LOCAL BOND SPLITTING BEHAVIOR OF RC MEMBERS WITH LATERAL REINFORCEMENT

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ABSTRACT :

This research features local bond splitting behavior and bond splitting strength of reinforced concrete members with confinement of lateral reinforcements. Lateral reinforcements contribute to confinement of main reinforcements, increase bond splitting strength and improve brittle failure. To make clear the correlation between local bond splitting behavior with confinement of lateral reinforcement in RC members, it is necessary to quantify effect of lateral confinement in bond splitting behavior. To obtain the local bond stress versus slippage relationship with confinement of lateral reinforcement, pull-out bond test is conducted. The test results show that maximum bond stress has an increment as lateral confinement stress also increases, and the slippage at maximum bond stress is influenced by splitting crack width and shape of main reinforcement. A new relationship between bond stress and slippage in case of confinement of lateral reinforcement is proposed using these results and effect of lateral confinement. A numerical analysis is performed to confirm the model with experimental results. The analytical results show a good agreement in bond splitting strength with experimental results of previous studies.

KEYWORDS: bond splitting, local behavior, lateral confinement, shape of main bar, crack width

1. INTRODUCTION

In many studies related to bond splitting behavior of reinforced concrete (RC) members, it is reported that many local bond stress versus slippage relationships and bond splitting strength calculation formulas and are proposed by the present [1,2]. It is essentially considered that local bond splitting behavior and average one in RC members are same destruction mechanism, regardless of with or without lateral reinforcement. However, the evaluation of bond splitting strength based on relationship between local bond splitting behavior and average one have not been developed. Most calculation formulas are proposed by regression analysis of experimental results and mechanical meaning considerations is not always done. And the relationship between local bond stress and slippage of reinforcement with lateral reinforcement has not been yet completely clear.

The authors focus attention on bond splitting behavior failed by splitting crack of surrounding concrete, investigate bond splitting behavior of RC members through pull-out bond test of which specimens have a short bond length, and have quantified local bond stress - slippage of reinforcement relationships without lateral reinforcement. From the results of the numerical analysis conducted to obtain average bond behavior using this model, analyzed bond splitting strengths showed a good correlation with experimental values observed [3]. The formula for bond splitting strength built up by solving second differential equation of bond problem using EBSB, which is defined as the area of EBSB has the same area of local bond stress versus slippage, agreed well with experimental results reported previously [4].

The purpose of this study is to derive local bond stress versus slippage relationship with lateral reinforcement based on effect of lateral confinement and correlation between local bond splitting behavior with lateral reinforcement. To obtain the relationship and the effect, pull-out bond test is conducted with lateral confinement force as a main parameter, and comparison of numerical analysis results using the model with experimental results reported previously is investigated.

2. LOCAL BOND EXPERIMENT WITH LATERAL CONFINEMENT

2.1. Outline of Experiment

To investigate local bond splitting behavior with lateral confinement, the authors have conducted pull-out bond test with lateral confinement force. The specimen is shown in Fig.1. The specimen with a bond length of four times of the diameter of reinforcement (d_b) is concrete block inserted one main reinforcement. The dimensions of specimen are 14d_b x 14d_b x 7d_b in rectangle. To apply the lateral confinement force to only the main reinforcement, the specimen has slits by steel and urethane form, which correspond to splitting crack of surrounding concrete. In order not to restrain the deformation inside and outside concrete of surrounding the main reinforcement, the specimen is set up on the loading plate provided the hole through four teflon sheets. The lateral confinement force is applied by two oil jacks to concrete block directly, which is kept constant during loading. A monotonic pull-out load is applied until failure occurred. The measured items are the pull-out load, the lateral confinement load, the slip of the free end of the main reinforcement and the crack width of concrete.

