Relation between Earthquake Damage and Splitting Bond Strength in R/C Columns after Emergency Retrofit with Prestressed External Hoops

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SUMMARY:
The aim of this paper is to find damage index, which can be used to express the splitting bond strength for main steel bars recovered by emergency retrofit with prestressed external hoops. A discussion was carried out based on the test results, which were obtained in the former experimental study. It was concluded that bond slip displacement at the end of first loading to introduce initial damage is to be the damage index. In addition, an investigation on the width of bond splitting crack was carried out to estimate the damage index indirectly.

Keywords: Splitting bond strength; Emergency retrofit; PC rod; Damage index

1. INTRODUCTION

Recently, seismic retrofit of the existing buildings with poor seismic resistance is progressing in Japan. It is noted however that some big earthquakes may occur before seismic retrofit for those buildings is completed. Yamakawa et al. (2000) proposed a new type permanent seismic retrofit method for the existing reinforced concrete (R/C) columns, in which active confining force to the R/C column is introduced by the stressing of external hoops. It can be expected from following features that this methods is effective for emergency retrofit for damaged columns right after earthquake attack.

(1) Crack width will reduce due to the active confining force (Yamakawa et al. (2004)).
(2) Any lifting machine is not required in the transportation and construction process because the external hoop is composed of some small parts, high strength steel rods and steel corner blocks.
(3) None of welding, mortar and adhesive is required.

Main objective of this paper is to find damage index, which can be used to express the splitting bond strength for main steel bars recovered by emergency retrofit with prestressed external hoops. A discussion was carried out based on the test results, which were obtained in the former experimental study (Ho et al. (2009), Ho et al. (2010)).

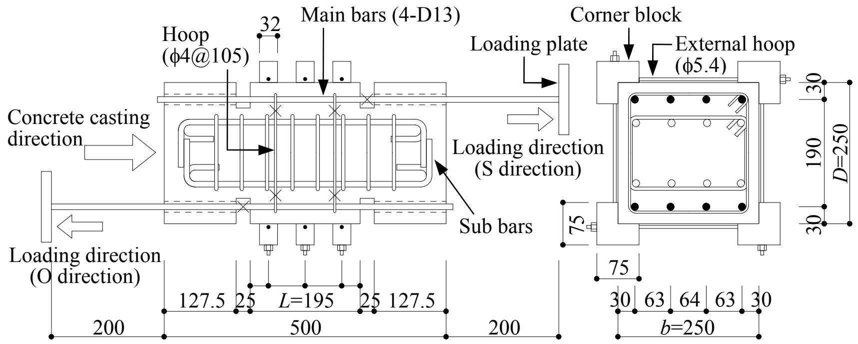
2. OUTLINE OF TEST

2.1. Test Specimens

Fig. 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, 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. In all specimens, one set of the main bars consists of four bars. Main experimental variables are specified concrete strength, F (20 and 30 N/mm^2), external reinforcement ratio, p_{eh} (0.28% and 0.47%), and magnitude of the initial lateral pressure, σ_r (0.04, 0.85, 1.42 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.



