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EVALUATION OF ANCHORAGE STRENGTH OF BEAM MAIN BARS ANCHORED MECHANICALLY IN R/C EXTERIOR BEAM-COLUMN JOINT

Toshihiko KIYOHARA[1], **Shinji KATO**[2], **Akira TASAI**[3]

SUMMARY

Recently, mechanical anchorage method applied to beam main bars in R/C beam-column joint has been diffused. Mechanical anchorage method is profitable for high-rise R/C buildings, because high-strength and large diameter main bars need no bent-up in beam-column joints. In Japan, mechanical anchorage strength for side cover splitting is estimated by the equation on an experimental basis. However, this equation has limitations due to test parameters. Especially, the effect of the anchorage length was not included in the equation.

In this paper, in order to improve the equation, factors to influence the side cover splitting failure in the joint around the mechanically anchored beam main bars were investigated based on a new database which was made by referencing recent many tests results in Japan. Investigation on database brought light that major factors affects mechanical anchorage strength are following; 1)concrete strength, 2)anchorage length, 3)side cover thickness of concrete, 4)distance between tension and compression resultants at a critical section, 5)area of bearing plate, and 6)lateral reinforcement in a beam-column joint.

Influence of each factor is assessed quantitative, and the equation for mechanical anchorage strength is improved. Effect of anchorage length and distance between tension and compression resultants are considered newly in the equation. Effects of concrete strength and lateral reinforcement have improved. The evaluation of mechanical anchorage strength by the improved equation is quite up to an average of test results. In any cases of anchorage length, appropriateness of the improved equation is remarkably better than that of the previous equation.

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[1] Horie Engineering & Architectural Research Institute, Tokyo, Japan, E-mail : kiyohara@horieken.co.jp
[2] Kajima Corporation, Tokyo, Japan, E-mail : s-kato@kajima.com
[3] Yokohama National University, Yokohama, Japan, E-mail : tasai@arc.ynu.ac.jp

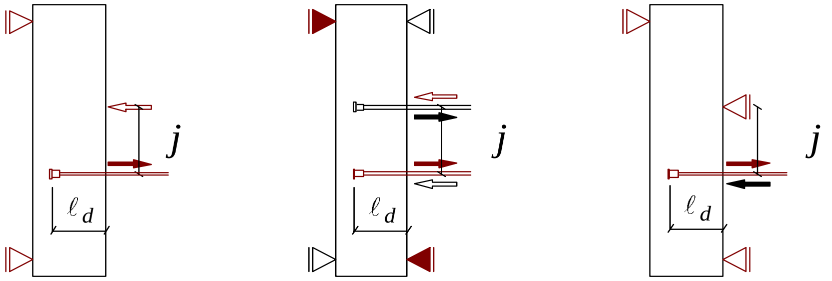
INTRODUCTION

Mechanical anchorage method applied to beam main bars in exterior beam column joints has been diffused practically in Japan. Mechanical anchorage method is profitable for high-rise R/C buildings, because high-strength and large diameter main bars need no bent-up in beam-column joints. The anchorage strength is usually estimated for the side cover splitting near the anchorage end plate by the equation, which was proposed in the New RC project in Japan (Murakami, Kubota, et al, 1993). The equation was obtained by regression from pull-out test results in consideration for some variables which affected pull-out strength. However, this equation has limitations due to test parameters. Especially, the effect of the anchorage length isn't included in the equation.

In this paper, in order to improve the equation, factors to influence the side cover splitting failure in the joint around the mechanically anchored beam main bars were investigated based on a new database which was made by referencing recent many test results in Japan. An equation for an anchorage strength of conventional bent-up rebar in a joint (Fujii and Morita, 1991) was used as reference as the improved equation.

INVESTIGATED TEST DATA

In the database, test results of 148 pull-out specimens, which were reported from 1992 to 2001 in Japan, are included. The specimens were commonly loaded as simulating the condition of resultants in an exterior beam column joint, as shown **Figure1**. The anchorage length ℓ_d was defined as a distance between a column face and an anchorage end plate of beam bars. The side cover thickness C_0 was defined as a distance between a center of the outer rebar and a column side surface.