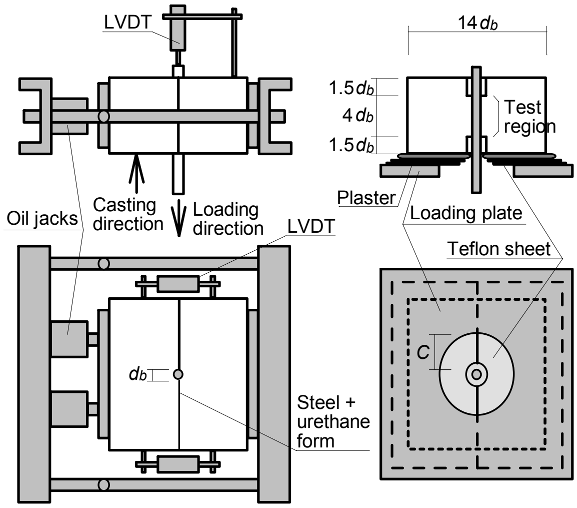

Fig.1 Outline of the specimen

2.2. Specimens and Materials

Two series of specimens is consisted in order to investigate the influence of shape of main reinforcement in the bond stress transfer mechanism. In series A, specimens is provided with generic deformed-bars and experimental factors are concrete strength (24, 30, 48 and 60MP), diameter of reinforcement (16 and 25mm), shape of reinforcement (lateral-type rib and screw-type rib), thickness of concrete cover (C/d_b: 1.5, 2.5 and 3.5) and lateral confinement force (2, 4, 6, 8, 10, and 12kN). In series B, specimens are provided with scraped and cutting deformed-bars. The test variables in series B are rib angle (45 and 90 degree), rib spacing (9.6, 16.0 and 24.0mm), rib height (1.2 and 2.4mm) of deformed-bars and lateral confinement force (2, 6, and 10kN). The material characteristics of concrete and deformed-bars used in this study are shown in Table 1, Table 2, and Fig.2. The list of specimens in series A and B is shown in Table 2.3 and Table 2.4 with test results, respectively. The concrete is normal weight concrete using coarse aggregate of maximum diameter of 20mm and specified compressive strength of 30, 60, 24, and 48MPa.

Table 1 Mechanical properties of concrete

series	Specified compressive strength	Compressive strength σ_B (MPa)	Splitting strength σ_t (MPa)	Elastic modulus E_c (GPa)
A	30MPa	32.9	2.75	23.1
	60MPa	62.8	3.60	28.2
	24MPa	23.6	2.01	22.6
	48MPa	55.5	3.79	29.2
B	36MPa	32.9	2.72	23.8

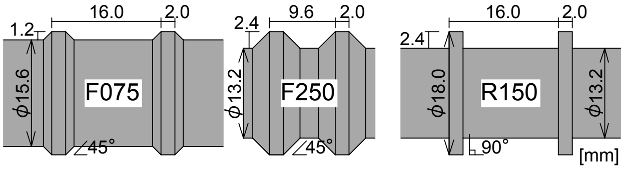

Fig.2 Shape of scraped bar in series B

Table 2 Mechanical properties of reinforcement

series	Reinforcing bar type	Cross-sectional area a_b (mm^2)	Diameter d_b (mm)	Perimeter ϕ_b (mm)	Rib height h (mm)	Rib spacing l_n (mm)	Rib angle θ (degrees)	Rib height -spacing ratio h/l_n	Yield strength ${}_s\sigma_y$ (MPa)	Elastic modulus E_b (GPa)
A	T (D16) Lateral-type rib	191	15.6	49.0	1.03	10.60	36	0.097	399	197
	N (D16) Screw-type rib	193	15.7	49.2	1.25	8.38	41	0.149	376	197
	LT (D25) Lateral-type rib	485	24.8	78.1	2.02	17.81	34	0.113	403	199
	LN (D25) Screw-type rib	492	25.0	78.6	1.73	9.96	39	0.174	393	197
B	F050	201	16.0	50.2	1.20	24.0	45	0.050	568	206
	F075	204	16.1	50.6	1.20	16.0	45	0.075		
	F150	168	14.6	46.0	2.40	16.0	45	0.150		
	F250	194	15.7	49.4	2.40	9.6	45	0.250		
	R150	152	13.9	43.6	2.40	16.0	90	0.150		

2.3. Experimental Results

Experimental results at the maximum load in series A and B are listed in Table 3 and Table 4, respectively. The bond stress is derived by dividing the tensile load by the surface area of main reinforcement. The loaded end slip is derived by adding the elongation of the reinforcement to the free end slip ignoring concrete deformation and assuming constant bond stress. The lateral confinement stress is calculated by dividing lateral confinement force by diameter of bar and bond length. The splitting crack width is half of slit deformation. Each experimental value in series A is average value of three specimens in same factors, one in series B is value of one specimen.

