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Study on size effect in bond splitting behavior of ECC

K. Asano & T. Kanakubo
University of Tsukuba, Tsukuba, Japan

ABSTRACT: This paper describes the test results of the pullout test in order to obtain the bond behavior between Engineered Cementitious Composites (ECC) and steel reinforcing bar. There is a possibility that the size of cover thickness of ECC around reinforcing bar affects the orientation of fiber, so bridging performance of fiber is influenced by specimen size. To evaluate the size effect, the main parameters of specimens are reinforcing bar diameter and cover thickness. The shape of specimen is a similarity shape based on reinforcing bar diameter. From the test results, bond strength tends to increase with cover thickness. Moreover, bond strength decreases with increasing reinforcing bar diameter. The length of internal crack is evaluated by the assumption of the "elastoplastic stage" in which the perimetric stress around the reinforcing bar is expressed by the summation of "partially cracked elastic stage" and "plastic stage". The length of internal crack is affected by cover thickness rather than the size of specimen.

1 INTRODUCTION

High Performance Fiber-Reinforced Cementitious Composites (HPFRCC), which show a strain hardening branch and multiple cracking under uniaxial tensile stress, have been focused by lots of researchers because of its unique mechanical performance. Engineered Cementitious Composites (ECC) exhibit a maximum tensile strain of several percent owing to the synergetic effect of high-performance fiber and specifically designed mortar matrix (Li, V. C. 1993). Unprecedented high-performance structural members can be expected when ECC is applied to seismic components (Kanda, T. 2006).

It has been cleared that cementitious materials such as concrete show scale effect on their mechanical properties due to size of aggregates, existence of air void, and so on. In addition, it is considered that the fiber in fiber-reinforced cementitious composite causes scale effect which is mainly influenced by fiber orientation. For example, the small size of specimens such as plate type shows higher tensile strength and deformation capacity because of two-dimensional fiber orientation (Kanakubo, T. 2006). If we use some test pieces to check the mechanical properties of ECC, it is necessary to have information about the relationships between properties obtained by test pieces and those in actual structures.

This paper describes the test results of the pullout test to obtain the local bond behavior between ECC and steel reinforcing bar. There is a possibility that the size of cover thickness of ECC around reinforcing bar affects the orientation of fiber as shown in Fig.1, so bridging performance of fiber at the splitting crack is influenced by specimen size. To evaluate the size effect, similar specimens using several diameters of reinforcing bars with same ratio of cover thickness to bar diameter are tested. The test results are mainly discussed in bond strength by stress of ECC.

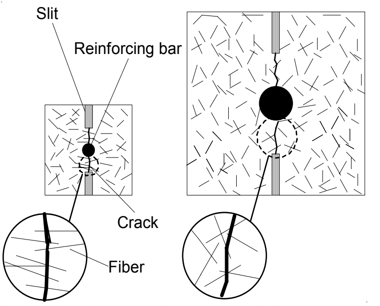

Fig.1 Fiber orientation according to size difference

2 EMPLOYED MATERIALS

Table.1 shows the characteristics of PVA (Polyvinyl Alcohol) fiber used in this study. The binders are ordinary Portland cement and fly ash. Fine aggregate is silica sand. The volume fraction of PVA fiber is

2.0%. Specimen is cast continuously to avoid the discontinuity of fiber. Table.2 shows the characteristics of ECC used in this study. Tensile strength and ultimate strain is calculated by 4-point bending test according to JCI-S-003-2007 (JCI. 2007).

Fig.2 shows bending moment and curvature curves obtained from the experiment. The deflection hardening behavior in which the load increases after first cracking can be recognized from the results shown in Fig.2.

Table.3 shows the characteristics of reinforcing bar. The data of D22 was not obtained by data error. In the experiment of this study, the reinforcing bar does not yield.