Monotonic Loading

Cyclic Loading (Positive and Negative)

Cyclic Loading (Positive Only)

Figure 1 Adopted Pull-out Tests in the Data-Base (j : Distance between Resultants)

According to the description in each paper, eighty five specimens failed in side cover splitting, twenty specimens in corn shape failure, fourteen specimens in joint failure, and fifteen specimens in fracture of rebar. The eighty-five specimens failed in the side cover splitting were adopted in the database to derive a new equation to estimate the anchorage strength. The reported maximum load of each specimen was identified as the anchorage strength.

DERIVATION OF EQUATION

Constitution of Equation

Investigation for test results of the eighty-five specimens revealed that the following five factors influenced the mechanical anchorage strength in side cover splitting, in addition to concrete strength.

k_1 : Effect of bearing area of anchorage end plate
k_2 : Effect of side cover thickness of concrete
k_3 : Effect of distance between compressive and tensile resultants at critical section
k_4 : Effect of anchorage length
k_5 : Effect of lateral reinforcement in a joint

Effect of concrete strength was represented by approximated curves of anchorage strength as a function of concrete compressive strength of specimens with the same value in each k_i ($i = 1$~5). Each factor $k_1 \sim k_5$ was represented based on the strength rate for the anchorage strength of a benchmark specimen in a group with the same value in other factors. In this paper, the anchorage strength is expressed in terms of the maximum axial stress of anchored rebars obtained from the test. The anchorage strength σ is constituted by multiplying every k_i by the benchmark strength σ_{std} as a function of concrete strength as follows.

$$\sigma = k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 \cdot \sigma_{std} \qquad (1)$$

Formula of Influence Factors

Each influence factors k_i in the equation (1) was formulated by analyzing test data in the database, whose ranges are shown in **Table 1**.

Table 1 Range of Influence Factors in Adopted Pull-out Tests

influence factor	parameter range
concrete compressive strength : σ_B	19.3～76.0 (N/mm^2)
ratio of bearing area	2.70～5.84
side covering depth : C_0 / d_b	2.57～6.58
lever arm : j / l_d	0.85～2.00
anchored length : l_d / d_b	7.89～18.67
l_d / D_c	0.50～0.84
ratio of lateral reinforcement : p_{jw}	0.00～1.10 (%)
ratio of peripheral hoop	0.00～0.63 (%)
ratio of core hoop	0.00～0.47 (%)
column size	300～650 (mm)

D_c : depth of column , d_b : diameter of reinforcing bar

(1)σ_{std} : Benchmark axial stress as a function of concrete compressive strength

There were six groups of total nineteen specimens in which varied only concrete strength. The anchorage strength vs. concrete strength relationship obtained from these specimens is shown in **Figure 2**.

