SPLITTING BOND STRENGTH OF MAIN STEEL BARS IN R/C COLUMNS RETROFITTED WITH PRESTRESSED EXTERNAL HOOPS

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ABSTRACT :

To investigate splitting bond strength for the main steel bars in R/C columns retrofitted with stressed external hoops, a total of 52 sets of main bars are pulled monotonically until failure. Test results indicate that the bond strength becomes higher with the increase in number of external hoops and their initial stress magnitude. This is due to active confining force given by the external hoops, and passive confining forces given by the external hoops and original hoops, in which the passive confinement effect varies depending on the magnitude of active confining force. An equation to express the splitting bond strengths is developed based on the test results of the present study.

KEYWORDS: Seismic retrofit, Splitting bond failure, R/C Column, Prestress

1. INTRODUCTION

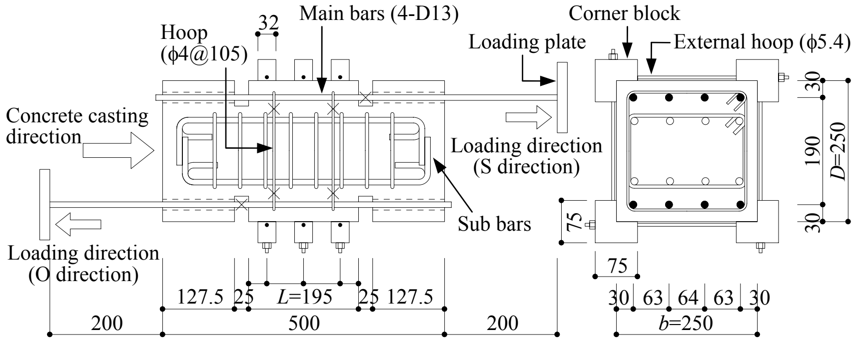
A new type seismic retrofit method for the existing reinforced concrete (R/C) columns was proposed by one of the authors [Yamakawa et. al. (1999)], in which active confining force to the R/C column is introduced by the stressing of external hoops that are composed of high strength steel rods and steel corner blocks as shown in Figure 1.1. Advantage of this method is that none of welding, mortar and adhesive is required.

Main objective of the present study is to investigate splitting bond strength for the deformed main steel bars in R/C columns retrofitted with this method, which would be useful information for predicting lateral load caring capacity of the column after retrofit.

2. TEST SPECIMENS

Figure 2.1 shows dimensions and bar arrangements of the typical test specimen. The test specimen is composed of two sets of main bars, which are loaded in the same (S) and opposite (O) directions as the concrete casting,

Figure 1.1 Seismic retrofit with stressed external hoops



[Remarks] x: location of strain gage, - - -: Bondless region, Unit: mm

Figure 2.1 Dimensions and bar arrangements of typical test specimen respectively. Slits are provided at boundary parts between bond and bondless regions. This is because concrete in the bondless region does not contribute to the splitting strength of the concrete in bond region. A large amount of sub steel bars are provided inside of the test specimen to prevent shear failure. Active or initial lateral confining force is introduced through L-shape steel blocks that placed at the four corners in cross-section.

Table 2.1 gives list of test specimens. Main experimental variables are loading direction (same and opposite as the concrete casting direction), bar diameter (10 and 13 mm), number of bars consisting one set of main bars (3, 4 and 5), specified concrete strength (18 and 28 N/mm^2), and magnitude of the initial lateral pressure varying from almost 0 to 2.37 N/mm^2 that are determined by number of external hoop sets and their initial stress.

Table 2.2 gives mechanical properties of the steel bars. For the main bars, shear area to bond area ratio (*SA*) and bearing area to bond area ratio (*BA*), which were defined by Kokubu et. al. (1972), are also given in Table 2.2. Compressive and tensile strengths of the concrete used in the test specimens are given in Table 2.1.