Table 3 List of specimens and test results in series A

Specimen	Reinforcement		concrete strength	Thickness of concrete cover	Lateral confinement		At maximum load				
	Shape (Bar type)	Rib height -spacing ratio			Force (kN)	Stress (MPa)	Load (kN)	Bond stress (MPa)	Slip (mm)		Crack width (mm)
									Loaded end	Free end	
T3015-2	T (D16)	0.097	Compressive 32.9MPa Splitting 2.75MPa	1.5	2.0	2.00	13.45	4.29	0.609	0.597	0.220
T3015-6					6.0	6.01	24.82	7.92	0.421	0.400	0.101
T3025-2				2.5	2.0	2.00	12.29	3.92	0.678	0.667	0.275
T3025-4					4.0	4.01	20.09	6.41	0.555	0.538	0.146
T3025-6					6.0	6.01	21.58	6.88	0.762	0.743	0.117
T3025-8					8.0	8.02	24.98	7.96	0.824	0.803	0.071
T3025-10					10.0	10.02	29.09	9.28	0.533	0.509	0.088
T3025-12					12.0	12.02	30.22	9.64	0.784	0.758	0.110
T3035-6				3.5	6.0	6.01	20.53	6.55	0.658	0.641	0.101
T3035-10					10.0	10.02	27.46	8.75	0.848	0.825	0.059
N3025-2	N (D16)	0.149		2.5	2.0	1.99	15.71	4.99	0.396	0.383	0.121
N3025-6					6.0	5.98	24.16	7.67	0.398	0.378	0.121
N3025-10					10.0	9.97	30.70	9.75	0.407	0.381	0.042
T6025-2	T (D16)	0.097	Compressive 62.8MPa Splitting 3.60MPa	2.5	2.0	2.00	22.15	7.06	0.538	0.519	0.412
T6025-4					4.0	4.01	28.36	9.04	0.691	0.667	0.287
T6025-6					6.0	6.01	32.71	10.43	0.655	0.627	0.210
T6025-8					8.0	8.02	38.03	12.13	0.467	0.435	0.136
T6025-10					10.0	10.02	40.12	12.79	0.582	0.548	0.124
T6025-12					12.0	12.02	43.26	13.79	0.437	0.401	0.102
LT2425-12.5	LT (D25)	0.113	Compressive 23.6MPa Splitting 2.01MPa	2.5	12.5	5.03	52.28	6.70	0.812	0.785	0.179
LN2425-12.5	LN (D25)	0.174			12.5	4.99	45.03	5.73	0.677	0.651	0.083
LT4825-12.5	LT (D25)	0.113	Compressive 55.5MPa Splitting 3.79MPa		12.5	5.03	62.16	7.96	1.253	1.221	0.506
LN4825-12.5	LN (D25)	0.174			12.5	4.99	69.30	8.81	0.655	0.619	0.337