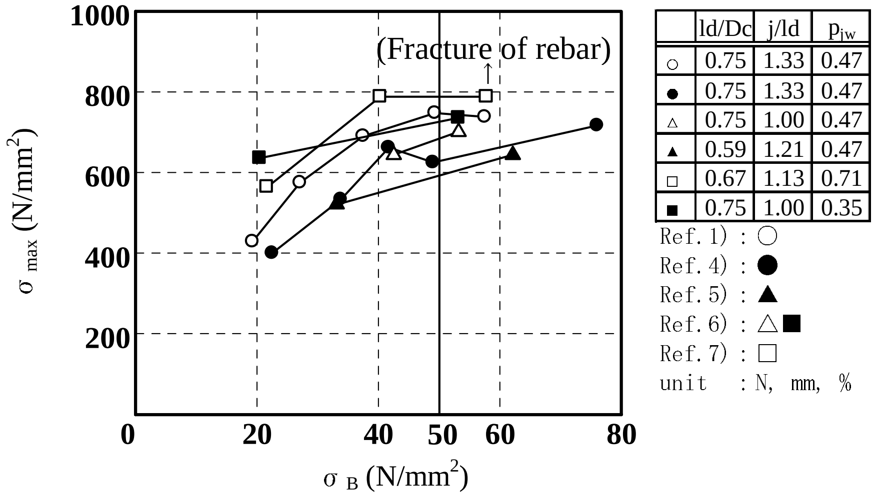


Figure 2 Influence of Concrete Compressive Strength

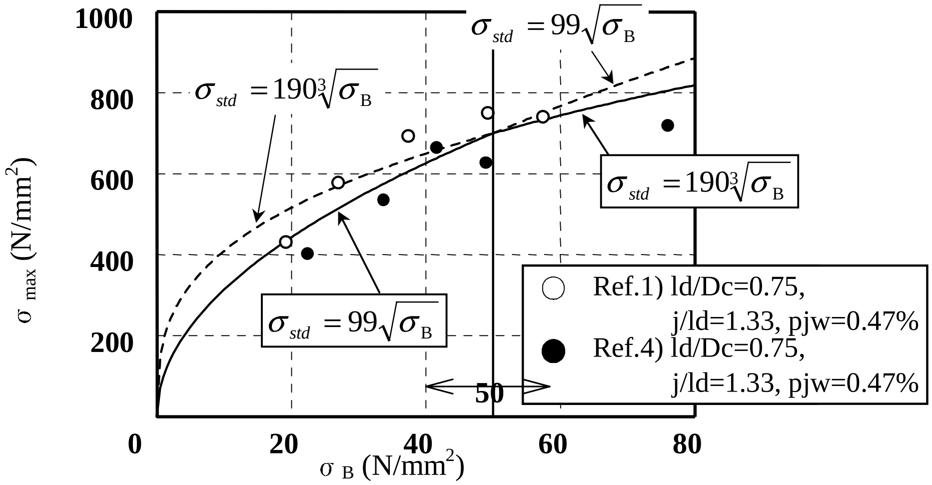


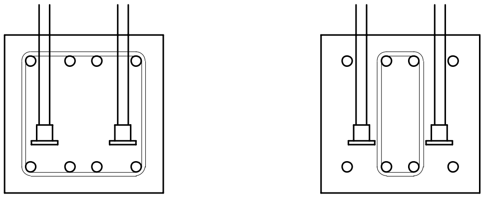
Figure 3 Benchmark Axial Stress of an Anchored Bar

In the range of concrete strength σ_B lower than 50*N/mm*^{2}, the anchorage strength increased proportionally to the concrete strength. However, in the range $\sigma_B > 50$*N/mm*^{2}, the anchorage strength did not increase so much. Ten specimens (denoted by the marks ○ and ● in the Figure) were selected to obtain the benchmark strengthσ_{std}, because all influence factors of these specimens were equal to 1.0. In the range of $\sigma_B \leqq 50$*N/mm*^{2}, the anchorage strength was assumed to be proportional to the square root of concrete strength and proportional to the cube root of concrete strength in the range of $\sigma_B > 50$*N/mm*^{2}, as shown in **Figure 3**. Hence, theσ_{std} was expressed as follows.

$$\sigma_{std} = 99\sqrt{\sigma_B} \qquad \text{in } \sigma_B \leqq 50\ N/mm^2$$

$$\sigma_{std} = 190\sqrt[3]{\sigma_B} \qquad \text{in } 50\ N/mm^2 < \sigma_B \leqq 76\ N/mm^2 \tag{2}$$

Incidentally, there is a difference on hoop allocation between specimens in ref.1(denoted by the marks ○) and specimens in ref.4(denoted by the marks ●),as shown in **figure 4**. In this paper, influence of hoop is considered by only lateral reinforcement ratio, not by hoop allocation.