Table 2.1 List of test specimens

Name of test specimen		Specifications											Test results							
													S direction loading				O direction loading			
		d_b (mm)	n (piece)	L (mm)	p_h (%)	F (N/mm^2)	n_{eh} (set)	p_{eh} (%)	ε_{eh0} (x10^{-6})	σ_r (N/mm^2)	σ_B (N/mm^2)	σ_t (N/mm^2)	$\tau_{bmax.c}$ (N/mm^2)	$\tau_{bmax.i}$ (N/mm^2)	τ_{bu} (N/mm^2)	Failre mode	$\tau_{bmax.c}$ (N/mm^2)	$\tau_{bmax.i}$ (N/mm^2)	τ_{bu} (N/mm^2)	Failure mode
No.1	RC	13	4	195	0.10	18	0	0			18.5	1.85	2.96	3.13	2.97	S	2.98	3.15	2.98	S
No.2	NPS						3	0.28	75	0.04	19.4	1.91	4.35	3.59	3.63	S	*	3.65	3.79	S
No.3	PS								2,450	1.42	17.2	1.94	5.91	4.13	4.51	S	6.30	4.59	5.09	S
No.4									1,225	0.71	17.4	1.86	4.64	3.94	4.08	S	5.45	4.38	4.64	S
No.5	NPS						5	0.47	75	0.07	19.7	2.10	*	*	3.22	S	*	*	3.70	S
No.6	PS								2,450	2.37	18.4	1.84	6.60	5.32	5.81	S/P	7.52	5.75	6.21	S/P
No.7	RC					28	0	0			31.7	2.75	4.19	4.08	3.87	S	4.49	4.06	4.13	S
No.8	NPS						3	0.28	75	0.04	32.6	2.88	*	4.28	4.52	S	4.99	4.50	4.53	S
No.9	PS								2,450	1.42	32.2	3.13	7.52	5.49	6.24	S	7.84	6.42	6.57	S
No.10									4,083	2.37	32.7	2.87	10.06	6.46	7.08	S	9.10	7.29	7.47	S
No.11	NPS						5	0.47	75	0.07	32.2	2.91	5.94	4.40	4.53	S	*	5.05	5.17	S
No.12	PS								2,450	2.37	32.1	2.80	10.37	6.54	7.35	S	10.87	6.56	7.45	S
No.13	RC	10	4	130	0.15	18	0	0			19.1	1.76	3.73	4.62	4.15	S	4.29	4.91	4.59	S
No.14	NPS						2	0.28	75	0.04	18.2	1.79	4.63	4.27	4.34	S	5.42	5.64	5.53	S
No.15	PS								2,450	1.42	17.7	1.64	5.90	5.83	5.54	P	6.31	6.04	5.98	P
No.16									3,675	2.13	18.7	1.95	6.43	5.58	5.72	P	6.36	6.02	6.02	P
No.17	NPS						3	0.42	75	0.07	21.9	1.90	4.49	3.93	4.00	S	*	4.89	5.17	S
No.18	PS								2,450	2.13	18.7	1.84	*	5.67	5.51	P	6.84	5.74	6.00	P
No.21	RC	13	5	195	0.10	18	0	0			22.0	2.34	2.44	2.77	2.64	S	2.74	2.75	2.74	S
No.28	NPS						3	0.28	75	0.04	20.2	2.17	3.18	2.92	2.84	S	3.59	3.38	3.36	S
No.19	PS								2,450	1.42	22.7	2.25	5.80	3.76	4.18	S	6.62	4.30	4.44	S/P
No.20									3,675	2.13	21.7	2.35	6.22	4.23	4.60	S/P	6.86	4.44	4.82	S/P
No.24	RC		3	195	0.10	18	0	0			22.4	1.97	3.58	3.89	3.68	S	*	*	3.80	S
No.29	NPS						3	0.28	75	0.04	20.0	2.28	5.11	4.53	4.81	S	5.05	4.84	4.93	S
No.23	PS								1,225	0.71	22.4	1.99	5.67	4.85	5.28	S	6.12	4.95	5.45	S
No.22									2,450	1.42	21.9	2.15	6.12	6.02	6.03	P	*	*	6.24	P

[Remarks] d_b and n: diameter and number of main bars, L: bond length, p_h: hoop reinforcement ratio=$2a_h n_h/(bL)$, F: specified concrete strength, p_{eh}: external hoop reinforcement ratio=$2a_{eh}n_{eh}/(bL)$, ε_{eh0}: initial strain of external hoops, σ_r: initial lateral pressure, σ_B and σ_t: compressive and tensile strength of concrete, $\tau_{bmax.c}$ and $\tau_{bmax.i}$: bond strengths for corner and intermediate bars, τ_{bu}: bond strength for set of bars, S indicates side split failure, S/P means corner and intermediate bars failed in pullout and splitting modes, respectively, P means both of the corner and intermediate bars failed in pullout mode.