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

Figure 2.1. Dimensions and bar arrangements of typical test specimen

Table 2.1. List of test specimens

Name of test specimen	d_b (mm)	n	L (mm)	p_h (%)	σ_B (N/mm^2)	σ_t (N/mm^2)	Damage introduced (S direction loading): Maximum width of bond splitting cracks* (mm), Top surface	Side surface West	Side surface East	s_{cd} (mm)	Details of emergency retrofit: n_{eh} (set)	p_{eh} (%)	ε_{eh0} ($\times10^{-6}$)	σ_r (N/mm^2)	Bond strength for set of bars after emergency retrofit (S direction loading) τ_{bru} (N/mm^2)
R1	13	4	195	0.10	21.3	2.11	0.20	0.30	0.45	0.44	3	0.28	75	0.04	2.57
R2					19.7	1.93	0.15	0.25	0.45	0.86			1,470	0.85	3.60
R3					17.1	1.61	0.15	0.25	0.40	0.45	5	0.47		1.42	4.17
R4	13	4	195	0.10	22.4	2.05	0.85	0.55	0.55	1.47	3	0.28	75	0.04	1.34
R5					19.6	1.92	0.55	1.10	0.40	1.77			1,470	0.85	2.24
R6					22.5	2.20	1.40	1.10	0.45	1.78	5	0.47		1.42	2.98
R7	10	4	130	0.15	18.1	1.71	0.05	0.15	0.25	0.34	2	0.28	2,450	1.42	5.00
R8					19.1	1.87	0.15	0.50	0.25	0.53					4.29
R9					19.2	1.86	0.40	1.40	0.75	1.64					3.38
R10	13	4	195	0.10	19.0	1.89	0.05	0.15	0.15	0.19	3	0.28	75	0.04	3.17
R11					19.8	1.90	0.10	0.25	0.20	0.37			1,470	0.85	4.12
R12					20.8	1.64	0.10	0.10	0.25	0.25	5	0.47		1.42	4.73
R13	13	4	195	0.10	30.4	2.18	0.60	0.75	0.75	1.23	3	0.28	2,450	1.42	4.54
R14					31.1	2.48	0.10	0.20	0.15	0.24					5.20
R15					30.7	2.69	0.90	0.60	1.80	1.41					3.70
R16	13	4	195	0.10	19.6	1.82	0.10	0.20	0.20	0.30	3	0.28	2,450	1.42	4.37
R17					18.3	1.87	0.40	0.45	0.20	0.97					3.48
R18					18.3	1.71	0.25	0.35	1.40	1.13					3.13

[Remarks]

d_b : diameter of main bars
n : number of main bars
L : bond length
p_h : hoop reinforcement ratio=$2a_h n_h/(bL)$
b : width of column
a_h : cross-section area of hoop
n_h : number of set of hoop reinforcement
σ_B : compressive strength of concrete
σ_t : tensile strength of concrete
n_{eh} : number of set of external hoops
p_{eh} : external hoop reinforcement ratio=$2a_{eh}n_{eh}/(bL)$
ε_{eh0} : initial strain of external hoops
σ_r : initial lateral pressure=$p_{eh}E_{eh}\varepsilon_{eh0}$
E_{eh} : elastic modululus of external hoop
a_{eh} : cross-section area of external hoop
s_{cd} : slip displacement for corner bars at the end of damage introduction loading
* : at the end of damage introduction loading

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)	507 *	599	Not measured	209		
ϕ 5.4 (External hoop)	1,034 *	1,115	Not measured	206		

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

2.2. Test Method

Fig. 2.2 shows the loading system for all the specimens, which is a cantilever type loading method. Displacement transducers measure slip displacements at free end for each main bar.
The test for each specimen consists of two loading stages, that is (1) damage introduction loading before emergency retrofit and (2) loading after the emergency retrofit.

In the damage introduction loading, each set of the main bars was pulled monotonically until a target crack width by a hydraulic jack with 1,000 kN capacity. A couple of horizontal steel rods shown in Fig. 2.2 are installed to carry a part of horizontal load passively. As the results, the total load which acts on the main bars of specimen and the horizontal steel rods become not to go into a downward region, even when the load to the main bars of specimen decreases. When the maximum width of cracks on the specimen had reached the target crack width of the specimen, the load was unloaded to zero and then the damage introduction loading was finished. The three different target crack widths of 0.1mm, 0.5mm and 1.5mm are adopted as damage level before the emergency retrofit.

After finishing the damage introduction loading, the external hoops were installed as the emergency retrofit. And then, each set of the main bars was pulled monotonically until failure, where a couple of horizontal steel rods shown in Fig. 2.2 were not used because rapid increase in bond slip displacement after developing the ultimate bond strength was inhibited due to the effect of retrofit.