Specimen in Ref.1
(Peripheral hoop only)

Specimen in Ref.4
(Core hoop only)

Figure 4 Difference on Hoop Allocation

(2) k_1: Effect of bearing area of anchorage end plate

The influence factor k_1 was represented by the same formula as the New RC equation, because the test data concerning bearing area was same as the original data for the New RC equation.

$$k_1 = 1 \qquad 2.7 \leqq \text{ bearing area ratio } \leqq 6.0 \tag{3}$$

(3) k_2: Effect of side cover thickness of concrete

The influence factor k_2 was also represented by the same formula as the New RC equation, because the test data concerning side cover thickness of concrete was same as the original data for the New RC equation.

$$k_2 = 0.96 + 0.01\,(C_0 / d_b) \tag{4}$$

(4) k_3: Effect of distance between compressive and tensile resultants

Fujii and Morita have pointed out that the distance between compressive and tensile resultants in the critical section of a beam significantly influenced the anchorage strength in case of the conventional bent-up anchorage(1991). In the mechanical anchorage, the same effect was also assumed; i.e. the higher of the anchorage strength in the shorter of the distance. The anchorage strength decreased linearly to j/ℓ_d as shown in **Figure 5**. Therefore, the following formula was obtained.

$$k_3 = -0.16\,(j/\ell_d) + 1.22 \tag{5}$$

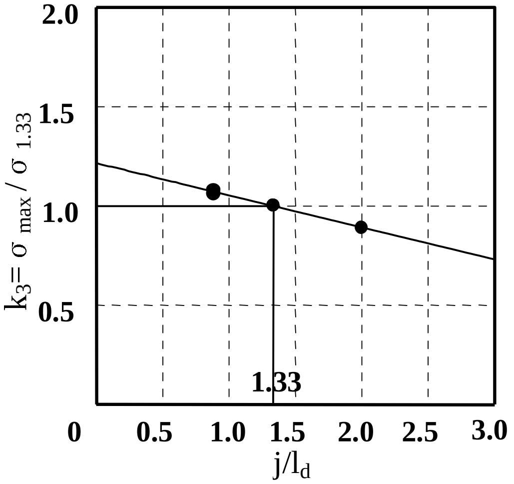


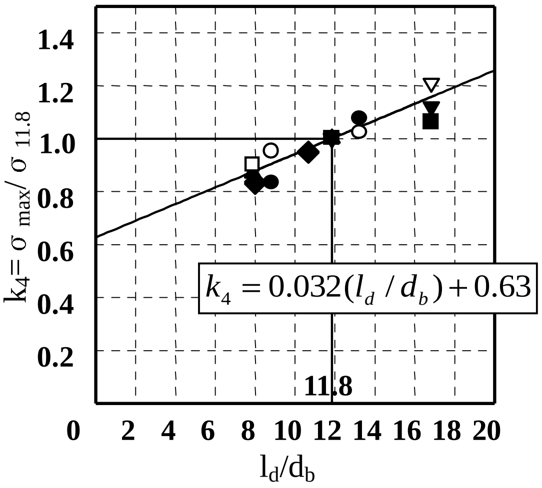
Figure 5 Influence of the Distance between both Resultants

($j/l_d=4/3=1.33$ was selected as the Benchmark)

(5) k_4: Effect of anchorage length

In the database, the anchorage length was varied in twenty specimens. The effect was studied as the ratio for the rebar diameter ℓ_d/d_b. However, the ratio j/ℓ_d also varied in conjunction with ℓ_d/d_b. The anchorage strength of the specimens was translated to the equivalent strength at $j/\ell_d=4/3$ using equation (5), so that the effect of anchorage length could be estimated independently. Science the ratio ℓ_d/d_b was 11.8 in the specimen with $j/\ell_d=4/3$, $\ell_d/d_b=11.8$ was chosen as the benchmark. The anchorage strength increased proportionally to the anchorage length as shown in **Figure 6**. The formula for k_4 was obtained as follows.

$$k_4=0.032(\ell_d/d_b)+0.63 \tag{6}$$



	σ B	db	j	p_{jw}
○	41.2	17	300	0.21
●	41.2	17	300	0.47
△	49.0	19	300	0.47
▲	49.0	19	200	0.47
□	49.0	19	200	0.47
■	33.1	35	500	0.47
▽	33.1	35	500	0.47
▼	33.1	35	500	0.16
◇	42.6	25	300	0.71
◆	42.6	25	300	0.71

