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Evaluation of the bond properties between concrete and reinforcement as a function of the degree of reinforcement corrosion

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Abstract

In order to investigate the effect of reinforcement corrosion on the bond properties between concrete and reinforcement, the pullout tests were conducted using reinforcements embedded in concrete specimens, which were corroded by an accelerated electric corrosion method. A finite element method (FEM) analysis was also carried out on the basis of the results of the pullout tests. The maximum bond strength (τ_{max}) and the bond rigidity (D_s) of specimens decreased in proportion to the increase of corrosion percentage (Δ_w), respectively. Also, the curves of bond stress–free end slip could be analyzed by the FEM, if the τ_{max} and D_s were determined as a function of corrosion percentage. The equations for calculating the maximum bond strength and the bond rigidity necessary for an FEM analysis of RC members with corroded reinforcements were obtained by the experiments and the FEM analysis of the pullout tests.

Keywords: Reinforcement corrosion; Bond property; Finite element analysis; Pullout test; Durability

1. Introduction

Losses in the structure performance of reinforced concrete members with corroded reinforcements are caused by losses in the effective cross-sectional area of concrete due to cracking in the cover concrete, losses in the mechanical performance of reinforcements due to the losses in their cross-sectional area, and losses in the bond performance of concrete with reinforcements [1–5].

On the other hand, in case the main reinforcement is corroded, the strength of RC structure damaged by reinforcement corrosion cannot be evaluated by conventional cross-section analysis of RC structures not only because of reduction of the bond strength and bond rigidity between corroded reinforcement and concrete, but also because of reduction of the mechanical properties of reinforcement due to their reduced cross-sectional areas [6,7]. Thus, it is needed to find a new evaluation method for the strength of RC structures damaged by reinforcement corrosion considering reduction of bond properties and mechanical properties of corroded reinforcement [8]. Accordingly, if material models representing the relationships between the degree of reinforcement corrosion and the bond properties and mechanical properties of corroded reinforcements can be obtained experimentally, we think it is possible to analyze the strength of RC structures damaged by reinforcement corrosion by the finite element method (FEM), one of the structural analysis methods for sound RC members [9,10].

The purpose of this study is to investigate the relationship between the degree of reinforcement corrosion and the bond properties, the maximum bond strength (τ_{max}) and the bond rigidity (D_s), as a function of the degree of reinforcement corrosion (Δ_w).

2. Constitutive law for bond elements between corroded reinforcements and concrete

There are methods of expressing the bonding in which bond link elements or bond interface elements are applied to the boundary between the reinforcement and concrete. Bond elements consist of the maximum bond strength (τ_{max}) and bond rigidity (D_s) as shown in Fig. 1. Accordingly, the constitutive laws for bond elements can be obtained by

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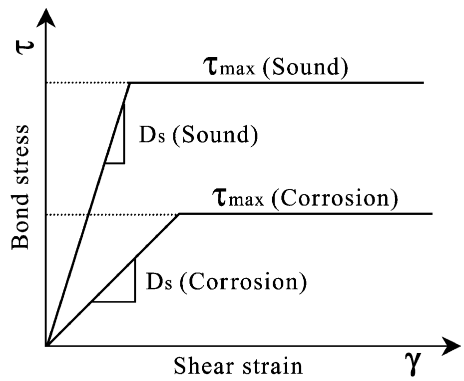

Fig. 1. Constitutive laws for bond element.

determining τ_{max} and D_s using the degree of reinforcement corrosion as a parameter. In the FEM analysis, bond elements were expressed by changing the maximum bond stress and bond rigidity, assuming that reinforcement corrosion causes no cracks in cover concrete, as shown in Fig. 2.

3. Experimental

3.1. Factors and levels of experiment

The main aim of these experiments is to evaluate the effects of reinforcement corrosion on the bond behavior between corroded reinforcement and reinforcement. The bond properties were also influenced on the compressive strength, lateral reinforcement and concrete cover. Table 1 shows the factors and levels of these experiments. In the experiments, pullout tests were conducted at different degrees of reinforcement corrosion.