Table 4 List of specimens and test results in series B

Specimen	Reinforcement		Concrete strength	Thickness of concrete cover	Lateral confinement		At maximum load				
	Rib angle (Diameter)	Rib height -spacing ratio			Force (kN)	Stress (MPa)	Load (kN)	Bond stress (MPa)	Slip (mm)		Crack width (mm)
									Loaded end	Free end	
F050-2	45 degrees (16.0mm)	0.050	Compressive 32.9MPa Splitting 2.72MPa	2.5	2.0	1.96	10.09	3.14	1.422	1.414	0.297
F050-6					6.0	5.87	21.18	6.59	1.012	0.996	0.172
F050-10					10.0	9.78	27.68	8.62	1.359	1.338	0.156
F075-2	45 degrees (16.1mm)	0.075			2.0	1.94	16.40	5.06	0.782	0.769	0.310
F075-6					6.0	5.82	26.72	8.25	0.624	0.604	0.213
F075-10					10.0	9.70	31.48	9.72	0.888	0.864	0.193
F150-2	45 degrees (14.6mm)	0.150			2.0	2.13	15.30	5.20	0.466	0.452	0.241
F150-6					6.0	6.40	25.44	8.64	0.716	0.692	0.268
F150-10					10.0	10.67	36.87	12.53	0.612	0.578	0.206
F250-2	45 degrees (15.7mm)	0.250			2.0	1.99	15.19	4.80	0.368	0.356	0.245
F250-6					6.0	5.96	23.87	7.55	0.481	0.442	0.177
F250-10					10.0	9.94	34.21	10.82	0.369	0.342	0.075
R150-2	90 degrees (13.9mm)	0.150			2.0	2.25	14.82	5.31	0.439	0.424	0.222
R150-6					6.0	6.75	27.38	9.80	0.506	0.478	0.202
R150-10					10.0	11.25	34.67	12.41	0.684	0.648	0.207

2.3.1 Maximum Bond Stress

Fig.3 shows the relationship between maximum bond stress and lateral confinement stress (a formula in the figure mentioned later). Maximum bond stress and lateral confinement stress are normalized by concrete compressive strength to remove the influence by the difference of concrete compressive strength. Maximum bond stress increases linearly as lateral confinement stress increases in almost specimens, not influenced by the difference of diameter, rib height, rib spacing, rib angle of reinforcing bar, and thickness of concrete cover.

2.3.2 Slippage of Reinforcement

Fig.4 shows slippage of reinforcement at maximum load versus rib height of reinforcement, one versus rib spacing of reinforcement. Slippage of reinforcement at maximum load decreases slightly as rib height of reinforcing bar increases, increases approximately linearly as rib spacing of reinforcement increases. In specimens used deformed-bar of D25 in series A, slippage of reinforcement at maximum load increases markedly as concrete compressive strength increases. It is observed that the difference of concrete compressive strength on the front of rib affects slippage of reinforcing bar, which regarded as tri-axial compressive stress by the effect of lateral confinement.

2.3.3 Crack Width

Fig.5 shows splitting crack width at maximum load versus concrete compressive strength and rib height of reinforcing bar. Splitting crack width at maximum load increases as concrete compressive strength and rib height of reinforcement increase. It is recognized that splitting crack width strongly relates to concrete stiffness on the front of rib, bearing strength of concrete, and effect of lateral confinement.

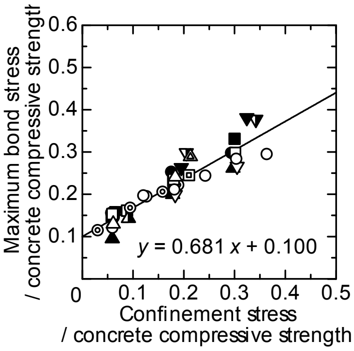

Fig.3 Maximum bond stress - confinement stress relationship

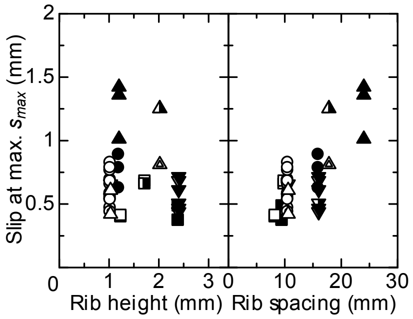

Fig.4 Loaded end slip - rib height and rib spacing relationship

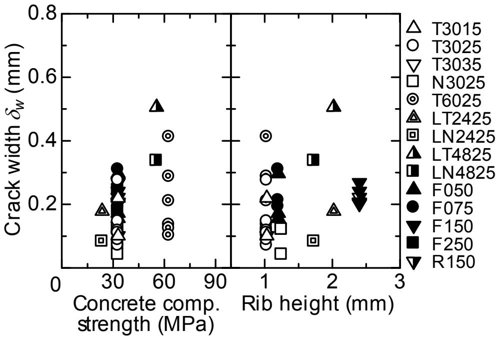

Fig.5 Crack width - concrete strength and rib height relationship

2.4. Local Bond Stress - Slip Model

It is considered that bearing strength and effect of lateral confinement are greatly affected by lateral confinement condition of surrounding concrete on bond action between deformed bars and concrete assumed that bearing stress acts on the front of rib of main reinforcement, which are depending on mechanical interaction and splitting crack width. A new relationship between local bond stress and slip with lateral reinforcement is proposed based on concrete stress condition on the front of rib and consideration of mechanical behavior.

