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論文　Experimental Research on the Effect of Rib Shape and Bar Diameter on Bond Strength

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ABSTRACT: Pull-out and lap splice tests were conducted to study the effect of scale and rib shape on the bond strength of deformed bars without transverse reinforcement. A strong scale effect was observed for both types of tests, whereas the effect of rib shape was small.

Keyword: Reinforced Concrete, Scale Effect, Rib Shape, Bond Strength, Concrete Cover Thickness, and Splice.

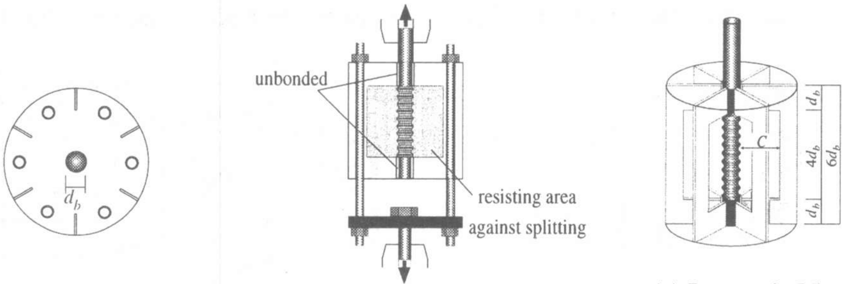
1. INTRODUCTION

A large amount of experimental and analytical work has studied the effects of scale on the shear strength or flexural strength of reinforced concrete, while relatively less effort has been devoted to studying scale effects on the bond strength of reinforcement [1]. This paper investigates the effects of bar diameter and rib shape on bond strength, as determined by pull-out and lap splice experiments.

2. PULL-OUT TESTS

(1) Test setup and specimen parameters

Figure 1 shows the specimen geometry and loading apparatus for the pull-out testing reported here. The loading system is similar to that developed by Jinno et al.[1]. **Table 1** indicates the parameter settings for the 12 series of specimens that were tested. The specimen designation has three components indicating (in order): Bar diameter, concrete cover to bar



(a) Horizontal Section　(b) Section with Loading System　(c) Isometric View

Fig. 1 Pull-out Specimens

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diameter ratio and bar angle. The ratio of rib height to rib spacing is the same as shown in **Fig. 2**. Six slit boards were used to control the concrete cover thickness C, which was either $1d_b$ or $2d_b$. The bond length is $4d_b$. Note that all specimen dimensions are scaled according to bar diameter. The fifth column of **Table 1** indicates the number of specimens belonging to each series; overall, 31 specimens were tested. The surfaces of the specimens were kept at 100%RH for 30 days and afterwards kept dry for 40 to 55 days. The mechanical properties of concrete are shown in **Table 2**, where G_F is measured according to recommendations given by Hillerborg[2]. **Figure 3** shows the test setup used for measuring G_F. High strength concrete is used to enhance the scale effect.

Table 1 Pull-out Specimens

Designation	d_b (mm)	C/d_b	Rib Angle(deg)	Number	Age at Testing(days)
2-1-45	20	1	45	3	75~85
2-1-60			60		
2-2-45		2	45		
2-2-60			60		
4-1-45	40	1	45	2	70~80
4-1-60			60	3	
4-2-45		2	45		
4-2-60			60	2	
6-1-45	60	1	45	1	75~80
6-1-60			60	3	
6-2-45		2	45	2	
6-2-60			60	3	

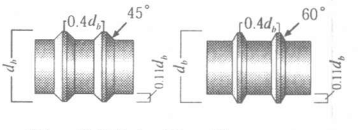


Fig. 2 Main Bar Geometry

Table 2 Mechanical Properties of Concrete

	Comp. Strength σ_B(N/mm^2)	Tensile Strength σ_t(N/mm^2)	Secant Modulus at $\sigma_B/3$ E (N/mm^2)	Fracture Energy G_F (N/m)
Average	54.0	4.0	2.69×10^4	94.4
Standard Dev.	0.81	0.14	0.03×10^4	22.9

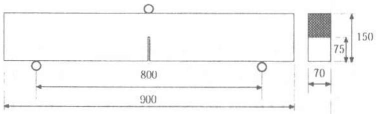


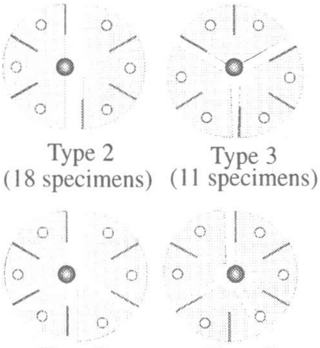
Fig. 3 Specimens for Determiniing G_F (dimensions in mm)

(2) Failure pattern

Four types of failure pattern were observed as shown in **Fig. 4**. The number of specimens exhibiting each failure pattern is also indicated in the figure. The three parameters (bar diameter, cover thickness, and rib angle) did not significantly affect the failure pattern.