3.2. Mechanical property of reinforcement and mix proportion of concrete

Table 2 shows the mechanical properties of reinforcement. Also, the mixing proportion of concrete and the mechanical properties of concrete are shown in Tables 3 and 4, respectively.

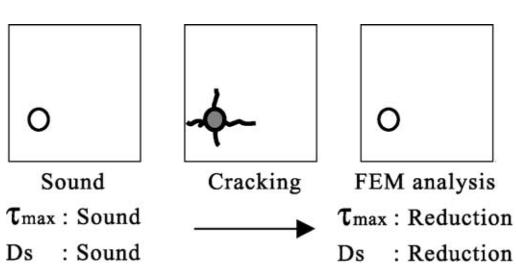

Fig. 2. Expression of bond in FEM analysis.

Table 1
Factors and levels of experiment

Factors	Levels
Strength of concrete	W/C: 65%, 55%, 45%
Concrete cover	1.5D, 2.5D, 3.5D
	(D: diameter of reinforcement)
Lateral reinforcement	None, reinforcement
Level of corrosion	No corrosion (0%)
(5 levels)	At the time of cracks (3%)
(%):	0.4 mm (15%), 0.5 mm (20%)
Corrosion percentage	0.6 mm (30%)

Table 2
Mechanical properties of reinforcement

Type	Yield point (N/mm^2)	Tensile strength (N/mm^2)	Elastic modulus (N/mm^2)	Elongation (%)
SD 295A D13	315	452	183,384	21.0

Table 3
Mix proportion of concrete

No.	W/C (%)	Slump (cm)	Unit weight (kg/m^3) W	C	S	G	Cl^-
1	45	18	185	411	657	1023	6
2	55	18	185	336	718	1023	6
3	65	18	185	285	776	1007	6

Table 4
Mechanical properties of concrete

W/C (%)	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)	Poisson's ratio (%)
45	42.1	3.6	25.5	0.19
55	33.0	3.2	23.5	0.17
65	24.7	2.7	22.6	0.17

3.3. Accelerated corrosion method of reinforcement

The shape of the specimen is shown in Fig. 3. The electrolytic corrosion method is shown in Fig. 4. The level of corrosion was controlled by impressing direct current of 1 A on the specimens for specified periods using a constant

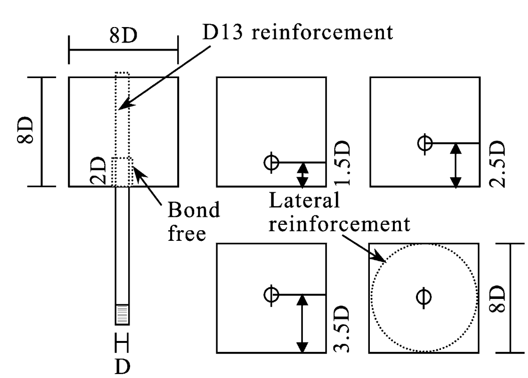

Fig. 3. The shape of the specimen.

