BOND SPLITTING STRENGTH IN REINFORCED CONCRETE MEMBERS

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ABSTRACT

Simply supported beams were tested to investigate bond splitting strength of longitudinal bars in a shear span. The variables of specimens were the number and the diameter of longitudinal bars, spacing and arrangement of lateral reinforcement, and position of a bar relative to the height of concrete. Maximum bond stresses of longitudinal bars were compared with bond splitting strengths calculated by previously proposed formulas.

From the test results, bond splitting strength of intermediate bars was observed to improve by the use of sub-ties. Previously proposed formulas for bond splitting strength did not properly evaluate the contribution of lateral reinforcement.

1. INTRODUCTION

Lateral reinforcement, such as hoops and sub-ties, is effective to prevent bond splitting failure along deformed bars in a reinforced concrete member. Design Guidelines of Architectural Institute of Japan (AIJ)[Ref. 1] proposed a design formula for bond splitting strength based on experimental equations proposed by Fujii and Morita [Ref. 2]. However, it was pointed out that AIJ's formula underestimates the bond splitting strength of intermediate longitudinal bars supported by sub-ties [Ref. 3].

Simply supported beams were tested to study bond splitting strength. The test results were compared with AIJ's formula and some previously proposed formulas for bond splitting strength.

2. OUTLINE OF EXPERIMENT

2.1 SPECIMENS

Five simply supported beams were designed following specimens tested by Ichinose and Yokoo [Ref. 4]. The dimensions and reinforcing details of a specimen are shown in Fig. 1. The specimens were designed to fail in bond splitting (side splitting mode) of longitudinal bars (test 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 (Table 1). Four deformed bars and three deformed bars (D19 : 1.91 cm diameter, 6.0 cm perimeter and 2.87 cm^2 area) were used as test bars in specimens No.1,No.2 and No.3, and in specimen No.4, respectively. Three deformed bars (D25 : 2.54 cm diameter, 8.0 cm perimeter and 5.07 cm^2 area)

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were used as test bars in specimen No.5. 6ϕ round bars (6.0 mm diameter) were used as Hoops and sub–ties.

In a beam end zone, top and bottom bars were unbonded from surrounding concrete by covering with steel sleeves so that the bars were not confined by supporting force. A 26 cm zone along top or bottom bars next to an unbonded zone was a test zone in which test bars were expected to fail in bond splitting and bond stress of test bars was calculated. Each specimen had four test zones. The test zones contained top (TOP) or bottom (BTM) bars. In the right span (2), every test bar was supported by a hoop or a sub–tie, and in the left span (1) intermediate bars were unsupported. A 10 mm wide and 40 mm deep notch was introduced between an unbonded zone and a test zone to prevent surrounding concrete in the unbonded zone from influencing bond splitting strength of test bars in the test zone. In order to measure strains of test bars without damaging the shape of test bars in a test zone and to make uniform the occurring location of shear cracks and bond splitting cracks, a 30 mm wide and 70 mm deep notch was introduced at the other end of a test zone (35 cm outward from loading point).

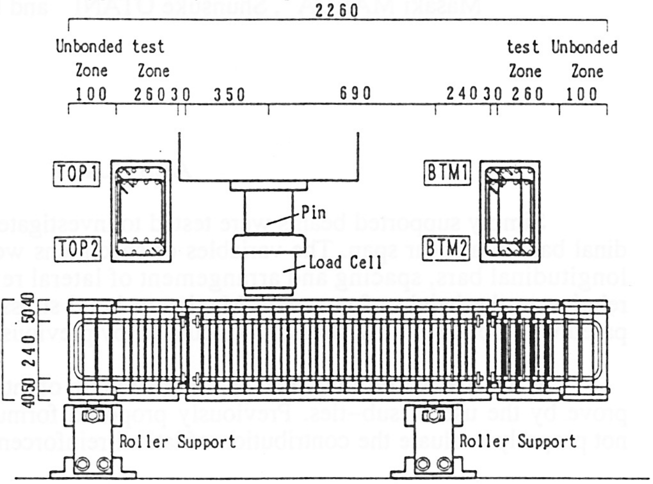


Fig. 1 Details of specimen (Unit : mm)