Table 2.2 Mechanical properties of steel bars

Bar size	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Elastic modulus (kN/mm^2)	*SA*	*BA*
D13 or #4 (Main bar)	855 *	924	9.7	184	0.53	0.061
D10 or #3 (Main bar)	849 *	903	9.0	181	0.54	0.059
ϕ 4 (Hoop)	501 *	549	11.7	202		
ϕ 5.4 (External hoop)	1,034 *	1,115	Not measured	206		

SA : Shear area to bond area ratio, *BA* : Bearing area to bond area ratio [Kokubu et. al. (1972)], *: 0.2 % offset strength

3. TEST PROCEDURE AND INSTRUMENTS

Figure 3.1 shows loading apparatus used in the present study. Each set of main bars was pulled monotonically until failure by a hydraulic jack with 1,000 kN capacity. A load cell measures total tensile load applied to the set of main bars. Displacement transducers measure slip displacements at free end for each main bar.

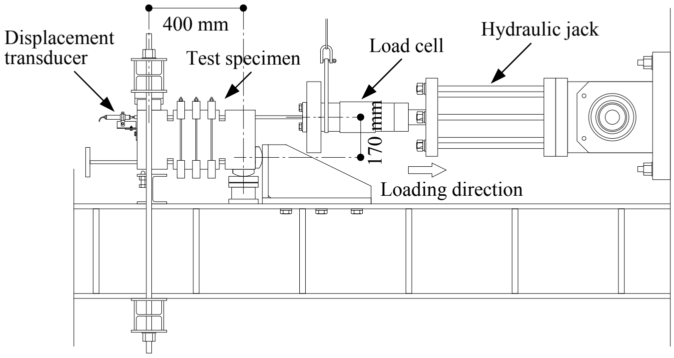


Figure 3.1 Loading apparatus

4. TEST RESULTS

Figure 4.1 shows test results on the bond stress (τ_b) versus slip displacement (s) relations for the selected test specimens in S direction loading, and final crack patterns for corresponding test specimens are shown in Figure 4.2. Solid curves in Figure 4.1 represent τ_b-s relations for the corner bars, and dashed curves represent τ_b-s relations for the intermediate bars that are located between two corner bars. Circular mark represents bond stress and slip displacement at the maximum tensile load that measured by the load cell.

Figures 4.1 (a) to 4.1 (d) were obtained from the specimens with main bars of 4-D13 (4-#4) and specified concrete strength of 18 N/mm^2. Specimen No.1, which does not have any external hoops, failed in side split failure mode as shown in Figure 4.2 (a). Corner and intermediate bars developed almost same bond strength.