(3) Effects of size and rib shape on bond strength

Figure 5 shows the experimentally measured bond strengths. A large scale effect was observed. Increasing the bar diameter from 20 to 40mm gave a 35% reduction in bond strength;



Type 2
(18 specimens)

Type 3
(11 specimens)

Type 3a
(1 specimen)

Type 3b
(1 specimen)

Fig.4 Failure Pattern of Pull-out Specimens

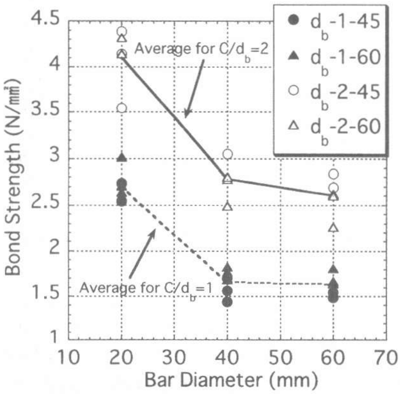


Fig. 5 Bond Strength of Pull Out Specimens

increasing the bar diameter from 40 to 60mm gave a 6% reduction in bond strength. The effect of concrete cover thickness was also larger. When the thickness increased from $1d_b$ to $2d_b$, the bond strength increased 1.6 times. The effect of the rib angle was relatively small. When the rib angle was increased from 45 to 60 degrees, the bond strength increased by only 2%.

(4) Inclination of principal compressive stress due to bond action

Based on the Tepfers theory[3], the following relation can be used to calculate bond strength:

$$\tau_{b\max} = 0.601 \cdot \sigma_t \frac{r_u}{d_b} \cdot \cot\alpha \qquad (1)$$

where σ_t is the splitting tensile strength, r_u is the distance from concrete edge to the center of the bar and α is the angle between the principal compressive bond stress and the axis of the reinforcing bar. Tepfers assumed that α is 45 degrees whereas Kanakubo[4] determined α to be 34 degrees through experimentation. **Figure 6** compares the calculated and experimental results. Our experiments indicate that α should be 62 degrees, which is much larger than Kanakubo's result. This angle may be more reliable because our specimens had cover concrete only over the bonded length of the specimen ($4d_b$ in **Fig. 1(c)**), whereas Kanakubo's specimens had effective cover concrete extending over the unbonded regions ($6d_b$ in **Fig. 1(c)**).

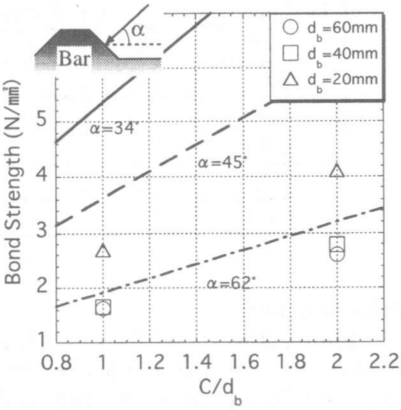
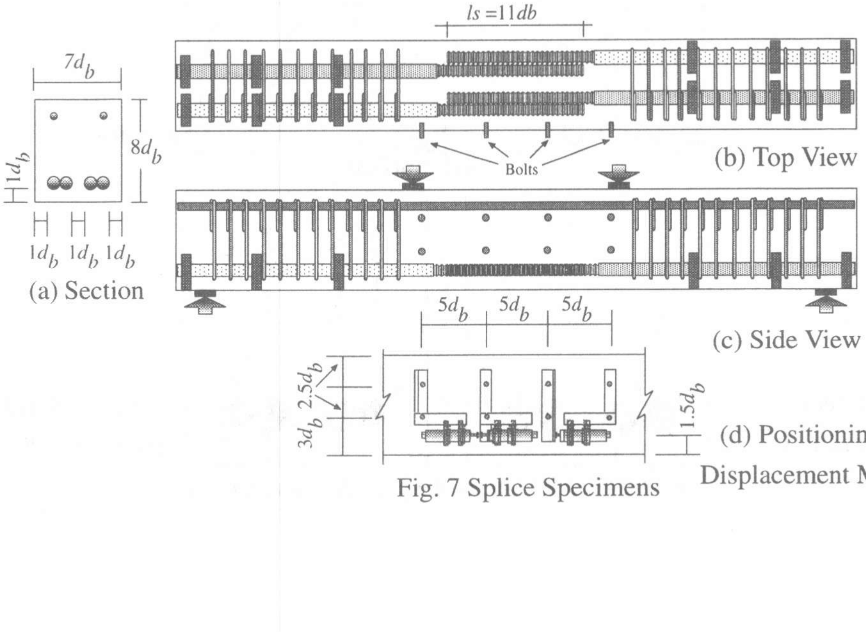