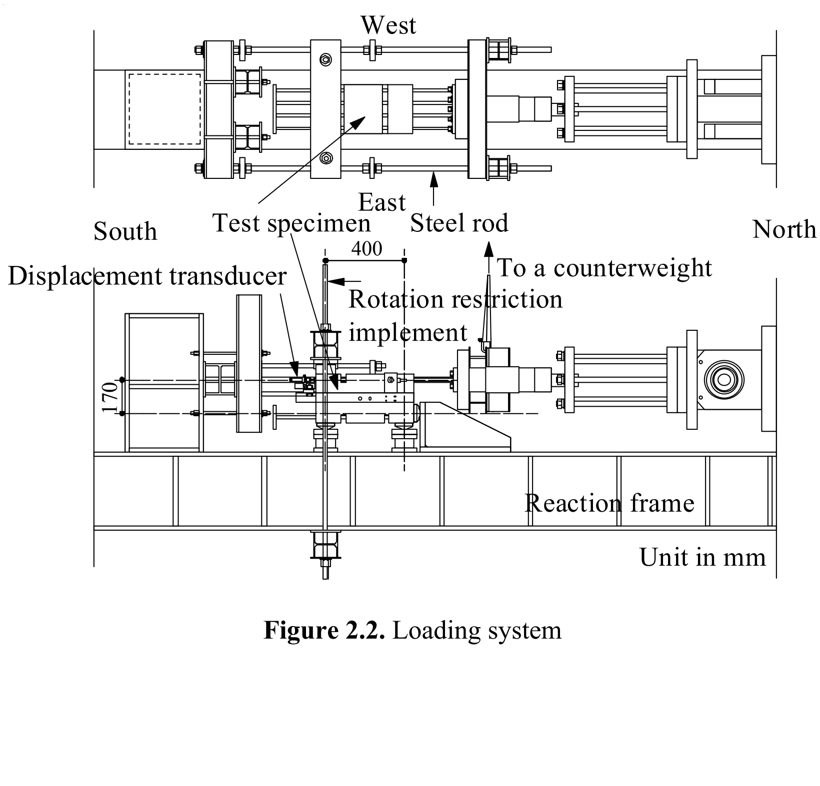


Figure 2.2. Loading system

2.3. Test Results

Fig. 2.3 shows test results on the bond stress (τ_b) versus bond slip displacement (s_c) relations for the selected test specimens in S direction loading, where s_c is average of bond slip displacements for two corner bars. s_{cd} is bond slip displacement for corner bar at the end of damage introduction loading stage. τ_{bru} represent ultimate bond strength after emergency retrofit. For all test specimens, s_{cd} and τ_{bru} are given in Table 2.1.

Fig. 2.4 shows final crack patterns for the test specimens shown in Fig. 2.3. Thin curves represent cracks observed at the end of damage introduction loading stage, and numerals are width of the cracks in mm. Thick curves represent cracks formed in the loading stage after emergency retrofit. For all test specimens, maximum width of the bond splitting cracks observed at the end of damage introduction loading stage are given in Table 2.1.

Specimens R4, R5 and R6 are different each other in the amount of emergency retrofit, where side split failure occurred in the damage introduction loading stages. Specimens R16, R17 and R18 are different each other in damage level. It is not clear in Specimen R16 that bond split failure occurred in the damage introduction loading stage. On the contrary, side split failure occurred in the damage introduction loading stages in Specimens R17 and R18. In the loading stage after emergency retrofit, all test specimens failed in side split failure mode.

Fig. 2.5 shows relation between bond slip displacement at the end of the damage introduction loading stage for corner bar (s_{cd}) and that for intermediate bar (s_{id}). Since s_{cd} and s_{id} are almost equal, s_{cd} is used in the following discussions.