2.4.1 Maximum Bond Stress

Mechanical interaction is regarded as being dominant on bond action between deformed bars and concrete with lateral confinement after the occurrence of splitting crack, thus bond stress and splitting stress are described as shown in Eq.(1). Because it is recognized that relationship between bond stress and splitting stress is linear as shown in Fig.3, the angle between the principal bond stress and the axis of the main reinforcement is 56 degrees from the slop of linear curve calculated by least square method.

$$\tau_{bs,max} = \sigma_l \cdot \cot\theta \tag{1}$$

where, $\tau_{bs,max}$: maximum bond stress, σ_l : lateral confinement stress,
θ : angle between the principal bond stress and the axis of reinforcement (= 56degrees)

2.4.2 Effect of Lateral Confinement

The coefficient of bearing strength (f_{bear}) is described as Eq.(2), which is defined as ratio of bearing stress exerted apparently on all area of the front of rib at maximum load to concrete compressive strength. Fig.6 shows coefficient of bearing strength versus crack width relation as maximum load. It is observed that bearing strength of the front of rib is 1-3 times of concrete compressive strength, also that coefficient of bearing strength decreases as splitting crack width increases. Maximum bond stress, bearing strength, and mechanical interaction can be expressed by relationship between lateral confinement stress and crack width, considering that maximum bond stress versus lateral confinement stress relation is described by Eq.(1).

$$f_{bear} = \frac{\sqrt{(\tau_{bs,max} \cdot \phi_b \cdot l_b)^2 + (\sigma_l \cdot d_b \cdot l_b)^2}}{\phi_b \cdot h} \cdot \frac{l_n}{l_b} \bigg/ \sigma_B \tag{2}$$

where, σ_B : concrete compressive strength, ϕ_b : perimeter of reinforcement,
h : rib height, l_n : rib spacing, d_b : diameter of reinforcing bar, l_b : bond length

Lateral confinement stress versus crack width relation is shown in Fig.7. Lateral confinement stress and crack width are normalized by concrete compressive strength and rib height of reinforcing bar, respectively, to remove the influence by concrete strength and shape of main reinforcements. It is confirmed that crack width decreases as lateral confinement stress increases to enhance effect of lateral confinement. Formula calculated by least square method is obtained as shown in Fig.7, thus, bearing strength on the front of rib and least upper bound of lateral confinement effect given by bearing strength are expressed by function of crack width.