To prevent any other unfavorable failure, auxiliary longitudinal and transverse reinforcing bars were arranged between the top and bottom test bars. Four deformed bars (D16 : 1.61 cm diameter, 5.0 cm perimeter and 1.98 cm^2 area) were used in specimens No.1, No.2 and No.3 as the auxiliary longitudinal reinforcement, three bars (D16) in specimen No.4, and three bars (D19) in specimen No.5. In each specimen, 6ϕ round bars were used as the auxiliary transverse reinforcement at 60 mm spacing.

Concrete compressive strength σ_B was 317 kgf/cm^2 in specimens No.1, No.2 and No.3 and 341 kgf/cm^2 in specimens No.4 and No.5. The properties of reinforcing bars are shown in Table 2.

Table 1 Test parameters

Specimen		Longitudinal reinforcement	Lateral reinforcement	
			Details	pw(%)
No. 1	TOP1 BTM1	4-D19	2-6φ@120	0.19
	TOP2 BTM2		4-6φ@120	0.37
No. 2	TOP1 BTM1	4-D19	2-6φ @60	0.37
	TOP2 BTM2		4-6φ @60	0.75
No. 3	TOP1 BTM1	4-D19	2-6φ @40	0.56
	TOP2 BTM2		4-6φ @40	1.12
No. 4	TOP1 BTM1	3-D19	2-6φ @60	0.37
	TOP2 BTM2		3-6φ @60	0.56
No. 5	TOP1 BTM1	3-D25	2-6φ @60	0.37
	TOP2 BTM2		2-6φ @60	0.56

2.2 LOADING PROCEDURE AND INSTRUMENTATION

Every specimen was subjected to monotonic loading. Test zone TOP1 (without sub–ties), whose test bars were expected to have the lowest bond splitting strength of the four test zones, was tested first. After testing test zone TOP2, the specimen was turned upside down, and then test zones BTM1 and BTM2 were tested.

Table 2 Properties of reinforcement

	σ_y kgf/cm^2	E. 10^6 kg/cm^2
6φ	5385	1.992
D16	3746	1.855
D19	3670	1.850
D25	3623	1.816

Load P was measured by a load cell located between a 200 ton universal testing machine and a test beam. The displacement δ at loading point was measured by a transducer with respect to the test floor. Slip S of a test bar was measured by a transducer with respect to the concrete at an end of a test beam. Strain gauges were bonded on the surface of a test bar in a notch near the loading point and of hoops and sub–ties in test zones.

3. TEST RESULTS

3.1 FAILURE MODE

The relations of load P and displacement δ are shown in Fig. 2. Many bond splitting cracks were observed on top and side faces along test bars in a test zone after flexural cracks and shear cracks occurred. Every specimen failed in bond splitting along test bars in a test zone. Typical crack patterns are shown in Fig. 3. The solid lines indicate cracks observed at the final loading stage and the broken lines indicate cracks observed in previous loadings.

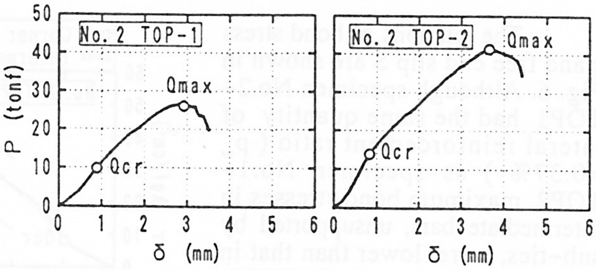
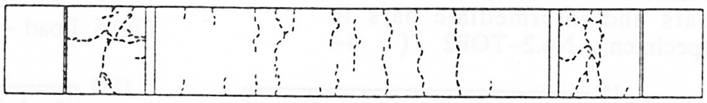
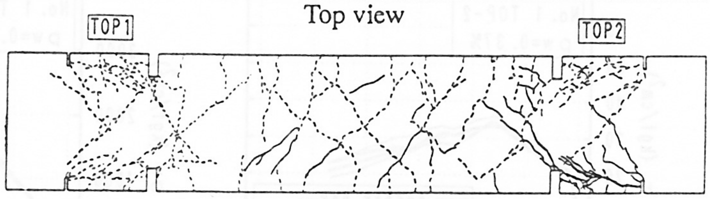