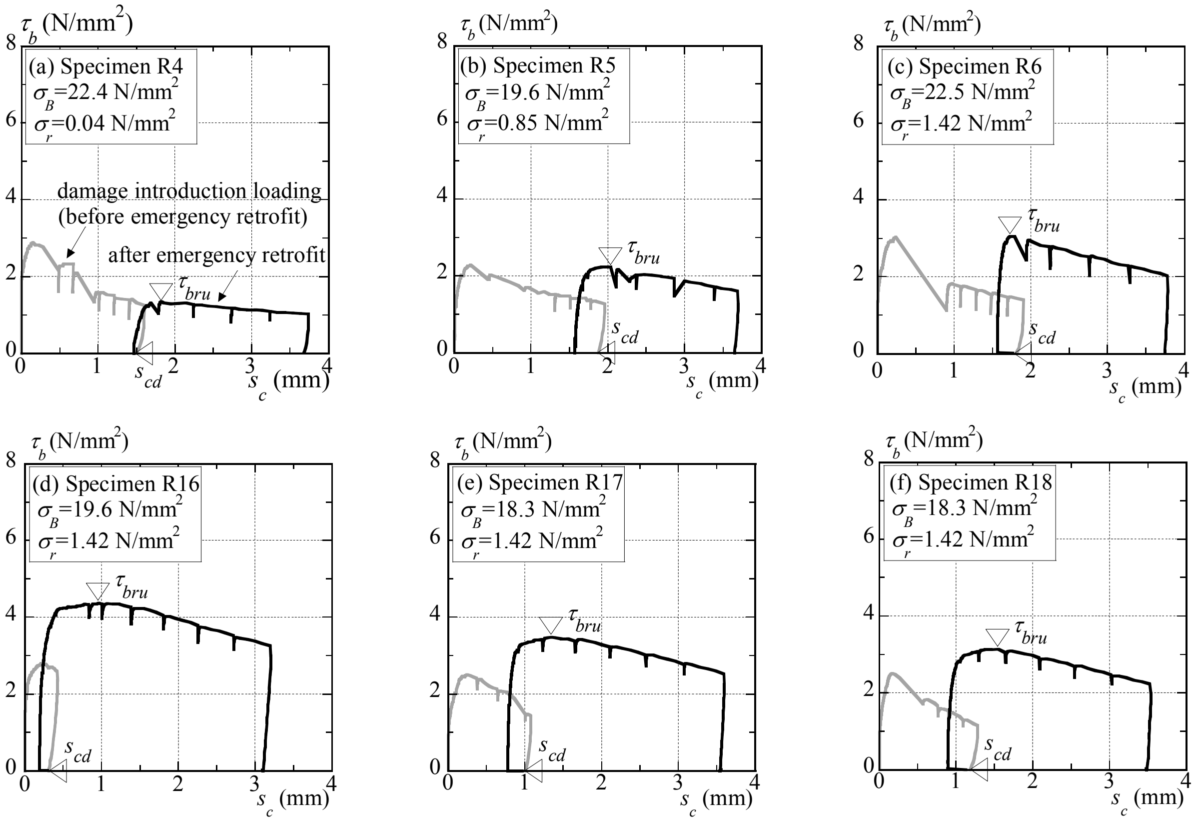
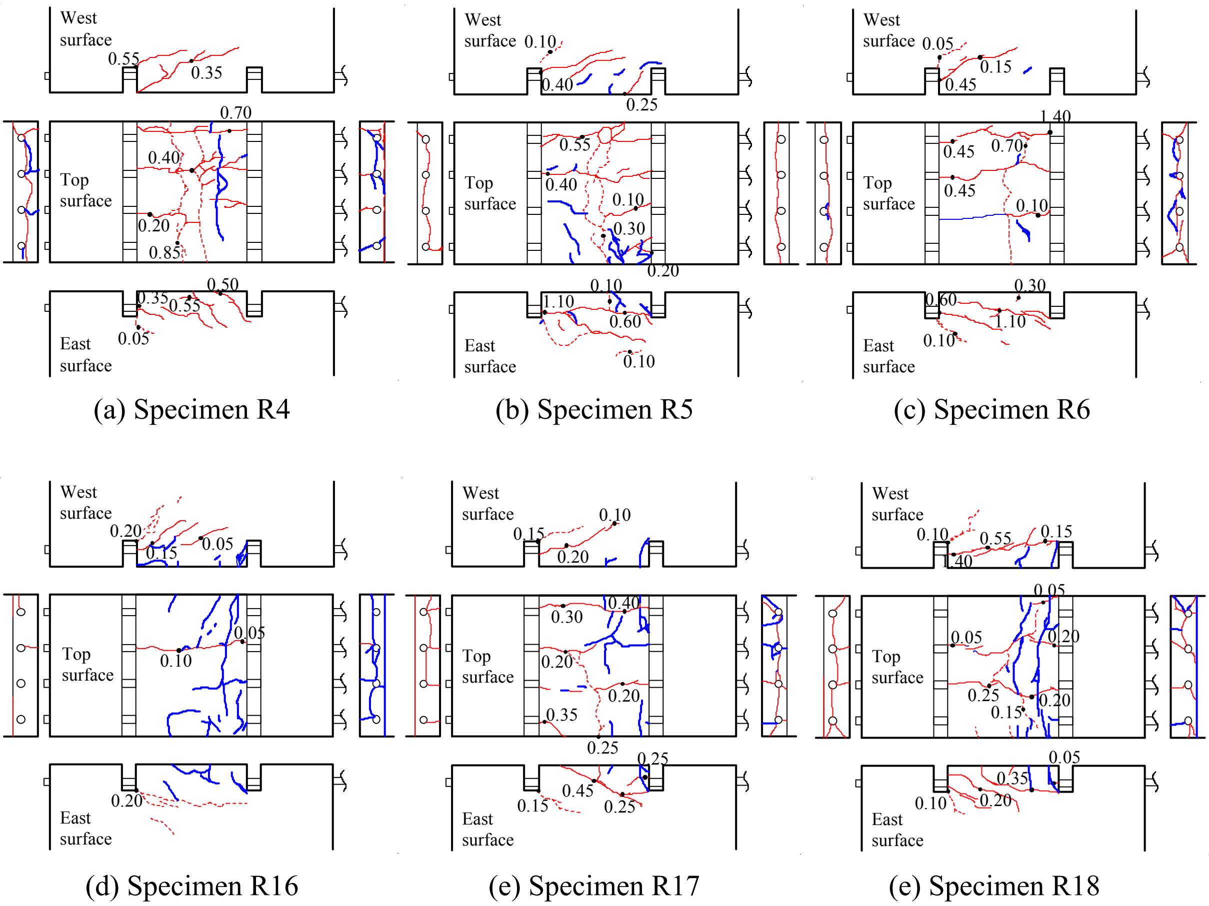