Table.1 Characteristics of PVA fiber

Length (mm)	Diameter (mm)	Tensile strength (MPa)	Elastic modulus (GPa)
12.0	0.04	1690	40.6

Table.2 Characteristics of ECC

Fiber volume fraction (%)	Tensile strength* (MPa)	Ultimate strain* (%)	Compressive strength (MPa)	Elastic modulus (GPa)
2.0	4.24	1.25	47.9	16.2

* By 4-point bending test (JCI-S-003-2007)

Table.3 Characteristics of reinforcing bar

Type of bar	Yield strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)
D10	378	533	192
D13	369	543	193
D16	442	665	190
D22			190*

*: value of D16

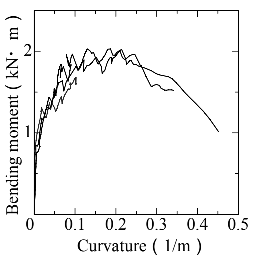

Fig.2 Bending moment and Curvature curves

3 SPECIMENS

The shape of specimen is shown in Fig.3. The slits are set in the two side of specimen to cause splitting cracks around reinforcing bar. The parameters of specimens are reinforcing bar diameter (d_b=10, 13, 16, 22 mm) and cover thickness (C). Cover thickness is adjusted by the size of slit.

Three specimens are tested for each parameter, and total number is 48. Specimen list is shown in Table.4. To investigate the size effect of bond behavior between ECC and reinforcing bar, size of specimen is proportionate to the diameter of reinforcing bar. Sectional size of specimen is set to square by 14 times of reinforcing bar diameter, and bond length is 4 times of the bar diameter. The other parameter is cover thickness, which is set to 0.5 – 2.0 times of reinforcing bar diameter. At the both ends of reinforcing bar of 1.5 times of the bar diameter, the bar is covered by Teflon sheet to insulate the bond to ECC.

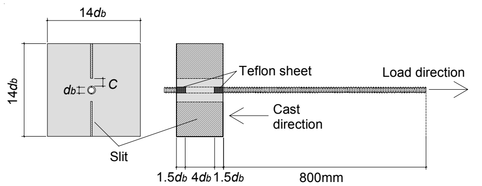

Fig.3 Shape of specimen

Table.4 Specimen list

Name of specimen		Diameter d_b (mm)	Sectional size (mm)	C/d_b	Cover thick-ness C (mm)
D10-05-	1~3	10	140×140	0.5	5
D10-10-	1~3			1.0	10
D10-15-	1~3			1.5	15
D10-20-	1~3			2.0	20
D13-05-	1~3	13	182×182	0.5	6.5
D13-10-	1~3			1.0	13
D13-15-	1~3			1.5	19.5
D13-20-	1~3			2.0	26
D16-05-	1~3	16	224×224	0.5	8
D16-10-	1~3			1.0	16
D16-15-	1~3			1.5	24
D16-20-	1~3			2.0	32
D22-05-	1~3	22	308×308	0.5	11
D22-10-	1~3			1.0	22
D22-15-	1~3			1.5	33
D22-20-	1~3			2.0	44

4 LOADING AND MEASUREMENTS

Fig.4 shows the method of loading. The loading is conducted by monotonic pullout test. Teflon sheet is set between specimen and support plate to not restrict lateral displacement of ECC block. Measurement items are pullout load and free end slippage. (Refer to the Fig.4 for the meaning of "load end" and "free end".)

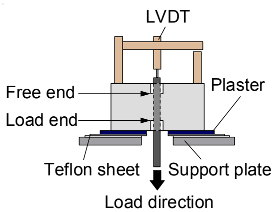

Fig.4 Method of pullout test

5 TEST RESULTS

Fig.5 shows the examples of sketch of specimens after loading. In case of the small cover thickness, splitting cracks were recognized between reinforcing bar and the slit at the load end.

The reinforcing bar diameter increases, the tendency that the splitting cracks took place through both slits is observed. The observed crack of load end is more remarkable than free end.

Fig.6 shows the relationship between bond stress and load end slippage (τ-s relationship). Bond stress is the average value of bonding surface area. The load end slippage is calculated by free end slippage adding elongation of reinforcing bar under the uniform bond stress assumption. After the maximum bond stress, the bond stress decreases gradually without sudden failure. The slope of decrement of bond stress becomes larger as the maximum bond stress increases.

Fig.7 shows the relationship between bond strength (τ_{max}) and reinforcing bar diameter. In all cases, bond strength decreases with increasing reinforcing bar diameter. Fig.8 shows the relationship between the bond strength and cover thickness. Bond strength tends to increase with cover thickness. The size of reinforcing bar seems to not so effect on the increasing ratio.