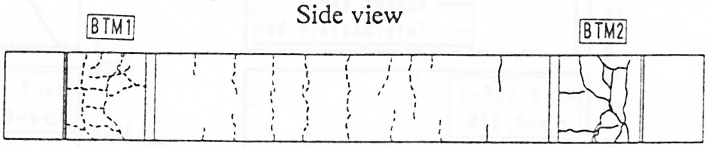
Fig. 2 Load – displacement relationship



Top view



Side view



Bottom view

Fig. 3 Crack patterns

3.2 LOAD - BOND STRESS RELATIONSHIP

The stress σ of a test bar at a notch near loading point was calculated from a strain measured by strain gauges. Although test bars in specimen No.3–BTM2 yielded before the specimen failed in bond splitting, maximum strains of test bars were about 2200μ. Test bars of the other specimens remained elastic throughout their loading. The stress of a test bar was zero at the end of a test zone near an unbonded zone. Bond stress τ was calculated by

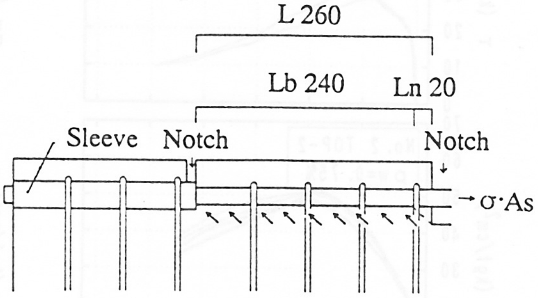


Fig. 4 Development length of test bar (Unit : mm)

$$\tau = \sigma As / \psi Lb$$

where, As = cross–section area of a test bar, ψ = perimeter of a test bar, Lb = development length of a test bar = L– Ln, L = test zone length, and Ln = length of a test bar ineffective for bond splitting strength.

Load P and bond stress τ relations are shown in Fig. 5. The difference between a corner bar (thick line) and an intermediate bar (thin line) is not observed in specimen

No.2–TOP2 throughout to maximum load (Q_{max}). However, bond stress in an intermediate bar in specimen No.2–TOP1 reached its peak before maximum load (Q_{max}) and then decreased, although the bond stress of a corner bar increased until the bond splitting failure occurred.

3.3 BOND STRESS – FREE END SLIP RELATIONS

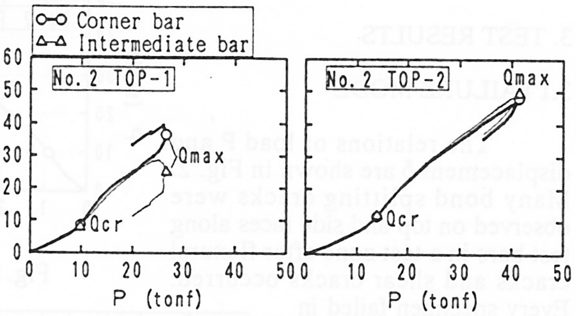


Fig. 5 Load – bond stress relationship

The relations of bond stress τ and free end slip S are shown in Fig. 6. Although specimen No.2–TOP1 had the same quantity of lateral reinforcement ratio (p_w =0.37%) as specimen No.1–TOP2, maximum bond stresses in intermediate bars, unsupported by sub–ties, were lower than that in bars in specimen No.1–TOP2. Maximum bond stresses in corner bars and intermediate bars in specimen No.2–TOP2 (4–