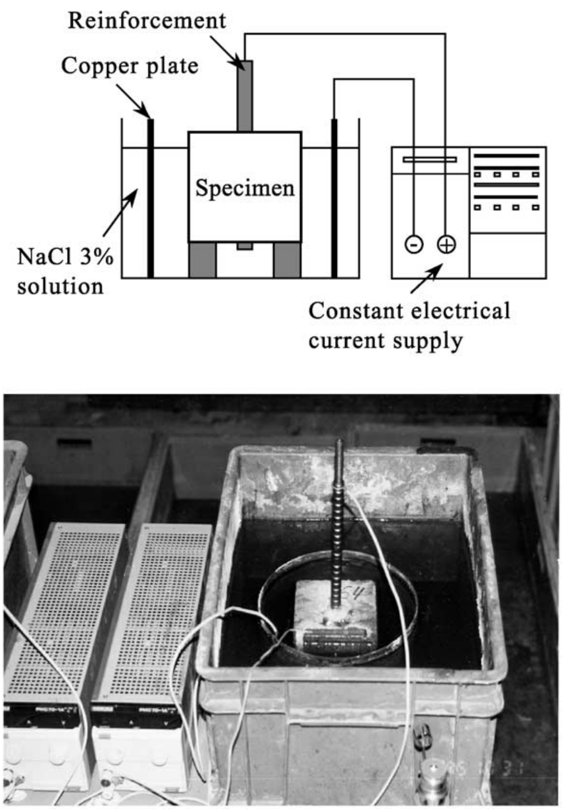

Fig. 4. Electric corrosion method.

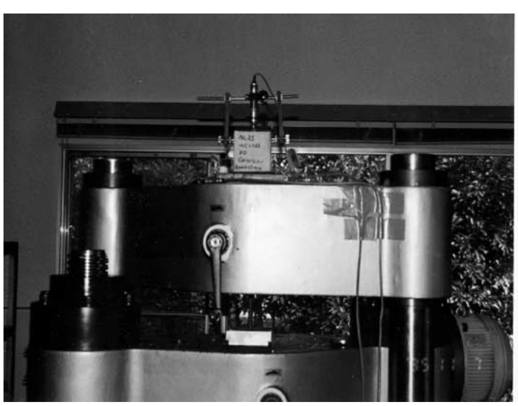

Fig. 5. Pullout test system.

electrical current supply. The current was so arranged that the reinforcement embedded in the specimens and a copper plate, both immersed in water, served as the anode and cathode, respectively. The corrosion percentage was determined by measuring the weight of the reinforcements after removing the rust with 10% diammonium hydrogen citrate.

3.4. Pullout test and measurement items

Fig. 5 shows the pullout test system. The load and free end slip were recorded for each loading level during the test. The bond stress was calculated from the external loads on the reinforcement and surface area of the embedded portion of the reinforcement, thereby representing an average stress along the bonded length of the reinforcement.

4. Results and discussion

4.1. Failure mode and bond stress–end slip curves

Cracking of cover concrete due to reinforcement corrosion occurred on the surface of specimen. Figs. 6 and 7

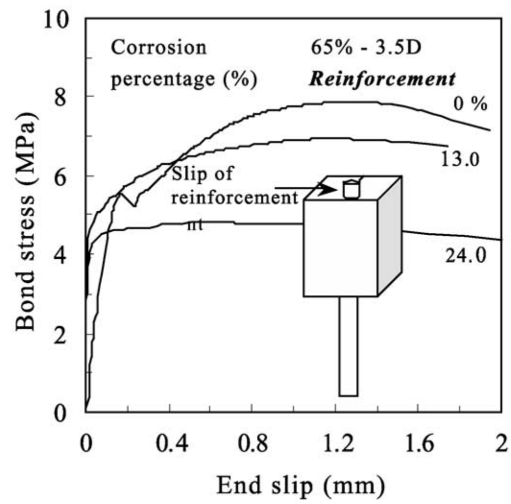

Fig. 6. Bond stress–end slip curves (reinforcement).

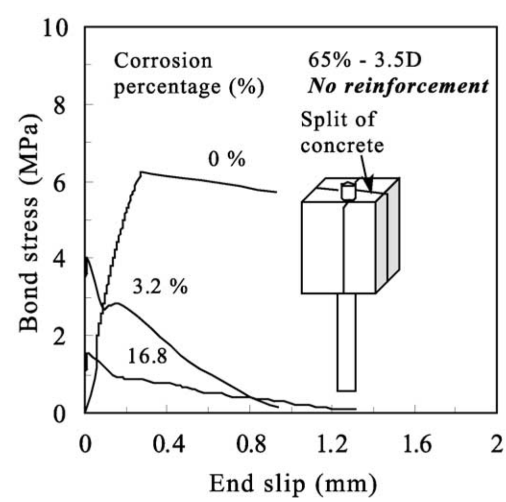

Fig. 7. Bond stress–end slip curves (no reinforcement).

