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EFFECT OF LATERAL CONFINEMENT IN BOND SPLITTING BEHAVIOR OF RC MEMBERS

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SUMMARY

For the purpose of quantifying local bond splitting behavior with lateral confinement in reinforced concrete (RC) members, pull-out bond test was carried out with lateral confinement force varied according to slippage of main reinforcement. The experimental factors are concrete strength, diameter of reinforcement, shape of reinforcement and proportional coefficient of confinement force. Test results show that the maximum local bond stress increases as proportional coefficient of confinement force and concrete compressive strength also increase, and the slippage at maximum bond stress is influenced largely by shape of reinforcement. From the test results, a new relationship between the local bond stress and the slippage of reinforcements with lateral reinforcement is proposed. The increase stage of relationship is expressed by parabolic curve that is determined by concrete compressive strength, diameter of reinforcement, proportional coefficient of confinement force and shape of reinforcement. The decrease stage of relationship is expressed by a line that is determined by rib spacing of reinforcement.

INTRODUCTION

The relationship between local bond stress and slippage of reinforcement with lateral reinforcement has not been yet completely clear. Therefore, the authors focus attention on bond splitting behavior failed by splitting crack of surrounding concrete, and investigate bond splitting behavior of RC members through pull-out bond test of which specimens have a short bond length. 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. The local bond stress versus slippage of reinforcement relationship without lateral reinforcement has been quantified [1]. From the results of local bond test with constant lateral confinement force, the local bond stress versus slippage of reinforcement relationship with lateral reinforcement has been expressed as bilinear curve that determined by concrete compressive strength, lateral confinement force and shape of reinforcement [2]. However, from results of local bond behavior on the cantilever specimens having a bond length of 23 times of the main reinforcement diameter, it is recognized that stress of the lateral reinforcement is in proportion to slippage of main reinforcement until maximum bond stress [3]. So that the lateral confinement force in RC members is thought to be similar to that.

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In this paper, to make clear the correlation between local bond splitting behavior with lateral reinforcement and effect of lateral confinement in RC members, pull-out bond test is conducted with lateral confinement force as a main parameter.

OUTLINE OF EXPERIMENT

Specimens and Test Method

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 is $14d_b$ x $14d_b$ x $14d_b$ 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 in proportion to slippage of main reinforcement until maximum load. After that, the confinement force at maximum load is kept constant. 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. The experimental factors are concrete strength (24 and 48MP), diameter of reinforcement (16 and 25mm), shape of reinforcement (lateral-type rib and screw-type rib) and proportional coefficient of confinement force (slope: 2 and 5 kN/mm). The identification of each type of specimen is explained in Fig.2. In the specimens which have the main reinforcement diameter of 25mm, visual observation of surrounding concrete through failure progress was conducted at feature 3 stages (A-C). Total number of specimens is 48.