Figure 2.3. Test results on bond stress (τ_b) versus bond slip displacement (s_c) relations



[Remarks] : Cracks observed at the end of damage introduction loading stage (Numerals are width of the cracks in mm.)
: Cracks formed in the loading stage after emergency retrofit

Figure 2.4. Final crack patterns

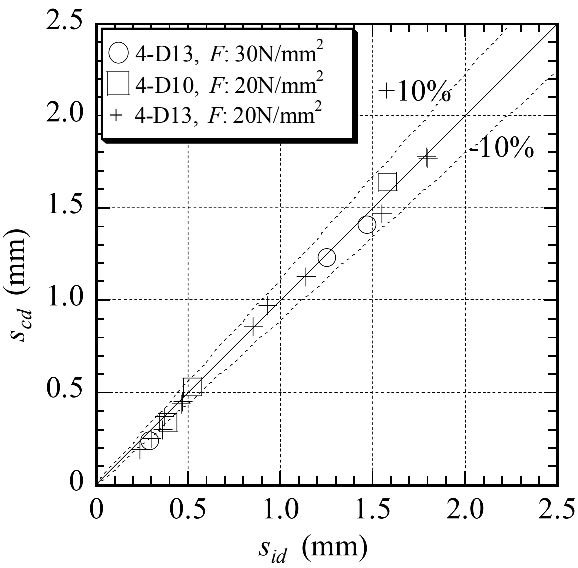


Figure 2.5. Relation between bond slip displacement at the end of the damage introduction loading stage for corner bar (s_{cd}) and that for intermediate bar (s_{id})

3. DISCUSSIONS ON DAMAGE INDEX

3.1. Procedure of Discussions

It is quite important to find suitable damage index for developing an equation to predict the ultimate bond strength after emergency retrofit (τ_{bru}). A discussion will be carried out based on the test results described in Chapter 2, where τ_{bru} is normalized by bond strength in case of no initial damage (τ_{bu}). Section 3.2 is for the description of an equation to estimate τ_{bu}. In Section 3.3, correlation between τ_{bru} and bond slip displacement at the end of damage introduction loading stage (s_{cd}) is investigated, and it is concluded that s_{cd} is to be a damage index. It is noted however that s_{cd} cannot be measured directly in the actual columns. Therefore, dependence of the s_{cd} on the bond splitting cracks is investigated in Section 3.4.