Fig. 6 Calculated and Experimental Bond Strengths

3. LAP SPLICE TESTS

(1) Test setup and specimen parameters

The specimen geometry and loading are shown in **Fig. 7**. The loading produces essen-



(a) Section

(b) Top View

(c) Side View

(d) Positioning of Displacement Meters

Fig. 7 Splice Specimens

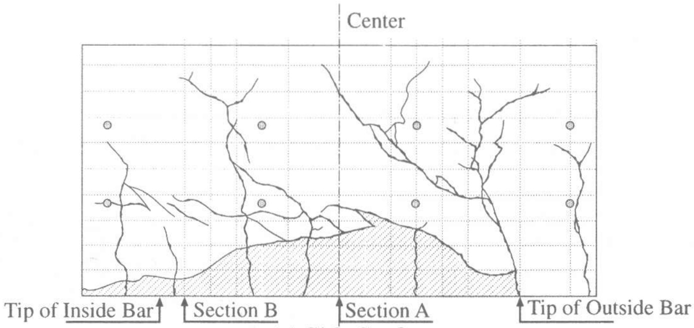
tially a constant moment over the splice length. **Table 3** indicates the parameter settings for the 6 series of specimens that were tested. The specimen parameters (i.e. bar diameters and rib angle) have the same values as for the pull-out tests. That is, the bar diameters are 20, 40, and 60mm, while the rib angles are 45 and 60 degrees. The ratios of rib height to rib spacing are also the same. Each specimen has two splices, each of length 11 d_b. There are no stirrups inside the splice length. The surfaces of the specimens are kept at 100%RH for 30 days and afterwards kept dry for 15 to 35 days. The concrete properties are same as those for the pull-out specimens.

Table 3 Splice Specimens

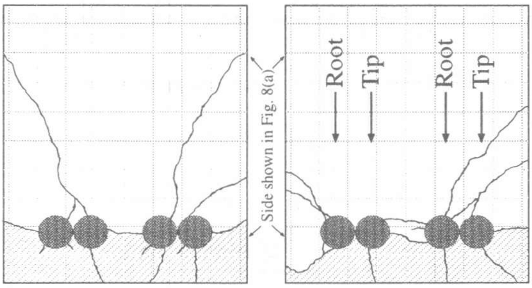
Designation	d_b(mm)	Rib Angle(deg.)	Number	Age at Testing(days)
2-45	20	45	3	60～65
2-60		60		
4-45	40	45	2	45～50
4-60		60		
6-45	60	45	1	55
6-60		60		

(2) Failure pattern

Figure 8(a) shows the typical crack pattern observed on the side surface of the specimen, local to the splice. The hatched region indicates material which spalls after peak strength. The pattern is not symmetrical about the center of the splice length. One of the cracks from the tip of the outside bar extends to the upper left at an inclination of about 45 degrees. **Figure 8(b)** and **(c)** show the typical crack patterns observed in the sections indicated in **Fig. 8(a)**. The cracks at the central section extend more upward than those at the section near the end of the splice.



(a) Side Surface



(b) Section A
(Seen from Left)

(c) Section B
(Seen from Right)

Fig. 8 Crack Pattern of Splice Specimen 6-45

(3) Average concrete strains local to splice

Eight bolts were embedded in each specimen to measure average concrete strain at the level of the spliced bars as shown in **Fig. 7(c)**. **Figure 9** shows the typical relationship between the load and the average concrete strain. When the load is small, the average strains in the three regions are about the same. When the load is larger than about one half of the strength, the strain in the left region increases relative to the other two measurements. The strain in the center region decreases as the load approaches the peak strength.

