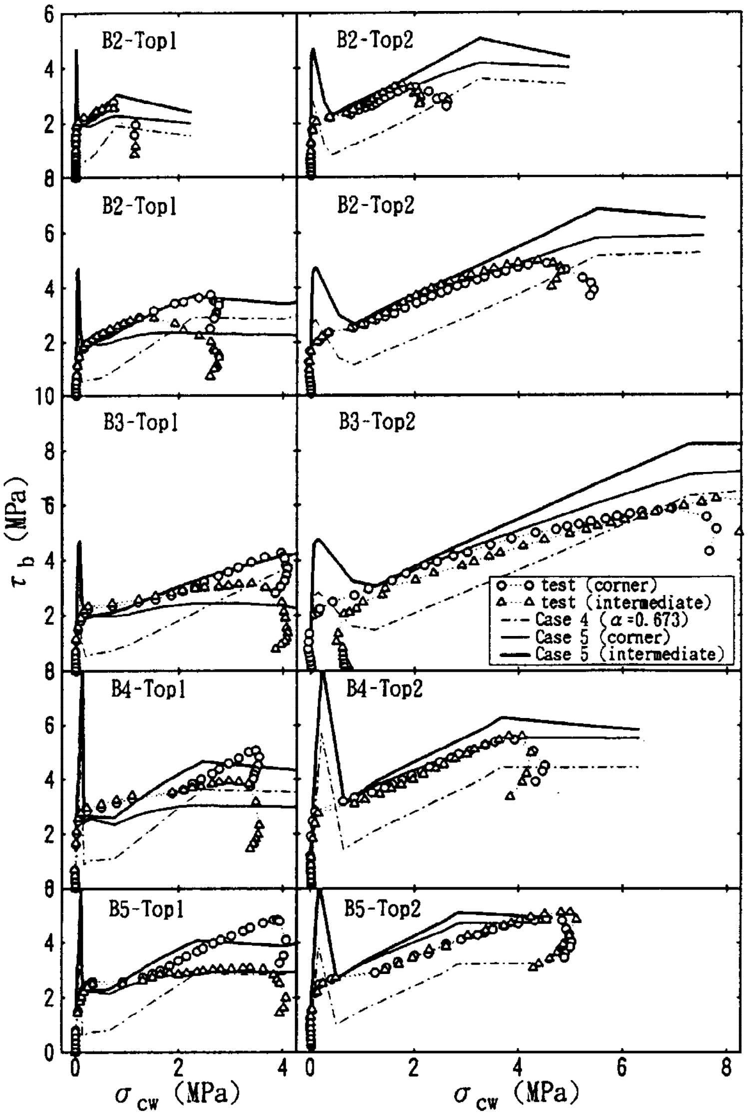

Fig. 12 Bond stress - confinement stress relationships

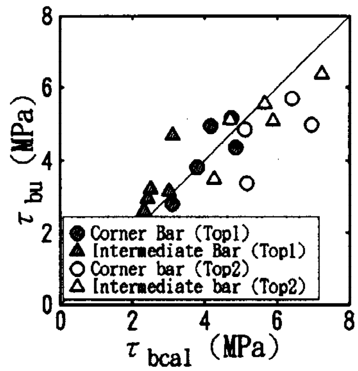

Fig. 13 Ultimate bond stress

CONCLUSIONS

1) Maximum bond stress of intermediate bars unsupported by sub-ties was lower than that of corner bars. Bond splitting strength of intermediate bars was improved by providing support with sub-ties and was as high as that of corner bars. Bond stress was governed by confinement stress of lateral reinforcement.
2) From an analytical study, the concrete between bars does not contribute to the confinement at ultimate state. Analytically predicted ultimate bond stresses agree with test results.

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