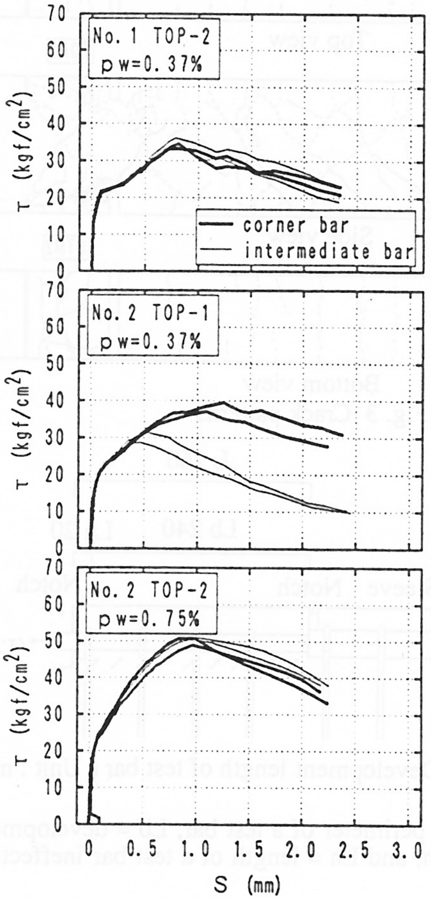


Fig. 6 τ – S relationship

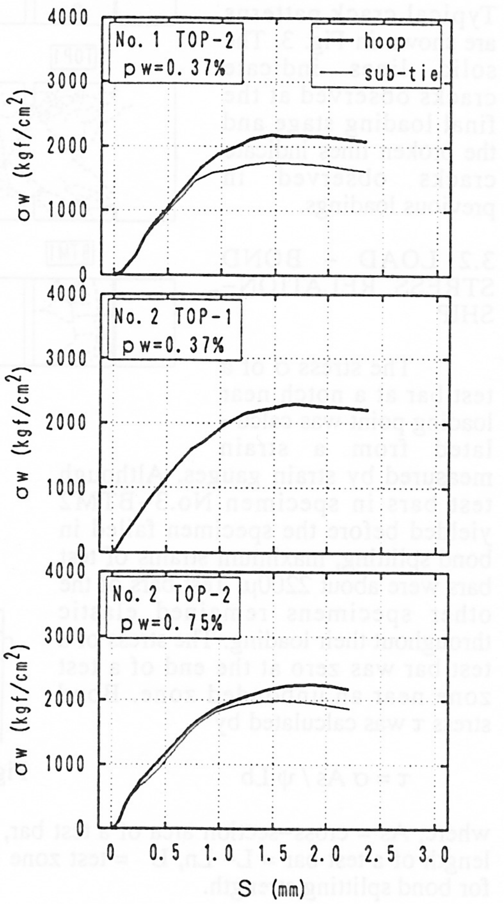


Fig. 7 σ_w – S relationship

6ϕ@60mm, p_w=0.75%) were higher than in specimen No.2–TOP1 (2–6ϕ@60mm, p_w=0.37%)

3.4 STRESSES IN LATERAL REINFORCEMENT

Hoops and sub–ties remained elastic in all test zones. The stress σ_w of hoops or sub–ties was calculated as an average stress of all hoops or sub–ties in a test zone. Figure 7 shows the relationship of stress σ_w of lateral reinforcement and free end slip S. σ_w increased, unless the bond stresses τ reached its peak. After bond stresses τ started declining, σ_w were constant at their peak level (about 2000 kgf/cm^2) in all test zones.