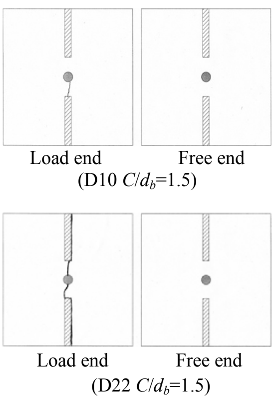

Fig.5 Splitting crack after loading

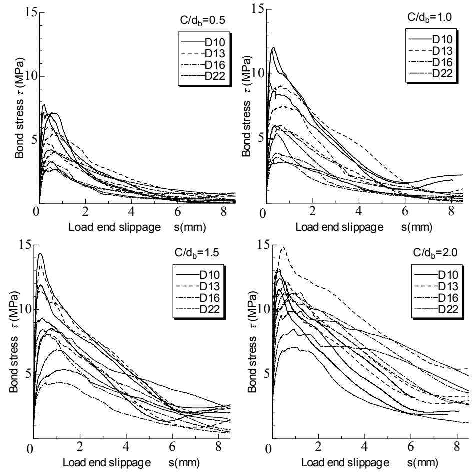

Fig.6 Bond stress and load end slippage curves

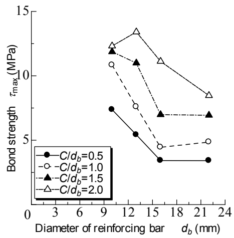

Fig.7 τ_{max}-d_b relation

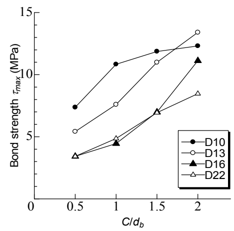

Fig.8 τ_{max}-C/d_b relation

6 SIZE EFFECT ON BOND STRENGTH

It is known that the size effect of HPFRCC is expressed by the power of the highly-stressed volume (Yamada, K. 2001). In this paper, the evaluation of size effect for bond strength is conducted quantitatively by the result of pullout test.

The highly-stressed volume in pullout test is defined as the volume of a cylindrical column as shown in Fig.9.

Fig.10 shows the relation between the normalized bond strength and the normalized highly-stressed volume. The bond strength is standardized by bond strength of D10 specimen. Similarly, the highly-stressed volume is standardized by volume of D10 specimen. As for specimen of each ratio of cover thickness to diameter of reinforcing bar, the normalized bond strength decreases with increasing of normalized highly-stressed volume. However, the united evaluation to all specimens is difficult. It may be considered that other indexes which represent stress condition of ECC around the reinforcing bar will be required.

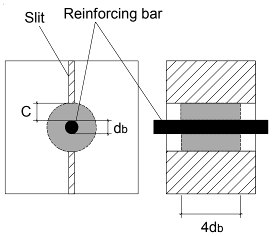

Fig.9 Definition of highly-stressed volume

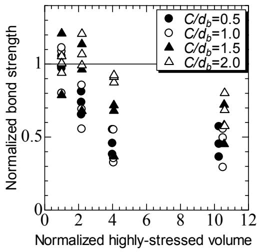

Fig.10 Normalized bond strength-normalized highly-stressed volume relation

In the case of ordinary reinforced concrete, Tepfers modeled the stress state in the circumference of a reinforcing bar in a hollow cylinder as shown in Fig.11, and calculated bond splitting strength (Tepfers, R. 1982). The perimetric stress has been assumed in three cases; (a) partially cracked elastic stage, (b) elastic stage and (c) plastic stage. Tepfers concluded that the bond splitting strength ranges between partially cracked elastic stage and plastic stage in case of ordinary concrete.

In the case of ECC, it is considered that the tensile stress after cracking takes place due to bridging effect of fiber. So, the perimetric stress in the circumference of the reinforcing bar in ECC is assumed as (d) elastoplastic stage. The bond strength (τ_{max}) is expressed by formula (1) as the summation of partially cracked elastic stage and plastic stage. The value of r_i represents the length of internal cracks.

In this study, the value of r_i is confirmed by reverse calculation from experimental bond strength using Formula (1). The value of cotα is assumed as the same value with ordinary concrete (Sakai, T., 1999). It the value of r_i exceeds r_u, r_i is fixed as r_u.