3.2. Equation to Estimate Bond Strength in Case of No Initial Damage

The bond strength in case of no initial damage is estimated by Eqns. 3.1 through 3.6 (Kuroki et al. (2008)).

$$\tau_{bu} = \left(0.32\gamma_b + 0.68\right)\cdot \tau_{bmax(\mathrm{wav})} \tag{3.1}$$

$$\tau_{bmax} = \tau_{co} + \tau_{ac} + \tau_{pa} \tag{3.2}$$

$$\tau_{co} = 1.22\left(0.0961 b_{si} + 0.134\right)\sqrt{\sigma_B} \quad \text{(Fujii and Morita (1982))} \tag{3.3}$$

$$\tau_{ac} = \begin{cases} 0.508\,\sigma_{c0} & \text{(for corner bars)} \\ 0.238\,\sigma_{c0} & \text{(for intermediate bars)} \end{cases} \tag{3.4}$$

$$\tau_{pa} = \begin{cases} 12.3\left(1-\dfrac{\sigma_{c0}}{\sigma_{cp.c}}\right)\dfrac{p_{eh}b}{nd_b}\sqrt{\sigma_B} + 16.5\left(1-\dfrac{\sigma_{c0}}{\sigma_{cp.i}}\right)\dfrac{p_h b}{nd_b}\sqrt{\sigma_B} & \text{(for corner bars)} \\ 5.51\left(1-\dfrac{\sigma_{c0}}{\sigma_{cp.c}}\right)\dfrac{p_{eh}b}{nd_b}\sqrt{\sigma_B} + 10.7\left(1-\dfrac{\sigma_{c0}}{\sigma_{cp.i}}\right)\dfrac{p_h b}{nd_b}\sqrt{\sigma_B} & \text{(for intermediate bars)} \end{cases} \tag{3.5}$$

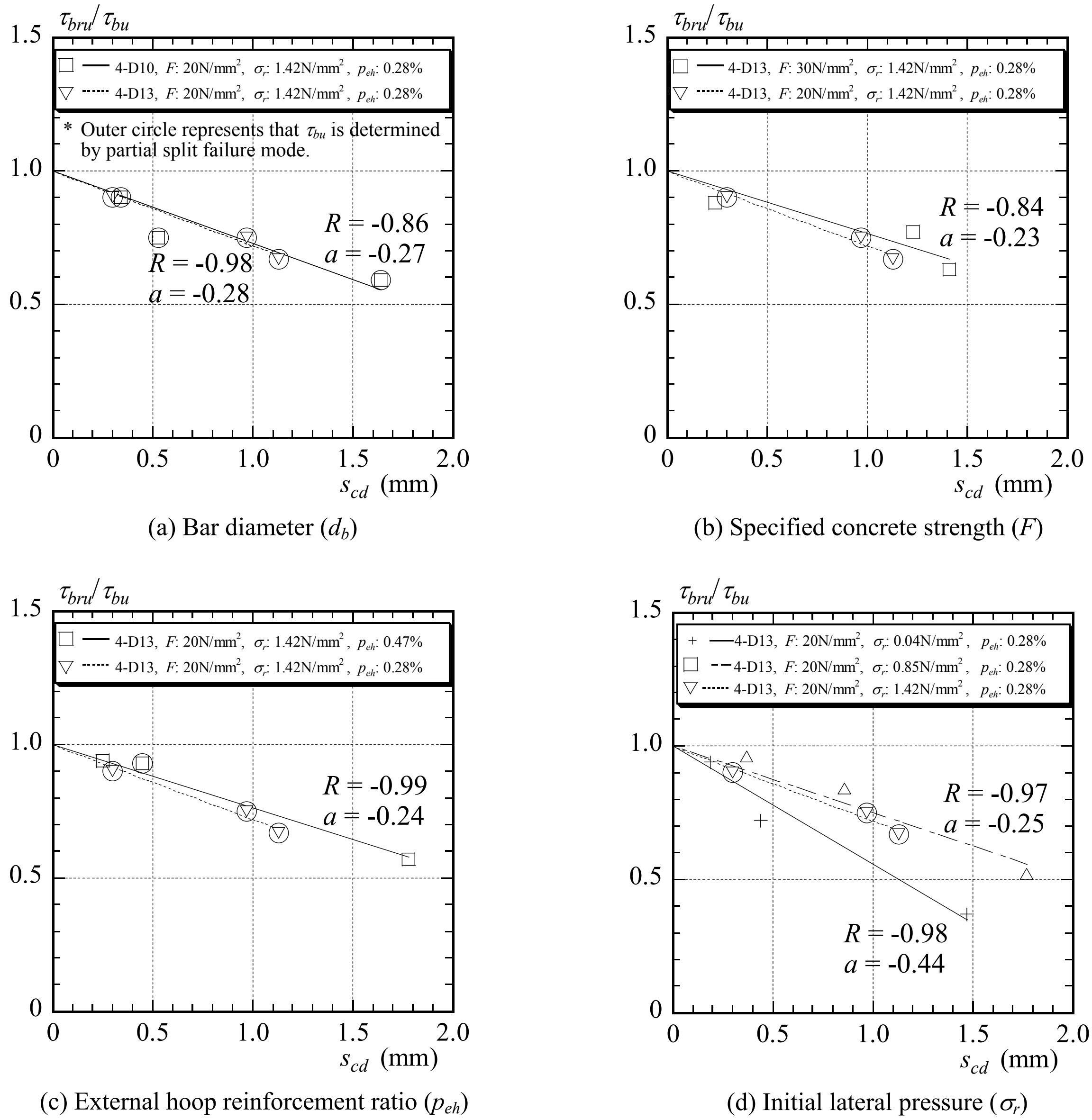
$$\sigma_{cp} : \begin{cases} \sigma_{cp.c} = (\tau_{po} - \tau_{co})/0.508 & \text{(for corner bars)} \\ \sigma_{cp.i} = (\tau_{po} - \tau_{co})/0.238 & \text{(for intermediate bars)} \end{cases} \tag{3.6}$$