4. DISCUSSIONS

4.1 COMPARISON OF TEST RESULTS WITH DESIGN FORMULAS

Table 3 Summary of test results

Specimen		Maximum bond stress (kgf/cm²)			Bond strength (kgf/cm²)			
		τ max1	τ max2	τ maxav	τ ojb	τ fm	τ bu	τ yk
No. 1	TOP1	27.8, 28.3	27.5, 25.7	27.1	26.6	22.8	22.7	21.7
	BTM1	39.4, 38.1	37.5, 34.3	37.3	34.6	27.8	28.4	26.5
	TOP2	33.1, 34.5	33.9, 36.1	34.4	26.6	25.5	24.5	30.9
	BTM2	47.2, 50.0	44.2, 45.2	46.0	34.6	31.1	30.6	37.7
No. 2	TOP1	39.5, 37.0	28.7, 31.3	31.3	33.5	25.5	25.3	26.7
	BTM1	51.8, 53.8	40.6, 34.7	44.6	43.5	31.1	31.7	32.6
	TOP2	48.9, 50.8	50.5, 51.2	49.4	33.5	31.0	28.9	63.5
	BTM2	57.5, 57.4	58.2, 57.5	57.2	43.5	37.8	36.1	77.5
No. 3	TOP1	47.0, 40.2	30.2, 34.2	36.3	33.5	28.2	28.0	35.2
	BTM1	54.0, 57.3	40.8, 37.6	46.6	43.5	34.4	35.0	42.8
	TOP2	57.9, 62.0	63.3, 64.1	61.9	33.5	36.4	33.3	117.9
	*) BTM2	73.2, 73.2	73.2, 73.2	73.2	43.5	44.5	41.6	143.9
No. 4	TOP1	50.3, 53.1	40.1	47.0	41.6	34.5	33.3	34.8
	BTM1	56.3, 54.3	43.0	49.6	54.1	42.1	41.7	42.4
	TOP2	53.5, 57.8	57.0	56.1	41.6	38.3	35.8	45.7
	BTM2	69.8, 68.5	65.1	67.5	54.1	46.7	44.7	55.8
No. 5	TOP1	49.6, 49.3	31.6	42.5	33.8	26.5	25.4	27.7
	BTM1	51.8, 46.8	35.4	43.7	44.0	32.3	31.8	33.9
	TOP2	50.2, 47.6	51.2	49.5	33.8	29.4	27.3	37.0
	BTM2	56.0, 52.9	52.3	53.7	44.0	35.8	34.1	45.1

*) Bond splitting failure after bar yielding, τ max1: Maximum bond stress of corner bar, τ max2: Maximum bond stress of intermediate bar, τ max.av: Maximum of average bond stress of whole bars in an test zone, τ bu: Bond splitting strength of AIJ's, τ fm: Bond splitting strengthof FUJII–MORITA's formula, τ ojb: Bond splitting strength of ORANGUN–JIRSA–BREEN's formula, τ yk: Bond splitting strength of KAKU–YAMADA's formula

$$\tau_{bu} = \left\{0.4+0.5\frac{b-\sum d_b}{\sum d_b}+\frac{20+5Nu+15Ns}{Nt}\cdot\frac{b\cdot p_w'}{d_b}\right\}\sqrt{\sigma_B} \quad \text{(multiplied by 0.8 for top bars)}$$

$$\tau_{fm} = \left\{0.427+0.307\frac{b-\sum d_b}{\sum d_b}+\frac{24.9b\cdot p_w}{Nt\cdot d_b}\right\}\sqrt{\sigma_B} \quad \text{(multiplied by 1.22 for bottom bars)}$$

$$\tau_{ojb} = \left\{1.2+\frac{3c}{d_b}+\frac{50d_b}{ls}+\frac{A_w\cdot {}_w\sigma_y}{35.2Nt\cdot s\cdot d_b}\right\}\cdot 0.265\sqrt{\sigma_B} \quad \text{(divided by 1.3 for top bars)}$$

$$\tau_{yk} = \left\{0.427+0.307\frac{b-\sum d_b}{\sum d_b}+0.85\frac{Ns^{1.65}\cdot A_w\cdot j_d}{s^2\cdot b_w}+7.40\frac{Ns^{1.65}\cdot A_w\cdot j_d}{s^2\cdot b_w}\right\}\sqrt{\sigma_B}$$