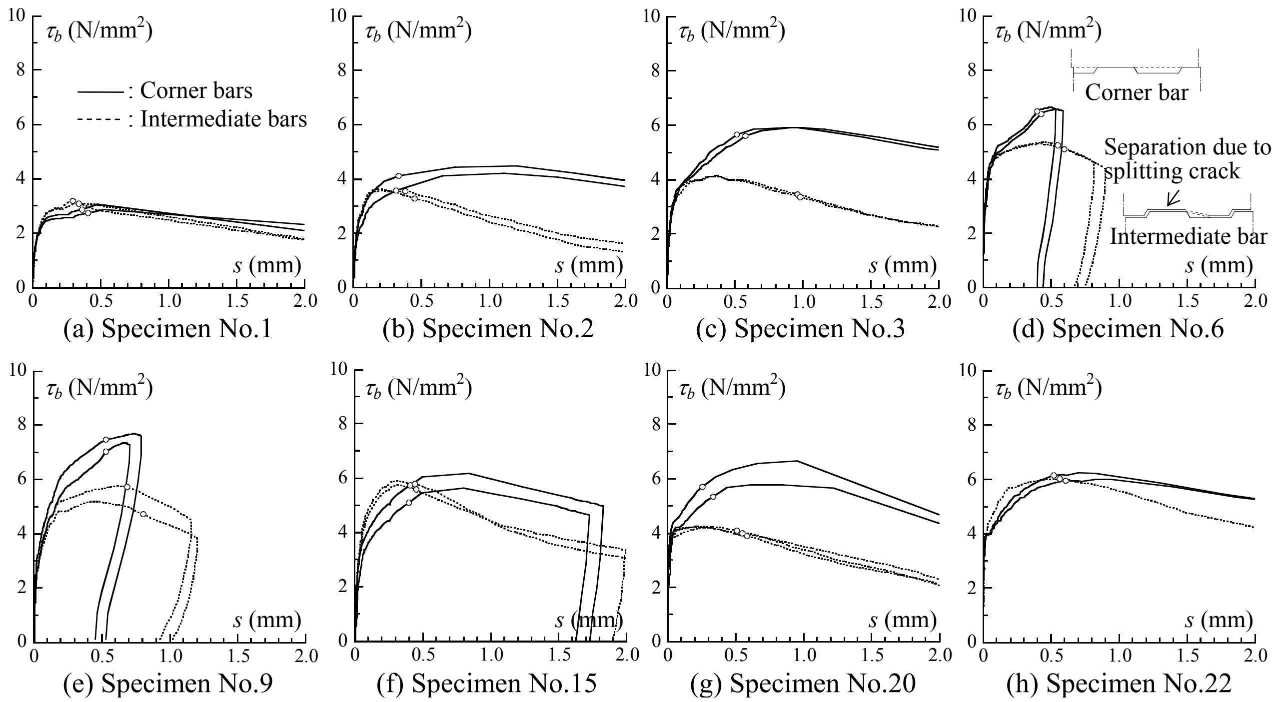
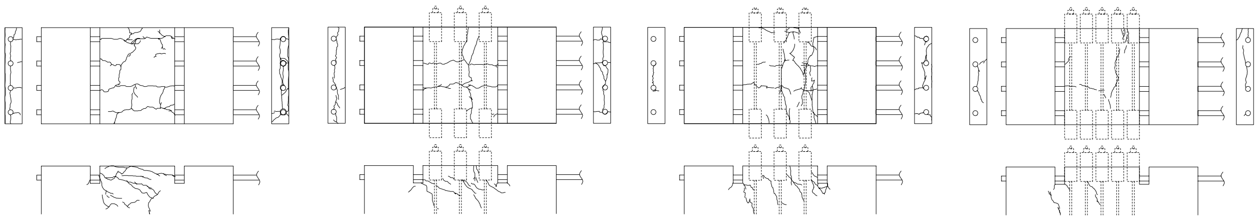
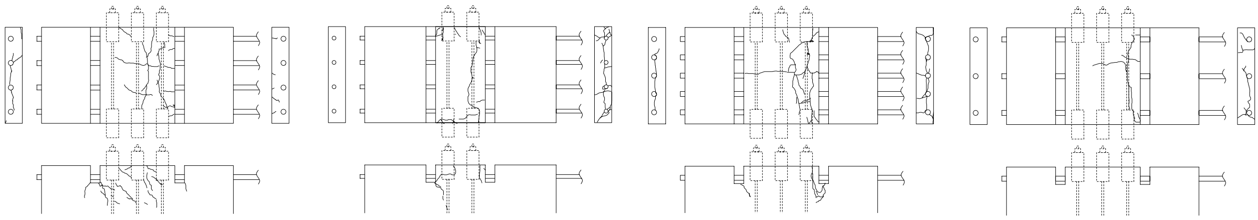


Figure 4.1 Bond stress (τ_b) versus slip displacement (s) relations (S direction loading)



(a) Specimen No.1 (b) Specimen No.2 (c) Specimen No.3 (d) Specimen No.6



(e) Specimen No.9 (f) Specimen No.15 (g) Specimen No.20 (h) Specimen No.22

Figure 4.2 Final crack patterns (S direction loading)

In Specimen No.2 with non-stressed external hoops, side split failure was observed, which is similar as Specimen No.1. Bond strength of the corner and intermediate bars were higher than those of Specimen No.1. In Specimen No.3 with stressed external hoops, clear side splitting crack running through over width was not formed, however, some inclined cracks along the corner bars were observed on the side surfaces. Bond strengths for respective corner and intermediate bars were improved more. In Specimen No.6 with relatively large amount of stressed external hoops, corner bars came out from the concrete without remarkable bond splitting cracks in the surrounding concrete as schematically shown in Figure 4.1 (d). Bond strengths for respective corner and intermediate bars were improved still more.

Figure 4.1 (e) is obtained from Specimen No.9, which is different from Specimen No.3 in the concrete strength. Bond strength of Specimen No.9 that constructed with specified concrete strength of 28 N/mm^2 is higher than that of Specimen No.3 in both of the corner and intermediate bars.