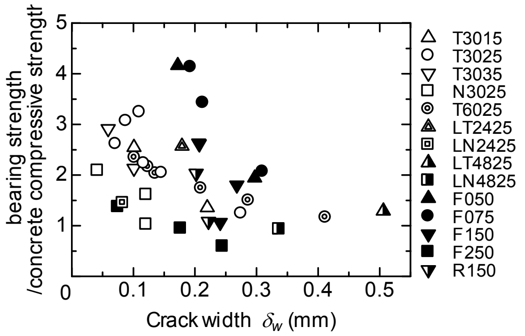

Fig.6 Coefficient of bearing strength versus crack width relationship

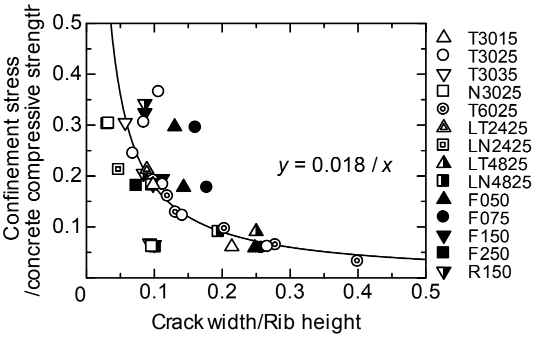

Fig.7 Lateral confinement stress versus crack width relationship

2.4.3 Slip at Maximum Bond Stress

Slip has been influenced by rib spacing and lateral confinement stress from investigation of test results. Slip at maximum bond stress versus crack width relation normalized by lateral confinement stress is shown in Fig.8. It is observed that slip at maximum bond stress increases linearly as splitting crack width increases. As results calculated by least square method, slip at maximum bond stress can be described as shown in Fig.8. It indicates that slip at maximum bond stress and crack width are proportion relations, also which rib spacing increases as slippage increases.

2.4.4 Relationship between Bond Stress and Slippage

Typical relationships between bond stress and loaded end slip are shown in Fig.9, which is normalized by measured maximum bond stress. The shape of the curve is not influenced by experimental factors, and each curve after the maximum stress trends to decrease linearly with slip of main reinforcement. The objective of this research is to present bond stress - slip model that has two stages. The increase stage is expressed by parabolic curve considering tri-axial compression state and failure progress of mechanical interaction and effect of lateral confinement. Because the area in which rib spacing concrete resists to shear force decreases linearly to the slip of the reinforcement after maximum load, the decrease stage is expressed by the straight line determined by rib spacing, as that the bond stress becomes zero when the slip of main reinforcement is equal to rib spacing. Bond stress - slip model is shown in Fig.9, which can express basically experimental results.

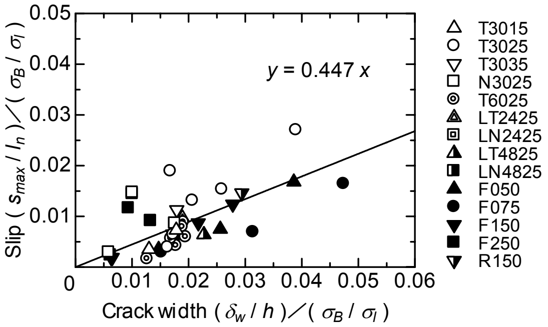

Fig.8 Normalized Slip at maximum stress versus crack width relationship

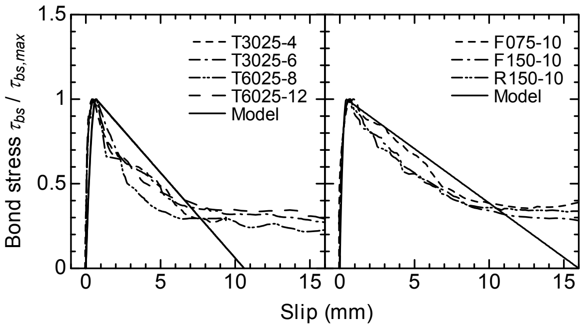

Fig.9 Relationship between bond stress and slip

3. BOND SPLITTING BEHAVIOR WITH LATERAL REINFORCEMENT

3.1. Confinement Stress Exerted by Lateral Reinforcement

Lateral confinement stress is provided by lateral reinforcement which restrain increase of crack width, and correlate with lateral reinforcement stress occurred by deformation of lateral reinforcement and crack width. Assuming that bond force of lateral reinforcement is distributed uniformly throughout entire bond effective length at maximum bond stress, lateral confinement stress can be expressed by Eq.(3), which is provided by stress of lateral reinforcement that is proportional to crack width. It represents lateral confinement stress that exerts uniform confinement force to orthogonal direction of crack side in side-splitting bond failure. On the other hand, because lateral confinement stress has upper limit of confinement effect determined by bearing strength as shown in Fig.10, lateral confinement stress at maximum bond stress is derived as Eq.(4) which is given by point at the intersection of Equation as shown in Fig.7 with Eq.(3) as shown in Fig.10. Also, in case that stress of lateral reinforcement calculated by Eq.(4) is more than yield strength, lateral confinement stress is given by Eq.(5).