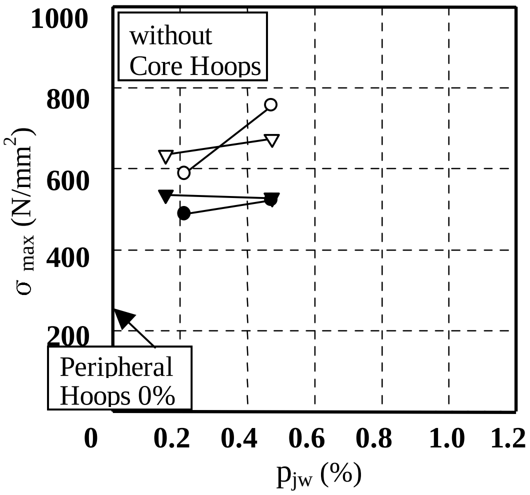
Ref. 4) : ○●△▲□
Ref. 5) : ■▽▼
Ref. 6) : ◇◆
unit : N, mm, %

Figure 6 Influence of Anchorage Length

($l_d/d_b=11.8$ was selected as the Benchmark)

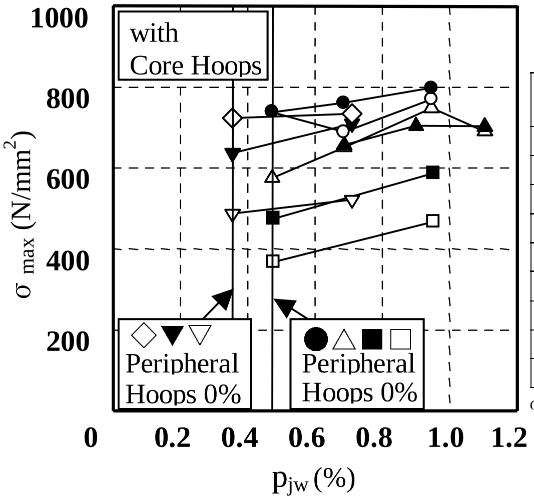
(6) k_5: Effect of lateral reinforcement in a joint

In the New RC equation, as the effect of lateral reinforcement in a joint, only peripheral hoops were considered. However, the database indicated that the core hoops developed almost the same effect as the peripheral hoops on the anchorage strength. In the improved equation, the effect of core hoops has been included. The ratio of lateral reinforcement p_{jw} was varied in total thirty-six specimens in the database. The anchorage strength is plotted versus p_{jw} in **Figure 7**. The strength increased linearly up to about p_{jw}=0.9%.



	Ref	σ_B (N/mm^2)	ld/Dc	j/ld
○	4	41.2	0.75	1.33
●	4	41.2	0.50	2.00
▽	5	33.1	0.84	0.84
▼	5	33.1	0.59	1.21

σ_B : Concrete strength



	Ref	σ_B (N/mm^2)	ld/Dc	j/ld
○	1	57.6	0.75	1.00
●	1	57.6	0.75	1.00
△	1	27.2	0.75	1.00
▲	1	26.8	0.75	1.00
□	8	20.5	0.75	1.33
■	8	20.5	0.75	1.33
▽	8	20.5	0.75	1.33
▼	8	20.5	0.75	1.33
◇	8	42.6	0.75	1.33

σ_B : Concrete strength

Figure 7 Influence of Lateral Reinforcement

The effect of lateral reinforcement was reported to decrease relatively in high strength concrete (Murakami, Kubota, 1997). In **Figure 8**, the test data is plotted in two cases of concrete strength for the same benchmark ratio of p_{jw}. The formula was determined by linear interpolation for the two cases, as follows.