Figures 4.1 (f) and 4.1 (h) are obtained from Specimens No.15 and No.22, which are different from Specimen No.3 in amount of main bars. Test results indicate that smaller amount of main bars results in pullout failure of the intermediate bars as well as the corner bars, and corner and intermediate bars develop almost same bond strength.

Figure 4.1 (g) is obtained from Specimen No.20, which have three pieces of intermediate bars. Locations of the intermediate bars were different, however, their τ_b-s relations were similar.

The bond strengths for the corner and intermediate bars ($\tau_{bmax.c}$ and $\tau_{bmax.i}$) and for the set of main bars (τ_{bu}) are given in Table 2.1. Failure modes are also given in Table 2.1. Loading direction gives a few effects on the bond strength. τ_{bu} loaded in the same direction as concrete casting is 7 % in average lower than that loaded in the opposite direction. Specimens No.15 and No.16, which failed in pullout mode (P), developed almost same τ_{bu} though their σ_r were different. This indicates that σ_r do not affect bond strength determined by pullout failure.

5. EXPRESSION OF BOND STRENGTH

5.1 Outline of Expression of Bond Strength

The test results indicate that, in most cases, bond strength for the intermediate bars is lower than that for the corner bars. This is because confining force given by the external hoops was introduced through steel corner blocks. Therefore, expressions of the bond strengths for corner and intermediate bars are investigated, respectively. Based on the test results in the S direction loading, the bond strengths for respective corner and intermediate bars are expressed as sum of the followings: 1) bond strength carried by splitting resistance of concrete, 2) strength increment due to active confinement given by external hoops, and 3) strength increment due to passive confinement given by external and original hoops.

The bond strength determined by the pullout failure without remarkable splitting cracks is expressed as the maximum. Expression of the bond strength for the set of main bars is done by employing the equations to evaluate bond strengths for respective corner and intermediate bars.

5.2 Expression of Bond Strength Carried by Splitting Resistance of Concrete

Eqn. 5.1 is an existing equation to express bond strength for the set of main bars (τ_{bu}) in pure R/C member [Fujii et. al. (1982)]. For both of the corner and intermediate bars, the first term of this equation (τ_{co}) is employed to evaluate bond strength carried by the splitting resistance of concrete in the present study.

$$\tau_{bu} = \tau_{co} + \tau_{st} = 1.22\left\{(0.0961 b_{si} + 0.134) + 7.80\frac{p_w b}{n d_b}\right\}\sqrt{\sigma_B} \quad (\text{N/mm}^2) \tag{5.1}$$

in which b_{si} is splitting length ratio for side split mode defined as $(b-nd_b)/(nd_b)$, σ_B is compressive strength of the concrete cylinder, b is width of column, n and d_b are number and diameter of the main bar, respectively.

5.3 Discussions on Bond Strength Increment due to External and Original Hoops

Figure 5.1 shows bond strength increment due to the external and original hoops ($\Delta\tau_{bmax}$) versus confining stress at the bond strength (σ_{cu}) relations. $\Delta\tau_{bmax}$ is obtained by subtracting τ_{co} from the experimental bond strength. σ_{cu} is given by Eqn. 5.2, which is based on the assumption that confining forces given by the external and original hoops work to corner and intermediate bars uniformly.

$$\sigma_{cu} = \sigma_{c0} + \Delta\sigma_c = \frac{E_{eh}\varepsilon_{eh0} 2a_{eh} n_{eh}}{n d_b L} + \left(\frac{E_{eh}\Delta\varepsilon_{eh} 2a_{eh} n_{eh}}{n d_b L} + \frac{E_h \varepsilon_h 2a_h n_h}{n d_b L}\right) \tag{5.2}$$

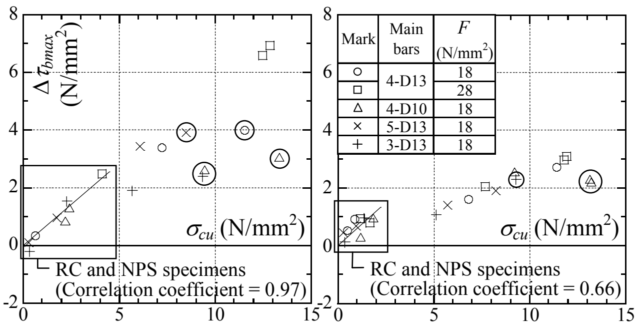
in which σ_{c0} is confining stress introduced initially by stressed external hoops (active confining stress), $\Delta\sigma_c$ is confining stress increment at τ_{bmax} (passive confining stress), E_{eh} and E_h are elastic modulus of the external and original hoops, respectively, ε_{eh0} and $\Delta\varepsilon_{eh}$ are initial strain and strain increment of the external hoops, respectively, ε_h is strain of the original hoops at τ_{bmax}.