$$\frac{\sigma_l}{\sigma_B} = \frac{b \cdot p_w}{N \cdot d_b} \cdot \frac{\delta_w}{l_{we}} \cdot \frac{E_{st}}{\sigma_B} \tag{3}$$

$$\sigma_{l,max} = \sqrt{k \cdot \frac{b \cdot p_w}{N \cdot d_b} \cdot \frac{h}{l_{we}} \cdot E_{st} \cdot \sigma_B} \tag{4}$$

$$\sigma_{ly} = \frac{b \cdot p_w}{N \cdot d_b} \cdot \sigma_{wy} \tag{5}$$

where, b : width of member, p_w : lateral reinforcement ratio, σ_{wy} : yield strength of lateral reinforcement, N : number of reinforcing bar, l_{we} : bond effective length, E_{st} : Elastic modulus of lateral reinforcement

3.2. Bond Stress - Slip Relationships

It is possible to express local bond behavior of RC members with lateral reinforcement as adding bond increment to local bond behavior without lateral reinforcement. Moreover, the local bond stress versus slip relation without lateral reinforcement has been quantified as shown in Eq.(7) [1]. Therefore, a new proposed relationship between local bond stress and slip with lateral reinforcement, which is described by adding bond stress of Eq.(7) to bond stress obtained from test results, becomes as follows:

$$\tau_b = \tau_{bc} + \tau_{bs} \tag{6}$$

$$\tau_{bc} = 2 \cdot \sigma_t \cdot \beta \cdot s \cdot \frac{(r_u/d_b)^2 - (\beta \cdot s)^2}{(r_u/d_b)^2 + (\beta \cdot s)^2} \cdot \cot\alpha \tag{7}$$

$$\tau_{bs} = \tau_{bs,max} \cdot (s/s_{max}) \cdot (2 - s/s_{max}) \qquad (s \le s_{max}) \tag{8}$$

$$\tau_{bs} = -\frac{\tau_{bs,max}}{l_n - s_{max}} \cdot (s - l_n) \qquad (s > s_{max}) \tag{9}$$

$$\tau_{bs,max} = \sigma_{l,max} \cdot \cot\theta \tag{10}$$

$$s_{max} = 0.008 \cdot l_n \cdot \frac{\sigma_B}{\sigma_{l,max}} \tag{11}$$

$$\sigma_{l,max} = \sqrt{0.018 \cdot \frac{b \cdot p_w}{N \cdot d_b} \cdot \frac{h}{l_{we}} \cdot E_{st} \cdot \sigma_B} \tag{12}$$

$$\sigma_{l,max} \le \sigma_{ly} = b \cdot p_w \cdot \sigma_{wy} / (N \cdot d_b) \tag{13}$$

where, τ_b : local bond stress, s : slip, β : coefficient between internal crack depth and slip (=10.2 (1/mm)), α : angle between the principal bond stress and the axis of reinforcing bar (= 34 degrees), σ_t : concrete tensile strength, r_u : $C + d_b/2$ (C : thickness of concrete cover), d_b : diameter of reinforcing bar

Examples of local bond stress - slip relation are shown in Fig.11, where bond effective length is 9 times of diameter of lateral reinforcement. Analytical results by numerical calculation of pull-out test are shown in Fig.12, which is conducted to obtain average bond behavior using this model and analysis method indicated in Reference 3. The dimensions and mechanical properties of specimens in the model and the analysis are shown in Fig.11 and Fig.12. Proposed local bond stress - slip relations have two extreme values, that one is at the occurrence of splitting crack and the other is at bearing strength of concrete on the front of rib by the acting of lateral confinement effect. Therefore, average bond stress - loaded end slip relations also have two peaks, that one is given by concrete splitting and the other is given by lateral confinement of reinforcement.