(multiplied by 1.22 for bottom bars)

where, b: width of a member, d_b:diametar of longitudinal bar, Ns: number of longitudinal bars supported by sub–ties, Nu: number of longitudinal bars unsupported, Nt: total number of longitudinal bars, p_w: lateral reinforcement ratio, p_w': ratio of lateral reinforcement arranged at extreme side, c: half clear spacing between bars or half available concrete width per bar resisting splitting in the failure plane, A_w: area of lateral reinforcement, ${}_w\sigma_y$: yielding strength of lateral reinforcement, ls: development length, s: spacing of lateral reinforment, j_d: distance between top and bottom bar, b_w: width confined by lateral reinforcement of a member

Maximum bond stress in a corner bar is τ_{max1}, and τ_{max2} is that in an intermediate bar. $\tau_{max.av}$ is the maximum of average bond stress in the whole test bars in a test zone. τ_{max1}, τ_{max2} and $\tau_{max.av}$ are shown in Table 3. Maximum bond stresses are regarded as experimental bond splitting strengths in the following investigation. Bond splitting strength calculated by AIJ's formula[Ref. 1], Fujii and Morita's formula[Ref. 2],Orangun, Jirsa and Breen's formula[Ref. 5], and Kaku and Yamada's formula[Ref. 6] are also shown in Table 3. Experimental bond splitting strength $\tau_{max.av}$ and calculated bond splitting strength are compared in Fig. 8.

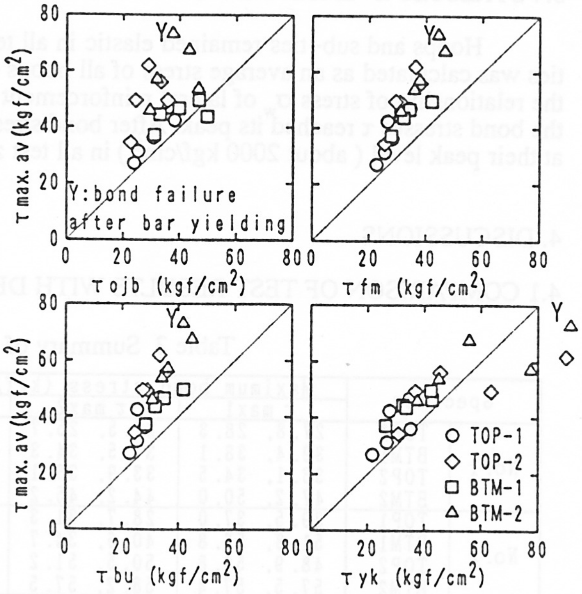


Fig. 8 Experimental and calculated bond strength

The bond strength is not affected by the use of sub-ties in the Orangun-Jirsa-Breen's formula and the Fujii-Morita's formula; the test results disagreed with bond splitting strength calculated by the Orangun-Jirsa-Breen's formula. The Fujii-Morita's formula underestimated the test results, especially in TOP2 and BTM2. The same can be said for the AIJ's formula, although bond splitting strength calculated by the AIJ's formula considers the contribution of sub-ties. Bond splitting strength calculated by the Kaku-Yamada's formula agrees well with most of the test results, but disagree with some test results in a high strength range.

4.2 BOND STRENGTH OF TOP AND BOTTOM BARS

A major parameter influencing bond splitting strength is the position of a bar relative to the height of concrete during casting. Bond strength of top bars is relatively lower than that of bottom bars. Experimental bond strengths observed in top bars and bottom bars are compared in Fig. 9. Experimental bond strengths of bottom bars were, on the average, 1.22 times larger than that of top bars with a standard deviation of 0.14. A similar ratio is reported in Ref. 2 and 5. Therefore, in the following investigation, experimental bond strengths of top bars are multiplied by 1.22 to normalize with respect to bottom bars.