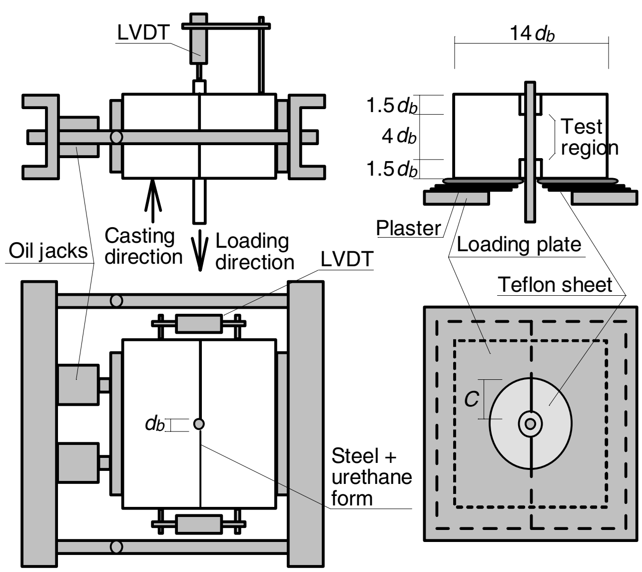

Fig.1 Outline of the specimen

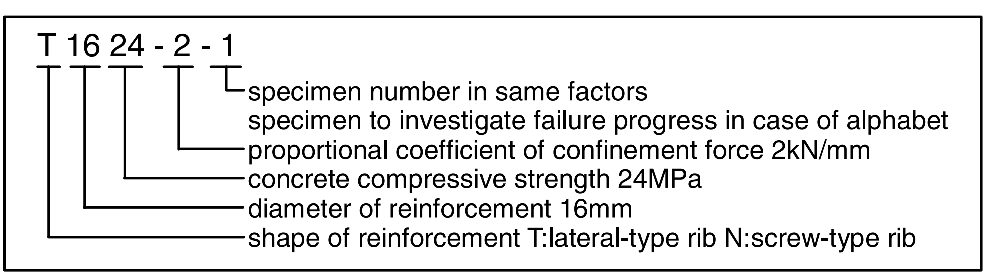

Fig.2 Identification of the specimen

Materials

The material test results of the concrete are shown in Table 1. The concrete is normal weight concrete using coarse aggregate of maximum diameter of 20mm and design compressive strength of 24 and 48MPa. Mechanical properties for the reinforcements are shown in Table 2. The reinforcements are deformed bar of nominal diameter 16 and 25mm. The cross-sectional area of the reinforcement is derived as round shape by measuring volume of reinforcements. The shapes of the reinforcement measured with the slide caliper are shown in Table 3.

Table 1 Mechanical properties of concrete

Concrete type	Compressive strength σ_B (MPa)	Splitting strength σ_t (MPa)	Elastic modulus E_c (GPa)
Normal F_c24	23.6	2.01	22.6
Normal F_c48	55.5	3.79	29.2

Table 2 Mechanical properties of reinforcement

Identification (Nominal diameter)	Shape (Cross-sectional area A_b)	Ultimate strength f_{su} (MPa)	Yield strength f_{sy} (MPa)	Elastic modulus E_s (MPa)
D16 (16mm)	Lateral-type rib (190mm^2)	589	403	188
	Screw-type rib (191mm^2)	600	403	197
D25 (25mm)	Lateral-type rib (485mm^2)	595	403	199
	Screw-type rib (492mm^2)	595	393	197

Table 3 Shape of reinforcement

Identification	Shape (Measured diamater d_b)	Rib height h (mm)	Width at top w_n (mm)	Rib spacing l_n (mm)	Rib height-spacing ratio h / l_n
D16	Lateral-type rib (15.5mm)	1.03	1.95	10.60	0.097
	Screw-type rib (15.6mm)	1.25	1.55	8.38	0.149
D25	Lateral-type rib (24.8mm)	2.02	2.23	17.81	0.113
	Screw-type rib (25.0mm)	1.73	2.32	9.96	0.174

EXPERIMENTAL RESULTS

Outline of Experimental Results

Experimental results at the maximum load are listed in Table 4. Each experimental value is average value of three specimens in same factors. The bond stress (τ_b) is derived by dividing the maximum load by the surface area of main reinforcement. The loaded end slip (s_l) 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 (σ_l) and the slope of the lateral confinement stress (γ) are calculated by Eq.(1) and Eq.(2).

$$\sigma_l = \frac{P_l}{d_b \cdot l_b} \tag{1}$$

$$\gamma = \frac{\sigma_l}{s_l} \tag{2}$$

Where,

P_l : lateral confinement force

d_b : diameter of reinforcement

l_b : bond length

s_l : loaded end slip

Table 4 Test results

Specimen	Concrete compressive strength σ_B (MPa)	Slope of confinement stress γ (MPa/mm)	At maximum load					
			Load P (kN)	Bond stress τ_b (MPa)	Confine-ment stress σ_l (MPa)	Slippage (mm)		Crack width w_{max} (mm)
						Loaded end s_l	Free end s_f	
T1624-2	23.6	2.0	16.61	5.32	5.08	2.54	2.52	1.32
T1624-5		5.0	22.21	7.11	10.5	2.12	2.10	0.90
N1624-2		2.0	13.68	4.37	3.02	1.56	1.53	1.12
N1624-5		5.0	18.16	5.79	5.95	1.19	1.17	0.78
T1648-2	55.5	2.0	29.03	9.29	5.66	2.77	2.75	1.41
T1648-5		5.0	32.06	10.26	14.44	2.94	2.91	1.41
N1648-2		2.0	19.37	6.18	3.65	1.97	1.96	1.53
N1648-5		5.0	24.25	7.74	8.81	1.73	1.71	1.22
T2524-5	23.6	2.0	45.22	5.79	5.89	3.33	3.30	1.58
N2524-5			27.64	3.51	2.56	1.31	1.30	1.07
T2548-5	55.5		53.55	6.86	3.03	4.16	4.13	1.69
N2548-5			35.89	4.56	2.27	1.31	1.29	1.40