in which γ_b is ratio of the bond strength for intermediate bar to that for corner bar, $\tau_{bmax(\mathrm{wav})}$ is weighted average of the bond strengths for corner and intermediate bars, τ_{bmax} is bond strengths for corner and intermediate bars, τ_{co} is bond strength carried by the splitting resistance of concrete, τ_{ac} is bond strength increment due to the active confinement, τ_{pa} is bond strength increment due to the passive confinement, 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, σ_{c0} is confining stress introduced initially by stressed external hoops (active confining stress) defined as $(\sigma_r b)/(nd_b)$, σ_{cp} is active confining stress corresponding to the boundary between splitting failure and pull-out failure, τ_{po} is bond strength determined by the pull-out failure expressed as $0.6\sigma_B SA$. In addition, τ_{bmax} does not exceed τ_{po}, $(1-\sigma_{c0}/\sigma_{cp.c})$ and $(1-\sigma_{c0}/\sigma_{cp.i})$ are not negative.

3.3. Relation between Normalized τ_{bru} and s_{cd}

Fig. 3.1 represents relations between τ_{bru} normalized by τ_{bu} and s_{cd}. Data for two groups with difference each other in bar diameter, concrete strength and external hoop reinforcement ratio are compared in Figs. 3.1a, 3.1b and 3.1c, respectively. Fig. 3.1d is to compare the data for three groups with difference in magnitude of initial lateral pressure. Outer circles in the figures indicate that τ_{bu} is determined by partial split failure mode, in which bond strengths for corner and intermediate bars are determined by the splitting failure and the pull-out failure without remarkable splitting cracks, respectively. Coefficient of correlation (R) for each group is given numerically. Solid, dotted and dashed lines represent results of linear regression of the data, and a is slope of each line.

It can be understood from Figs. 3.1a through 3.1d that τ_{bru} decreases linearly depending on s_{cd}. This indicates that s_{cd} is suitable as a damage index to express τ_{bru}. In addition, the slopes of regression lines for two groups are similar in Figs. 3.1a, 3.1b and 3.1c, however, those in Fig. 3.1d are different.