From the linear regression of the data obtained from the RC and NPS specimens, bond strength increment due to the passive confinement (τ_{pa}) can be expressed as Eqn. 5.3, in which $\Delta\sigma_c$ will be discussed in Section 5.6.

$$\tau_{pa} = \begin{cases} 0.566 \cdot \Delta\sigma_c & \text{(for corner bars)} \\ 0.590 \cdot \Delta\sigma_c & \text{(for intermediate bars)} \end{cases} \tag{5.3}$$

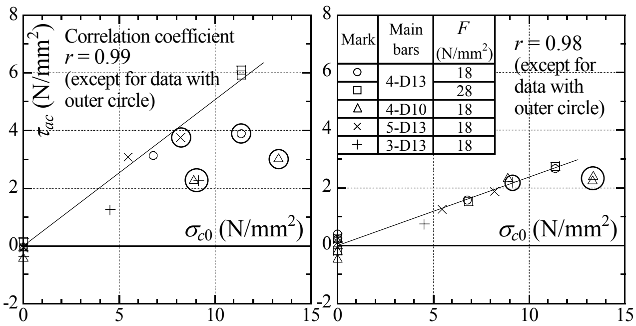
5.4 Expression of Bond Strength Increment due to Active Confinement

Figure 5.2 shows bond strength increment due to the active confinement (τ_{ac}) versus active confining stress (σ_{c0}) relations. τ_{ac} is obtained by subtracting τ_{pa} from the bond strength increment ($\Delta\tau_{bmax}$). Outer circles represent



(a) Corner bars (b) Intermediate bars

Figure 5.1 $\Delta\tau_{bmax}$ versus σ_{cu} relations



(a) Corner bars (b) Intermediate bars

Figure 5.2 τ_{ac} versus σ_{c0} relations

that bond strength determined by the pullout failure without remarkable splitting cracks. From the linear regression of the data except for ones with outer circle, τ_{ac} can be expressed as Eqn. 5.4.

$$\tau_{ac} = \begin{cases} 0.508 \cdot \sigma_{c0} & \text{(for corner bars)} \\ 0.238 \cdot \sigma_{c0} & \text{(for intermediate bars)} \end{cases} \tag{5.4}$$

5.5 Expression of Bond Strength Determined by Pullout failure without Remarkable Slitting Cracks

Based on the experimental bond strength that determined by pullout failure, shear strength of the concrete located between ribs of main bar (τ_{max}) is investigated. From the investigation result that average of τ_{max}/σ_B is 0.60, bond strength determined by the pullout failure (τ_{po}) can be expressed as Eqn. 5.5.

$$\tau_{po} = \tau_{max} \cdot SA = 0.60\sigma_B \cdot SA \tag{5.5}$$

Substitute τ_{po}-τ_{co} for τ_{ac} in Eqn. 5.4, then active confining stress corresponding to the boundary between splitting failure and pullout failure (σ_{cp}) can be expressed as Eqn. 5.6.

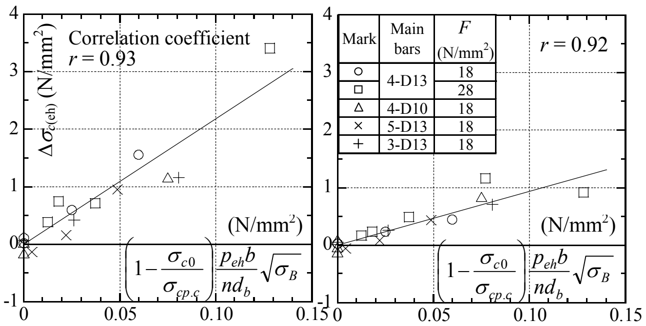
$$\sigma_{cp} : \begin{cases} \sigma_{cp.c} = (\tau_{po} - \tau_{co})/0.508 & \text{(for corner bars)} \\ \sigma_{cp.i} = (\tau_{po} - \tau_{co})/0.238 & \text{(for intermediate bars)} \end{cases} \tag{5.6}$$

5.6 Expression of Bond Strength Increment due to Passive Confinement

Figures 5.3 and 5.4 show passive confining stress versus dominating factor relations for the external and original hoops, respectively. Based on the test results that passive confining stress ($\Delta\sigma_c$) becomes smaller with the increase in active confining stress (σ_{c0}), $\sigma_{c0}/\sigma_{cp.c}$ and $\sigma_{c0}/\sigma_{cp.i}$ are taking into account in the dominating factor. From the linear regression of the data, $\Delta\sigma_c$ can be expressed as Eqn. 5.7.