Failure Progress

In the specimens which have the main reinforcement diameter of 25mm, visual observation of failure progress was conducted at feature 3 stages (A-C) of the relationship between load and deformation. The relationship between bond stress and deformation and failure situation of N2524-5 specimens are shown in Fig.3. The feature stage of the relationship between load and deformation are on the brink of maximum load (A), at the maximum load (B), at the lowest point of the load (C). At "A" point, the slip of the reinforcement and crack width are on the increase in the same way, and the front of rib spacing concrete chip away. At "B" point, the crack is observed at the places to connect the top part of the rib, and the rib spacing concrete partly become the condition of powder. At "C" point, the slip of the reinforcement reaches about 10mm which corresponds to the rib spacing, and the rib spacing concrete is greatly damaged. Because the crack width is about 1mm at "A" and "B", the rib spacing concrete is not completely scraped and is a little left. The area in which rib spacing concrete resists to shear force (equal to length of resisting concrete in axial direction) linearly decreases to the slip of the reinforcement from "B" to "C". So this causes the decrement of the bond stress linearly.

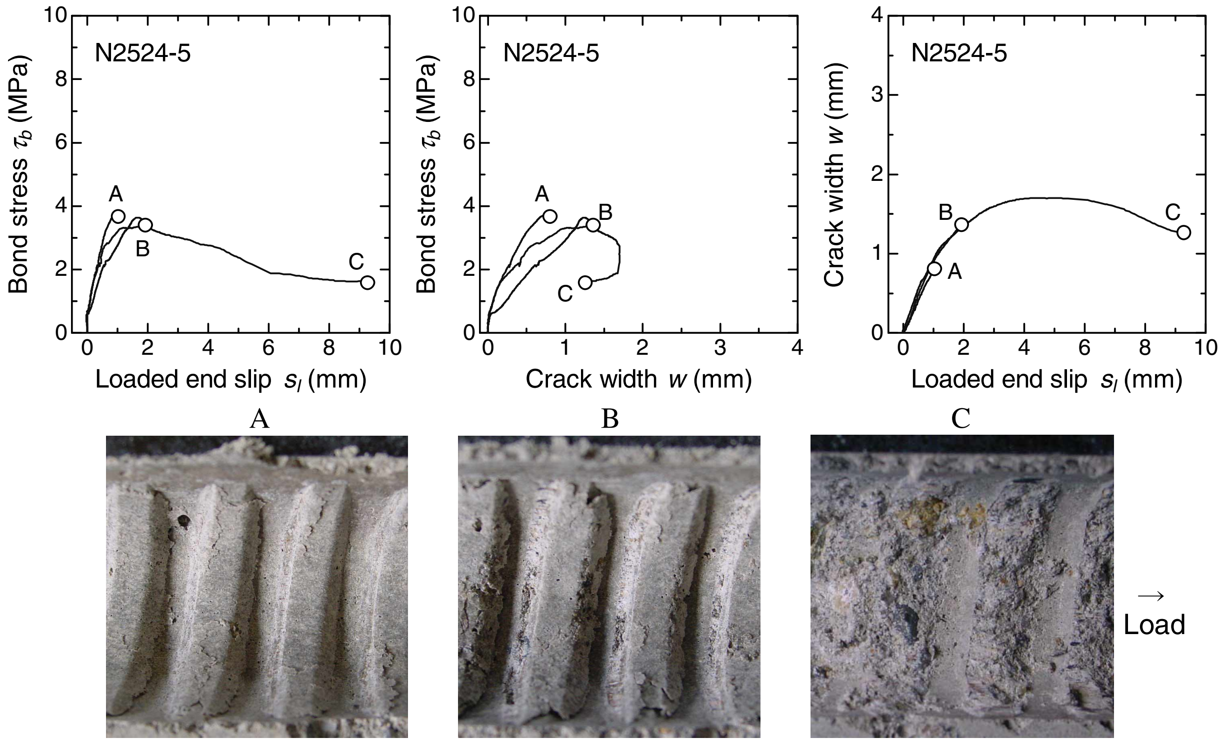

Fig.3 Relationship between load and displacement and failure progress

DISCUSSION OF EXPERIMENTAL RESULTS

Maximum Bond Stress

Fig.4 shows the relationship between maximum bond stress ($\tau_{b,max}$) and lateral confinement stress at maximum load (σ_l). Marks are changed for each type of shape of reinforcement and concrete strength. The maximum bond stress increases as the lateral confinement stress and concrete strength also increase in almost specimens. This effect is not influenced by the difference of shape of reinforcement.