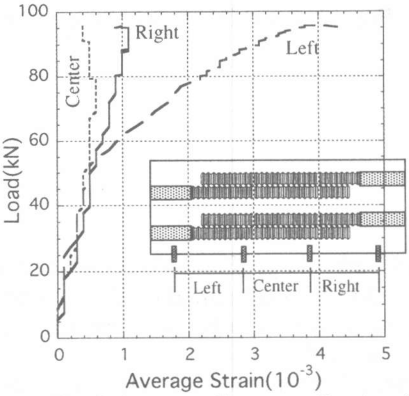


Fig. 9 Average Concrete Strain of Splice Specimen 2-45

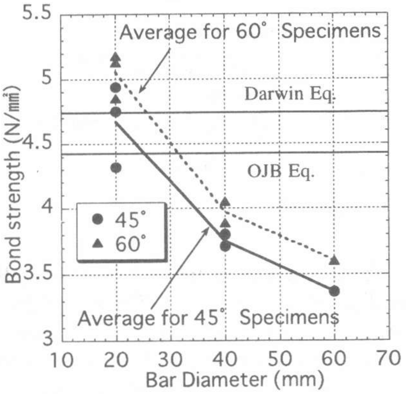


Fig. 10 Bond Strength from Splice Experiments

(4) Effects of size and rib shape on bond strength

Figure 10 shows the experimental results for bond strength calculated from the ultimate flexural moments M_u of the beams using the following equation, where the distance between the compressive and tensile forces in a section is assumed to be 0.9 times of the effective depth, $d(=6.5\ d_b)$.

$$\tau = \frac{M_u}{0.9d \cdot \Psi \cdot l_s} \qquad (2)$$

where Ψ is the perimeter length of two bars($=2\pi d_b$), and l_s is the splice length($=11d_b$).

When rib angle increased from 45 to 60 degrees, the bond strength increased about 7%. The rib angle effect on bond strength is larger than that in the pull-out experiments. When bar diameter increased from 20 to 40mm and from 40 to 60mm, the bond strength decreased 20% and 10%, respectively. The scale effect is smaller than that of the pull-out tests. **Figure 10** also shows calculated bond strength using equations given by Darwin[5] and OJB[6]. These bond strength predictions are independent of bar diameter and underestimated the observed results for the larger bar diameters.

Figure 11 shows the bond strengths calculated from bar strains outside the splice. The bond strengths of outside bars are about 80% of those of inside bars. This means that about 80% of the tensile stress in an inside bar was transferred from the neighbouring outside bar, whereas the remaining 20% was transferred from the other inside bar, as shown in **Fig. 12**.

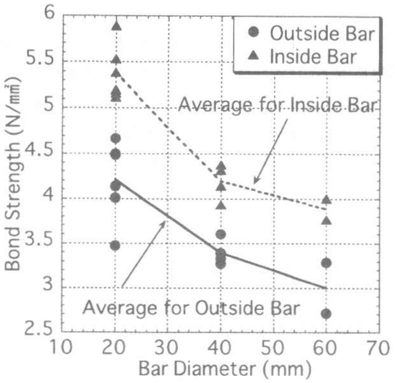


Fig. 11 Bond Strength Calculated from Bar Strain

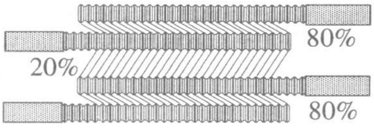


Fig. 12 Bond Stresses between Bars

4. CONCLUSIONS

(1) The effect of scale on bond strength is rather large. For the pull-out tests, increasing the bar diameter from 20 to 40mm and from 40 to 60mm resulted in 35% and 6% reductions in bond strength, respectively. For the same increases in bar size, the corresponding strength reductions in the splice tests were 20% and 10%.

(2) The effects of rib angle on bond strength are not significant. Changing the rib angle from 45 to 60 degrees, the bond strength only increased 2% in the pull-out tests and 7% in the splice tests.

(3) Based on the Tepfers theory for calculating the bond strength, our experiments indicate that the angle between the principal compressive stress due to bond action and the bar axis, α, is approximately 62 degrees.

(4) There is marked asymmetry in the observed cracking patterns local to the splices. Cracks tend to radiate from the tip of the outside bar. Bar axial stress and bond strength also differ according to inside or outside positioning of the bar.

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