for $p_{jw} \leqq 0.009$

$$k_5 = 51 p_{jw} - (1.37 p_{jw} - 0.0065)(\sigma_B - 27.2) + 0.76$$

for $p_{jw} > 0.009$

$$k_5 = 1.22 - 0.0059(\sigma_B - 27.2) \qquad (7)$$

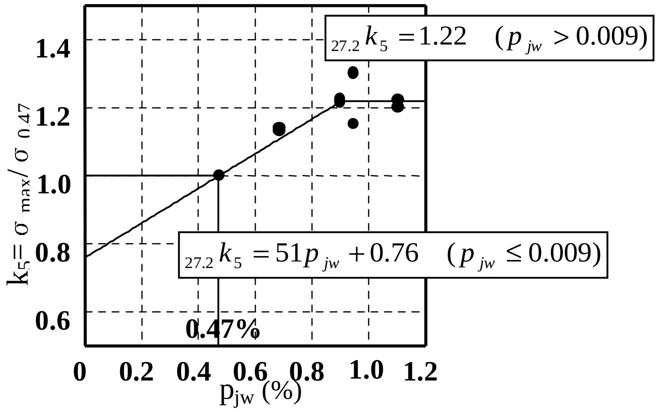


Figure 8-1 Influence of Lateral Reinforcement in case of $\sigma_B = 27.2N/mm^2$

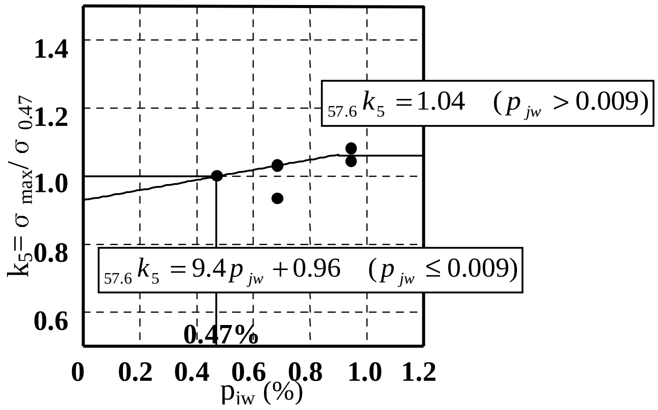


Figure 8-2 Influence of Lateral Reinforcement in case of $\sigma_B = 57.6N/mm^2$

Through referring **Figure 8-1** and **Figure 8-2**, in case of $p_{jw} < 0.47\%$, k_5 value is increasing with concrete strength, other side in case of $p_{jw} > 0.47\%$, k_5 value is decreasing with concrete strength. Therefore, in case of high strength concrete, k_5 value is decreasing with lateral reinforcement ratio according to the equation (7). This is considered to be unreasonable estimation. There are not enough data to estimate the influence of lateral reinforcement in high strength concrete, so that k_5 value should be fixed to 1.0 tentatively, in case of high strength concrete (above about $60 N/mm^2$).

Finally, the mechanical anchorage strength for side cover splitting can be estimated by using equations (1) to (7).

APPROPRIATENESS OF THE IMPROVED EQUATION

The calculated anchorage strength for side cover splitting was compared with the strength obtained from the test. The comparisons in three cases by the improved equation, by the New RC equation, and by the equation recommended by AIJ for the conventional bent-up anchorage after Fujii and Morita were represented in **Figure 9-1**, **Figure 9-2**, and **Figure 9-3**, respectively. Appropriateness of the improved equation (Ave.=1.012, SD=0.117) was remarkably better than that of the New RC equation (Ave.=0.942, SD=0.139).