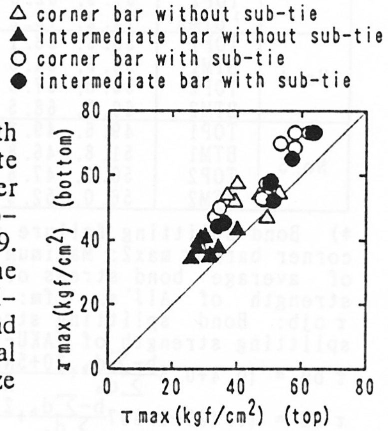


Fig. 9 Bond strength of top and bottom bars

4.3 LATERAL REINFORCEMENT

The bond splitting strength was expected to be governed by concrete tensile strength. Therefore, experimental bond strength τ_{max} was normalized by $\sqrt{\sigma_B}$ in order to remove the influence of concrete strength on bond splitting strength. The relationship of lateral reinforcement ratio p_w and normalized experimental bond strength $\tau_{max} / \sqrt{\sigma_B}$ is shown in Fig. 10. Figures 10(a), (b), (c) and (d) show the test results of corner bars in a test zone without sub-ties, corner bars in a test zone with sub-ties, intermediate bars in a test zone without sub-ties and intermediate bars in a test zone with sub-ties, respectively. The AIJ's formula (dotted line), the Orangun-Jirsa-Breen's formula (chained line) and the Kaku-Yamada's formula (solid line) are also shown in Fig. 10.

Normalized experimental bond strength $\tau_{max} / \sqrt{\sigma_B}$ increases in proportion to lateral reinforcement ratio p_w. Bond splitting strength calculated by the Orangun-Jirsa-Breen's formula increases in proportion to p_w up to 0.75% level, and then is constant. The AIJ's formula underestimates bond splitting strength in both corner bars and intermediate bars, especially in the bars in test zones with sub-ties (TOP2 and BTM2).

τ_{st} presents a contribution of lateral reinforcement to bond splitting strength. τ_{st} is given in proportion to the square of p_w in the Kaku-Yamada's formula. Although the Kaku-Yamada's formula agrees well with most of authors' test results, it overestimates some of the test results in the bars in test zones with sub-ties at large p_w level.

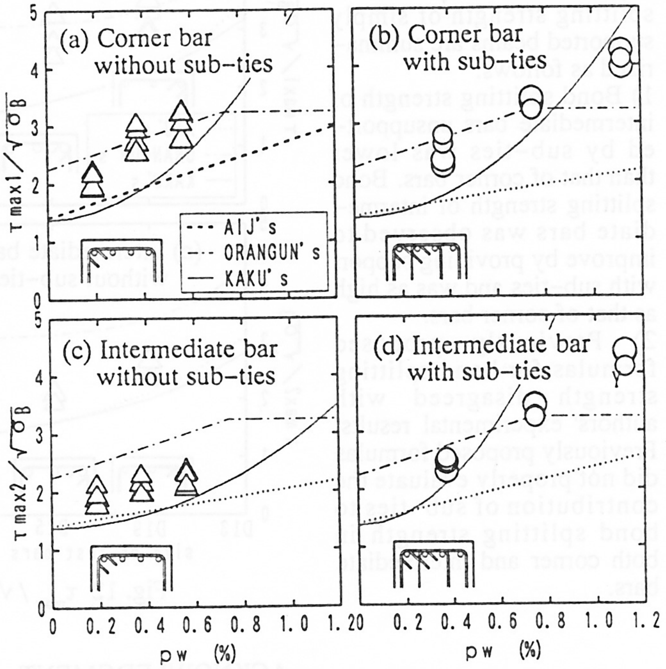


Fig. 10 $\tau_{max} / \sqrt{\sigma_B} - p_w$ relationship

4.4 LONGITUDINAL BARS

The relations of $\tau_{max} / \sqrt{\sigma_B}$ and the number of test bars in a test zone are shown in Fig.11, together with the curves computed by the previously proposed formulas. It is observed that $\tau_{max} / \sqrt{\sigma_B}$ decreases as the number of test bars increases. The test results agree better with the AIJ's formula and the Orangun-Jirsa-Breen's formula than the Kaku-Yamada's formula in which the bond strength is regarded to increase with the number of longitudinal bars in case of the bars in test zones with sub-ties.