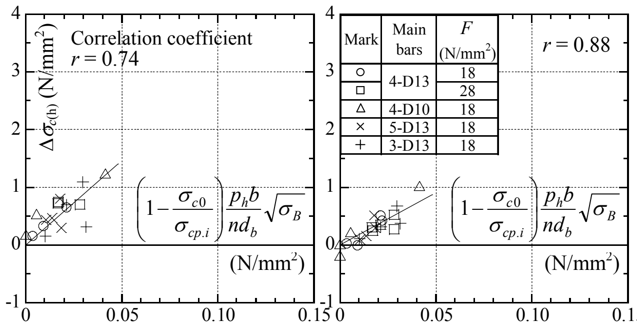
$$\Delta\sigma_c = \begin{cases} 21.7\left(1 - \dfrac{\sigma_{c0}}{\sigma_{cp.c}}\right)\dfrac{p_{eh}b}{nd_b}\sqrt{\sigma_B} + 29.2\left(1 - \dfrac{\sigma_{c0}}{\sigma_{cp.i}}\right)\dfrac{p_h b}{nd_b}\sqrt{\sigma_B} & \text{(for corner bars)} \\ 9.34\left(1 - \dfrac{\sigma_{c0}}{\sigma_{cp.c}}\right)\dfrac{p_{eh}b}{nd_b}\sqrt{\sigma_B} + 18.2\left(1 - \dfrac{\sigma_{c0}}{\sigma_{cp.i}}\right)\dfrac{p_h b}{nd_b}\sqrt{\sigma_B} & \text{(for intermediate bars)} \end{cases} \tag{5.7}$$

Substitute Eqn. 5.7 for $\Delta\sigma_c$ in Eqn. 5.3, then bond strength increment due to the passive confinement (τ_{pa}) can be



(a) Corner bars (b) Intermediate bars

Figure 5.3 Passive confining stresses by external hoops



(a) Corner bars (b) Intermediate bars

Figure 5.4 Passive confining stress by original hoops

expressed finally as Eqn. 5.8 on the condition that $(1\text{-}\sigma_{c0}/\sigma_{cp.c})$ and $(1\text{-}\sigma_{c0}/\sigma_{cp.i})$ are not negative.

$$\tau_{pa} = \begin{cases} 12.3\left(1-\dfrac{\sigma_{c0}}{\sigma_{cp.c}}\right)\dfrac{p_{eh}b}{nd_b}\sqrt{\sigma_B} + 16.5\left(1-\dfrac{\sigma_{c0}}{\sigma_{cp.i}}\right)\dfrac{p_h b}{nd_b}\sqrt{\sigma_B} & \text{(for corner bars)} \\ 5.51\left(1-\dfrac{\sigma_{c0}}{\sigma_{cp.c}}\right)\dfrac{p_{eh}b}{nd_b}\sqrt{\sigma_B} + 10.7\left(1-\dfrac{\sigma_{c0}}{\sigma_{cp.i}}\right)\dfrac{p_h b}{nd_b}\sqrt{\sigma_B} & \text{(for intermediate bars)} \end{cases} \tag{5.8}$$

5.7 Expression of Bond Strengths for Respective Corner and Intermediate Main Bars

From the expressions above, bond strengths for corner and intermediate bars (τ_{bmax}) can be expressed as Eqn. 5.9.

$$\tau_{bmax} = \tau_{co} + \tau_{ac} + \tau_{pa} \tag{5.9}$$

in which τ_{co} is bond strength carried by the splitting resistance of concrete that given by Eqn. 5.1, τ_{ac} is bond strength increment due to the active confinement given by Eqn. 5.4, and τ_{pa} is bond strength increment due to the passive confinement given by Eqn. 5.8. Average and standard deviation of the ratios of test result to calculation by Eqn. 5.9 are 0.99 and 0.10 for corner bars and 1.01 and 0.08 for intermediate bars.