Slippage of Reinforcement

Fig.5 shows that the relationship slippage of reinforcement at maximum load (s_{max}) and rib height-spacing ratio (a formula in the figure mentioned later). Slip of reinforcement is normalized by diameter of reinforcement (d_b) to remove the influence by the difference of diameter. Marks are changed for each type of concrete strength and slope of lateral confinement stress. The slippage of the reinforcement tends to increase as rib height-spacing ratio decreases. It is observed that the influence by the difference of concrete strength and slope of lateral confinement stress is small.

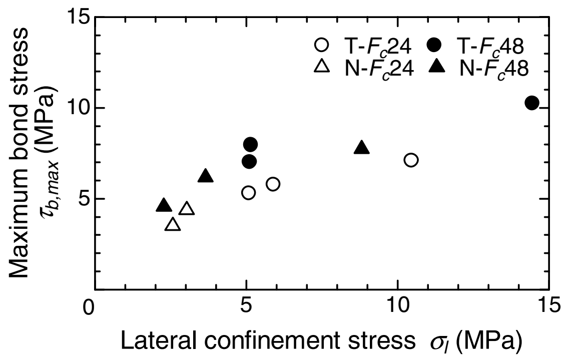

Fig.4 Relationship between maximum bond stress and lateral confinement stress

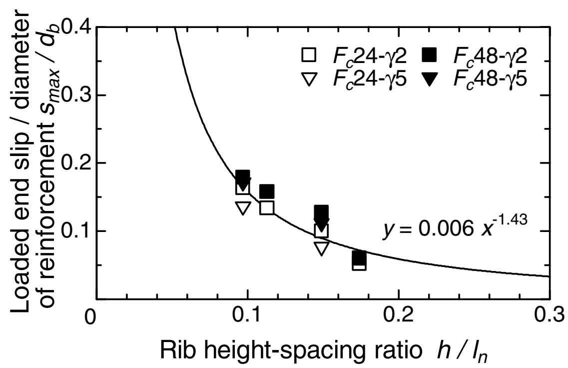

Fig.5 Relationship between slippage and rib height-spacing ratio

Crack Width

Fig.6 shows the relationship between crack width at maximum load (w_{max}) and loaded end slip at maximum load (s_{max}). Crack width is normalized by rib height of main reinforcement (h), and divided by two in order to indicate the detached quantity from main reinforcement. Marks are changed for each type of concrete strength and shape of main reinforcement. Slippage of reinforcement is normalized by rib spacing (l_n) to express slippage for one rib. It is recognized that crack width strongly relates to slippage of main reinforcement.

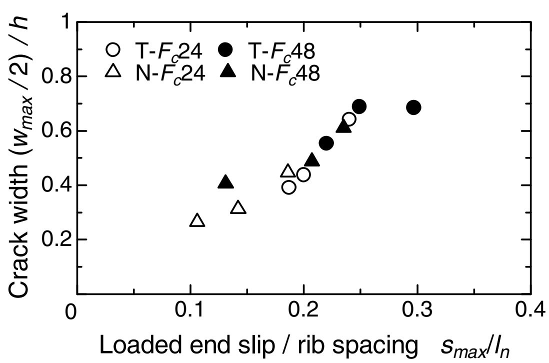

Fig.6 Relationship between crack width and slip

Relationship between Bond Stress and Slippage

Fig.7 shows the relationship between bond stress and loaded end slip in each specimen. The relationships are selected as typical result in three specimens of same factors. Bond stress is normalized by the maximum bond stress ($\tau_{b,max}$) of each specimen, loaded end slip is normalized by diameter of main

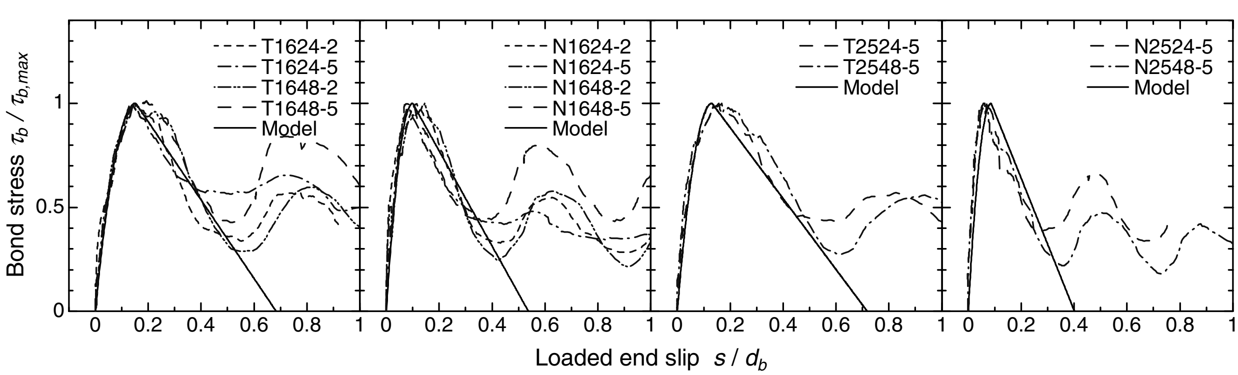

Fig.7 Normalized bond stress - loaded end slip relationship

reinforcement (d_b). The shape of the curve is not influenced by concrete strength, slope of lateral confinement stress and shape of main reinforcement. Each curve after the maximum stress trends to decrease linearly with slippage of main reinforcement.