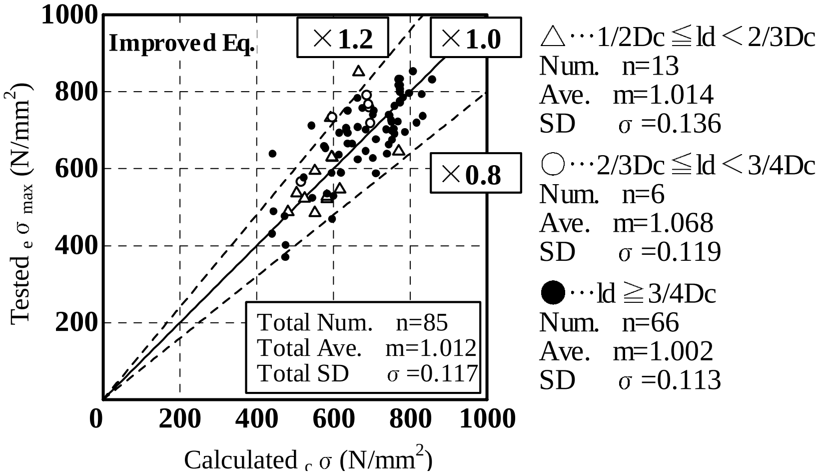


Figure 9-1 Appropriateness of the Improved Equation

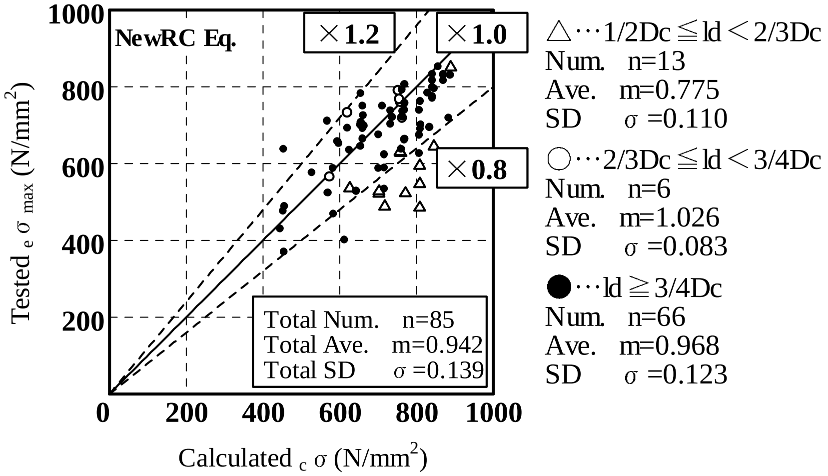


Figure 9-2 Appropriateness of the NewRC Equation

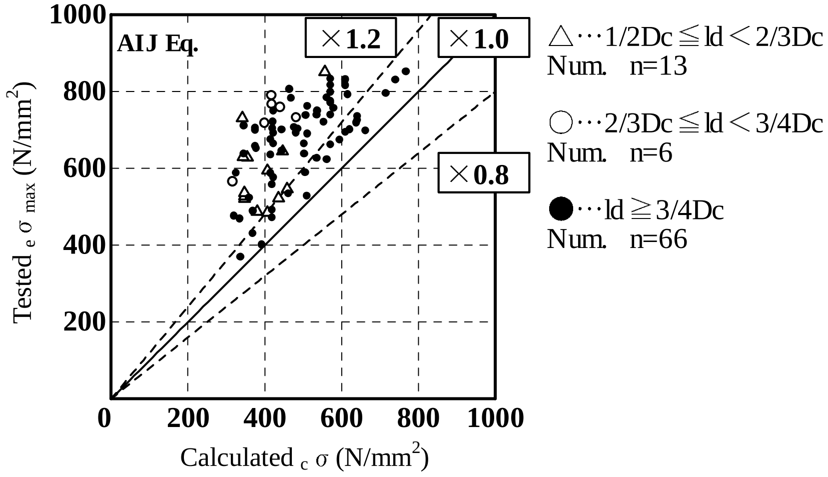


Figure 9-3 Appropriateness of the equation in the AIJ Guidline

However, in the improved equation, due to luck of test data, other many effects which may possibly influence the mechanical anchorage were not considered, for example, group effect of rebars, strength of hoops, layers of anchored rebars, width of compressive region in a beam, effect of orthogonal beams, difference between top and bottom rebar, column axial load, scale effect, and so on.

CONCLUSIONS

The equation to estimate the mechanical anchorage strength for the side cover splitting failure was improved based on the recent test data in Japan. Effect of anchorage length and distance between compressive and tensile resultants at critical section were considered in the equation, in addition to the effects of bearing area of anchorage plate, cover thickness of concrete, and lateral reinforcement in a joint. The equation predicted the mechanical anchorage strength appropriately.

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