5.8 Expression of Bond Strength for Set of Main Bars

The test results on the relation between $\tau_{bu}/\tau_{bmax(\mathrm{wav})}$ and $\tau_{bmax.i}/\tau_{bmax.c}$ is investigated in Figure 5.5. τ_{bu} is bond strength for the set of main bars. $\tau_{bmax(\mathrm{wav})}$ is weighted average of the bond strengths for corner and intermediate bars. $\tau_{bmax.i}$ and $\tau_{bmax.c}$ are bond strengths for the intermediate and corner bars, respectively. It can be understood from the figure that τ_{bu} becomes lower than $\tau_{bmax(\mathrm{wav})}$ with the decrease in $\tau_{bmax.i}/\tau_{bmax.c}$. This is coming from the intension that corner and intermediate bars do not reach their bond strengths at the same time. Result of the linier regression of the data is given in Figure 5.5. Based on that relation observed in the test results, bond strength for the set of main bars may be expressed as Eqn 5.10 employing $\tau_{bmax.i}$ and $\tau_{bmax.c}$ given by Eqn. 5.9.

$$\tau_{bu} = \left(0.32\frac{\tau_{bmax.i}}{\tau_{bmax.c}} + 0.68\right)\cdot\tau_{b\max(wav)} = \left(0.32\frac{\tau_{bmax.i}}{\tau_{bmax.c}} + 0.68\right)\cdot\frac{2\tau_{bmax.c} + (n-2)\tau_{bmax.i}}{n} \tag{5.10}$$

Figure 5.6 shows comparison of test results and calculations by Eqn. 5.10, in which calculations for the O direction loading are divided by 0.93 to consider effect of the loading direction. Average (m) and standard deviation (σ) of the ratios of test result to calculation are 0.99 and 0.07 for the S direction loading and 1.00 and 0.08 for the O direction loading.

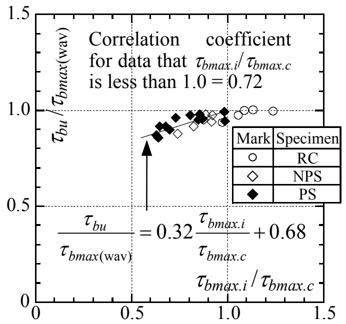


Figure 5.5 $\tau_{bu}/\tau_{bmax(wav)}$ versus $\tau_{bmax.i}/\tau_{bmax.c}$ relations

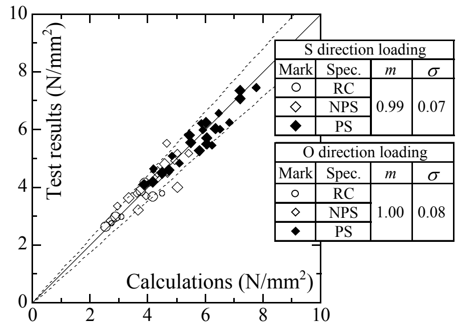


Figure 5.6 Test results and calculations on τ_{bu}

6. CONCLUSIONS

To investigate splitting bond strength for the main bars in the case that active confining force was introduced by the external hoops, an experimental investigation was carried out in the present study. Conclusions obtained are summarized as follows.

1) The splitting bond strength becomes higher if the active confining force was introduced. Increment of bond strength for the corner bars is larger than that for the intermediate bars.

2) At the bond strength stage, strain increments of the external and original hoops became smaller with the increase in the active confining force. This means that width of the splitting crack is restrained smaller, and this effect results in the increment of bond strength.

3) If the higher active confining force was introduced, entire main bars failed in pullout mode without the remarkable bond splitting cracks. Bond strength determined by this failure mode gives the maximum.

4) An equation to express splitting bond strengths for respective corner and intermediate bars is proposed as Eqn. 5.9. In addition, an equation to express bond strength for the set of main bars is proposed as Eqn. 5.10.

ACKNOWLEDGMENTS

The experimental study presented herein was made possible by a financial support of the Grant in Aid for Science Research of the Japan Society for Promotion of Science (JSPS). The Neturen Co. Ltd. offered external hoops. The authors wish to express many thanks to Tsuyoshi Hiramatsu, Technical staff of Oita University, for his cooperation in the experiment.

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