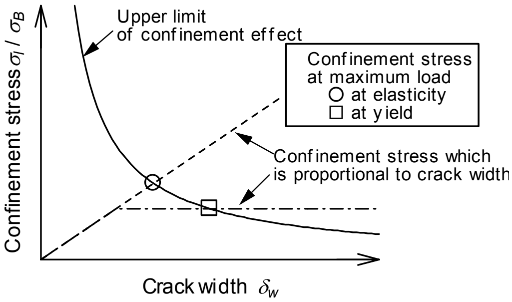

Fig.10 Lateral confinement stress versus crack width relationship

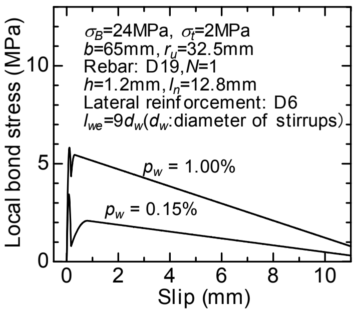

Fig.11 Local bond stress versus slip relationship

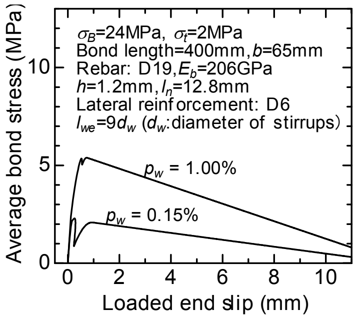

Fig.12 Average bond stress versus loaded end slip relationship

4. ADAPTATION OF PROPOSED MODEL

4.1. Confinement Contribution Ratio of Lateral reinforcement

It is confirmed that the effect of lateral confinement at the corner main reinforcement and at the middle one is different. Because the difference of bond splitting strength between at the corner main reinforcement and at the middle one is closely related to quantity of lateral reinforcement and effect of lateral confinement, confinement contribution ration of Lateral reinforcement is determined by ratio of bond splitting strength at corner and at middle versus ratio of lateral reinforcement relationship using previous test results. From test results of specimens that concrete compressive strength is under 30 MPa, and ratio of lateral reinforcement is over 0.5 %, average of bond splitting strength ratio is 0.62, which corresponds to confinement contribution ratio.

4.2. Bond Splitting Strength

To evaluate adaptation of the proposed model, the comparison between results of numerical analysis using the proposed model and experimental results is investigated. Experimental values are obtained by bond test of cantilever and beam type specimens done in previous studies. Fig.13 shows the comparison between experimental bond strength and analytical values calculated by the proposed model. The ratio of experimental values to analysis values is 1.07 in average, and the coefficient of variation is 19 percent. The predicted values show a good agreement with experimental results for most specimens.

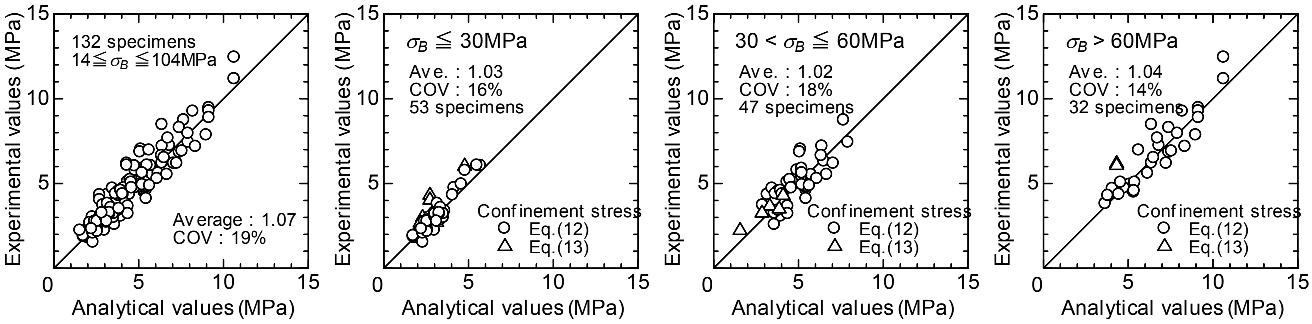

Fig.13 Comparison between experimental results and analytical results

5. CONCLUSIONS

To investigate the effect of lateral confinement on local bond behavior, pull-out bond test was conducted. A local bond stress versus slip model was proposed based on mechanical meaning considerations, which was derived from relationship between effect of lateral confinement and splitting crack width. The model was also verified by comparing the test results form previous studies with the analytical results obtained from the present model.

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