Fig.12 shows the relationship between the r_i and diameter of reinforcing bar. As for specimen of each ratio of cover thickness to diameter of reinforcing bar, r_i increases with increasing of diameter of reinforcing bar. However, the tendency is not remarkable.

Fig.13 shows the relationship between the r_i and cover thickness. As for all specimens, the r_i increases with increasing of cover thickness. The line shown in the figure is calculated by the least-square method and Formula (2) is obtained. As shown in Fig.14, this result leads that the length of internal crack is not sensitive to the size of specimen.

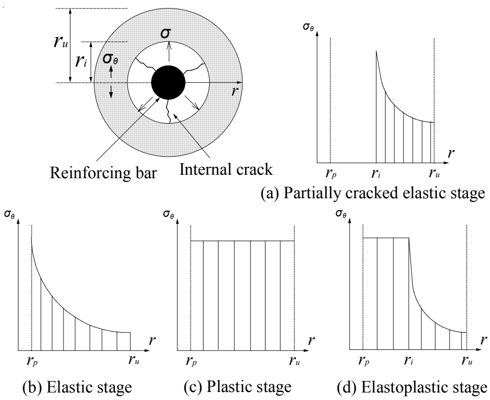

Fig.11 The state of the circumference stress of reinforcing bar

$$\frac{\tau_{\max}}{\sigma_t}=\frac{2}{d_b}\left\{(r_i-r_p)+\frac{r_i(r_u^2-r_i^2)}{r_u^2+r_i^2}\right\}\cot\alpha \tag{1}$$

r_i : Plastic zone length around reinforcing bar (mm)
r_u : $r_u = d_b/2+C$
r_p : $r_p = d_b/2$
σ_t : Tensile strength of ECC
d_b : Diameter of reinforcing bar
C : Cover thickness
α : Angle between splitting force to axial direction =34degree

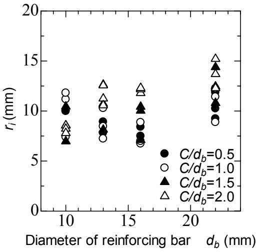

Fig.12 r_i-d_b relation

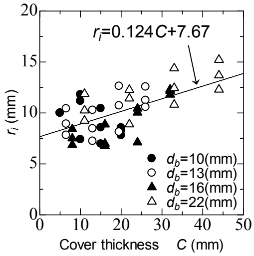

Fig.13 r_i -C relation

$$r_i = 0.124C + 7.67 \tag{2}$$

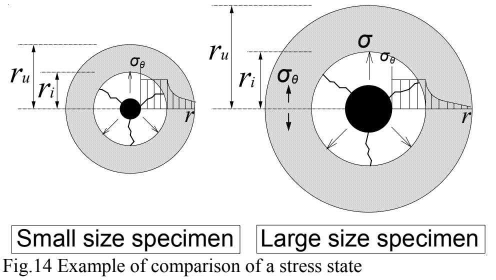

Fig.14 Example of comparison of a stress state

The length of internal crack is seemed to be affected by cover thickness, and it is suggested that stress transfer in the reinforcing bar circumference is determined by cover thickness.

Fig.15 shows the relationship between the experimental value and the calculated value of bond strength. The experimental values are averaged for three same specimens. The calculated value is obtained by Formulas (1) and (2). The calculated values well correspond to the experimental values.

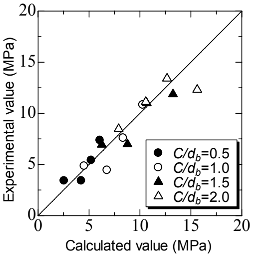

Fig.15 Experimental value-Calculated value relation of bond strength

7 CONCLUSIONS

1. In case of the small cover thickness, splitting cracks were recognized between reinforcing bar and the slit.
2. The size effect is clearly recognized on the bond strength by the ratio of cover thickness to diameter of reinforcing bars.
3. From the result of evaluation of bond strength using highly-stressed volume, the normalized bond strength decreases with increasing of normalized highly-stressed volume.
4. The length of internal crack is evaluated by the assumption of the elastoplastic stage in which the perimetric stress is expressed by the summation of partially cracked elastic stage and plastic stage. The length of internal crack is affected by cover thickness rather than the size of specimen.

ACKNOWLEDGEMENTS

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