[Remarks] R: Coefficient of correlation, a: slope of regression line with an intercept of 1.0 (unit in 1/mm)

Figure 3.1. Relations between τ_{bru} normalized by τ_{bu} and s_{cd}

3.4. Relation between width of bond splitting cracks and s_{cd}

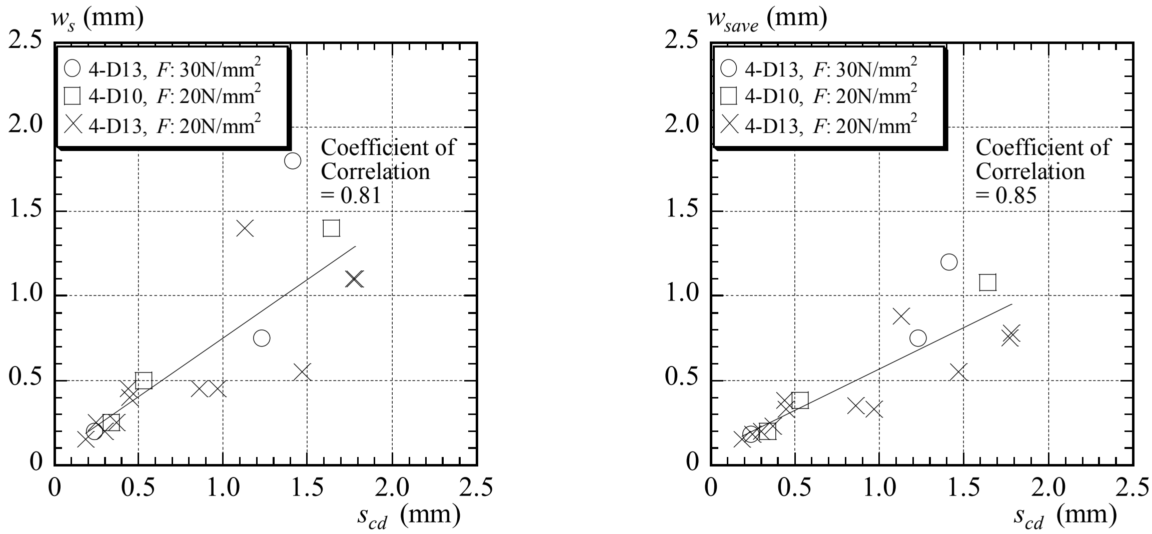
Fig. 3.2 shows relations between width of bond splitting cracks and s_{cd}. Two types of crack widths, w_s and w_{save} obtained by Eqns. 3.7 and 3.8, are adopted in Figs. 3.2a and 3.2b, respectively.

$$w_s = \max\left({}_e w_s \,,\, {}_w w_s\right) \tag{3.7}$$

$$w_{save} = \frac{{}_e w_s + {}_w w_s}{2} \tag{3.8}$$

in which ${}_e w_s$ is maximum width of bond splitting cracks in east side surface, which are observed at the end of damage introduction loading stage, ${}_w w_s$ is that in west side surface.

Fig. 3.2a indicates that correlation between w_s and s_{cd} is high as far as w_s does not exceed 0.4 mm, however, the correlation becomes lower as far as w_s exceeds 0.4 mm. The similar correlation is observed in Fig. 3.2b. Coefficient of correlation obtained by all data of Fig. 3b is a little bit higher than that of Fig. 3.2a.



(a) w_s: Greater value of maximum crack widths in two side surfaces

(b) w_{save}: Average value of maximum crack widths in two side surfaces

Figure 3.2. Relations between width of bond splitting cracks and s_{cd}

4. CONCLUSIONS

The aim of this paper is to find damage index, which can be used to express the splitting bond strength for main steel bars after emergency retrofit with prestressed external hoops. A discussion was carried out based on the test results, which were obtained in the former experimental study. Conclusions obtained are summarized as follows.

(1) A strong correlation can be founded between ultimate bond strength after emergency retrofit and bond slip displacement at the end of damage introduction loading stage. This indicates that the residual slip displacement is to be a damage index to express ultimate bond strength after emergency retrofit.

(2) Since it is impossible to measure the residual slip displacement in the actual columns directly, dependence of the bond slip displacement at the end of damage introduction loading stage on the splitting cracks is investigated, where respective maximum crack width in two side surfaces were picked up in the present study. As a result, the average value of those two maximum crack widths represents better correlation with the bond slip displacement in comparison with the greater value of those two maximum crack widths.

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