The relations of $\tau / \sqrt{\sigma_B}$ and the diameter of test bars are shown in Fig.12. $\tau_{max} / \sqrt{\sigma_B}$ decreases as the diameter of test bars increases. The test results agree with previously proposed formulas.

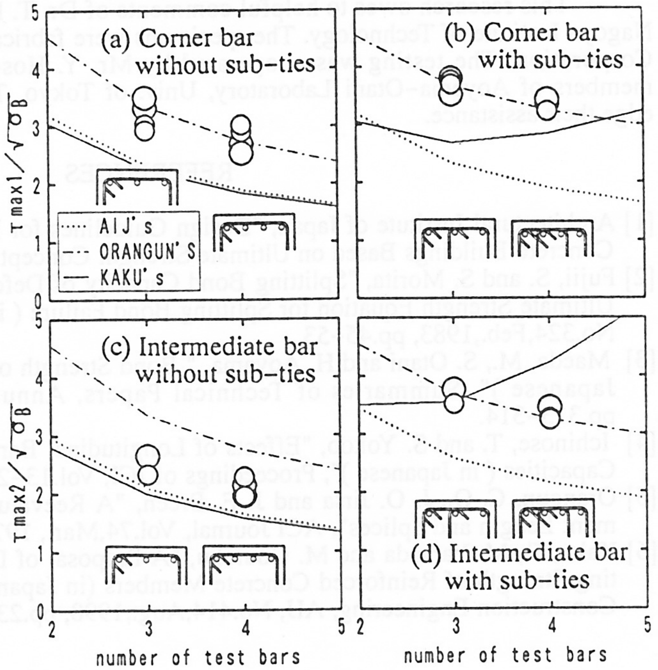


Fig. 11 $\tau_{max} / \sqrt{\sigma_B}$ vs. number of test bars

5. CONCLUSIONS

Findings from this experimental study on bond splitting strength of simply supported beams are summarized as follows:

1) Bond splitting strength of intermediate bars unsupported by sub-ties was lower than that of corner bars. Bond splitting strength of intermediate bars was observed to improve by providing support with sub-ties and was as high as that of corner bars.

2) Previously proposed formulas for bond splitting strength disagreed with authors' experimental results. Previously proposed formulas did not properly evaluate the contribution of sub-ties to bond splitting strength in both corner and intermediate bars.

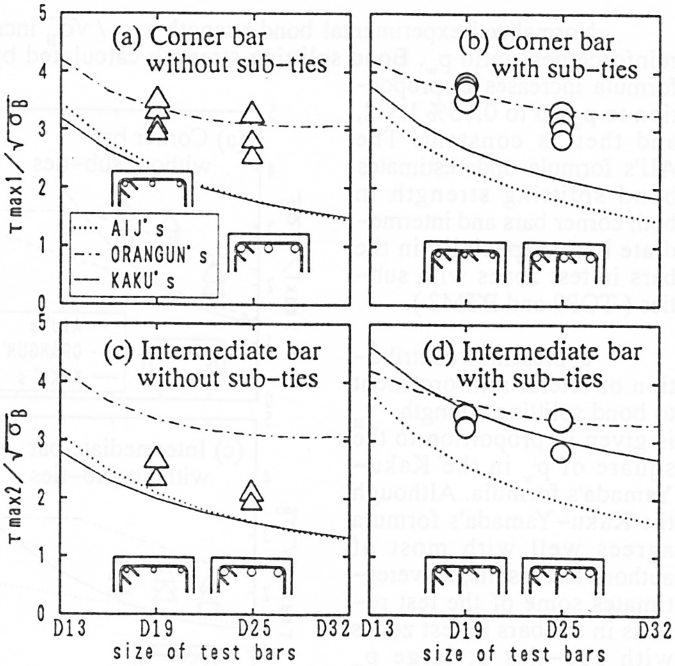


Fig. 12 $\tau_{max} / \sqrt{\sigma_B}$ vs. size of test bars

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