On bond action between deformed bars and concrete assumed that bearing stress acts on the front of rib of main reinforcement, bond stress and splitting stress are described as shown in Eq.(3) and Eq.(4), which are transferred by one of rib when splitting crack along main reinforcement takes place.[4]

$$\tau_b = \sigma_n \cdot \cot\theta \tag{3}$$

$$\sigma_n = f_b \cdot \frac{h - w/2}{l_n} \cdot \tan\theta \tag{4}$$

Where,

τ_b : bond stress

σ_n : splitting stress

f_b : bearing stress

h : rib height

w : crack width

l_n : rib spacing

θ : angle made bearing stress and axial of main reinforcement

Bearing stress with lateral confinement is regarded as tri-axial compressive stress, which is expressed by lateral confinement and uniaxial compressive strength. In this test, lateral confinement stress is splitting stress and in proportion to slip of main reinforcement. Therefore, the slip at maximum bond stress can be represented by uniaxial compressive strength, slope of lateral confinement stress, rib height, rib spacing, diameter of main reinforcement. Because crack width relates to slip of main reinforcement, the slip at maximum bond stress can be expressed by rib height-spacing ratio. The formula in Fig.6 is calculated by least square method using all specimens' results as follows

$$s_{\max} = 0.0149 \cdot d_b \cdot \left(\frac{l_n}{h}\right) \tag{5}$$

Where,

$s_{\max}$: slippage at maximum bond stress

d_b : diameter of reinforcement

l_n : rib spacing

h : rib height

And the maximum bond stress and the angle made by bearing stress and axial direction can be estimated by uniaxial compressive strength, slope of lateral confinement stress and slip of main reinforcement. To quantify contribution of uniaxial concrete compressive strength and effect of lateral confinement, the maximum bond stress is calculated by least square method as shown in Fig.8. The derived formula is shown in Eq.(6). The increase stage is expressed by parabolic curve considering tri-axial compression state and failure progress.

$$\tau_{b,\max} = 0.449 \cdot (\gamma \cdot s_{\max})^{0.493} \cdot \sigma_B{}^{0.507} \tag{6}$$

Where,

$\tau_{b,\max}$: maximum bond stress

γ : slope of lateral confinement stress

s_{max} : slippage of reinforcement at maximum bond stress

σ_B : uniaxial concrete compressive strength

In the decrease stage, the area in which rib spacing concrete resists to shear force decreases linearly to the slip of the reinforcement as described previously. Therefore, the relationship between bond stress and slip of main reinforcement 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. The proposed model for local bond stress - slip relationship with lateral confinement is shown in Fig.8. The proposed model can express experimental results well.

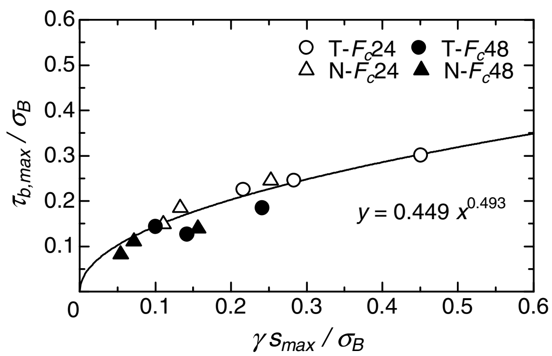

Fig.8 Relationship between maximum bond stress and lateral confinement stress

CONCLUSIONS

The followings are concluded by pull-out bond test that is conducted to quantify local bond splitting behavior with lateral confinement in RC members.

1. The maximum bond stress increases as slope of lateral confinement stress and concrete strength increase.
2. The slip of main reinforcement at the maximum bond stress is influenced strongly by shape of main reinforcement.
3. Crack width at the maximum bond stress relates to slippage of the main reinforcement.
4. A new relationship between the local bond stress and slippage of the main reinforcements is proposed.
5. The proposed model is expressed by concrete compressive strength, diameter of reinforcement, proportional coefficient of confinement force and shape of reinforcement.

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