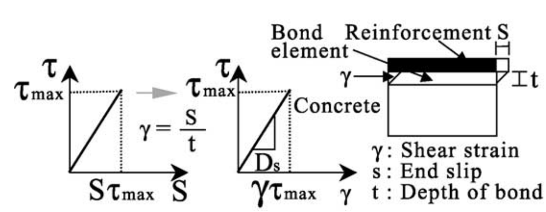

Fig. 8. Calculation method of τ_{max} and D_s in bond interface element.

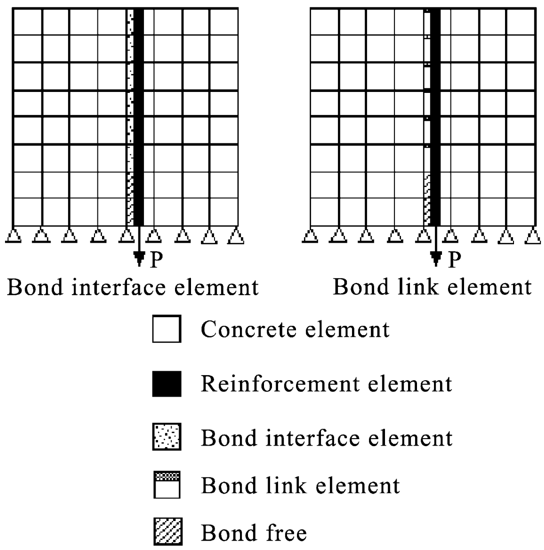

Fig. 9. Mesh for FEM analysis of pullout test.

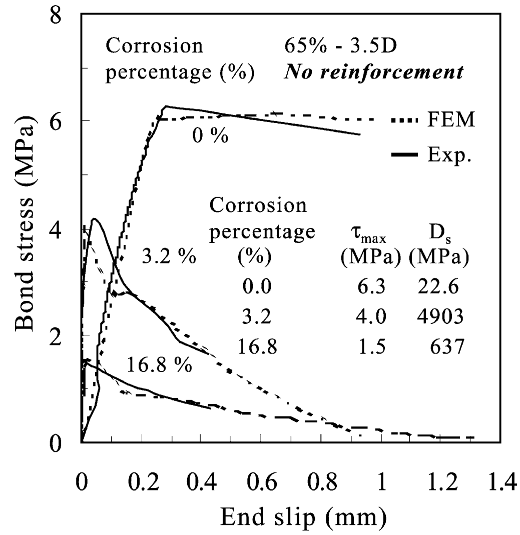

Fig. 11. Bond stress–end slip curves (back-analysis).

show the failure mode and bond stress–end slip curves, respectively. The maximum bond strength of laterally unreinforced specimens was abruptly lost by the split of concrete along the crack due to the reinforcement corrosion. The remaining bond stress after the maximum bond strength of laterally reinforced specimens was larger than those of laterally unreinforced specimens even though there was a crack due to reinforcement corrosion, because the laterally reinforcement prevented the split of concrete. As the corrosion percentage increased, the maximum bond stress rapidly decreased. From the survey of RC structures deteriorated by reinforcement corrosion in the field, it can be said that the influence of lateral reinforcement on the bond properties is small when the main reinforcement was severely corroded in flexural RC members.

4.2. Calculation method of τmax and Ds

The maximum bond stress (τ_{max}) was obtained by dividing the maximum tensile load by the bond area of reinforcement. First of all, the shear strain (γ) was obtained by dividing the end slip (*S*) by the depth of bond element (this study: 1 mm), as shown in Fig. 8. And then, the bond rigidity (D_s) was calculated by dividing the maximum bond stress (τ_{max}) by the shear strain (γ) at the maximum bond stress.

4.3. FEM analysis of pullout test

The bond link element or bond interface element is used as a bond element in FEM analysis as shown in Fig. 9. Fig. 10 shows the results of analysis. The analysis results

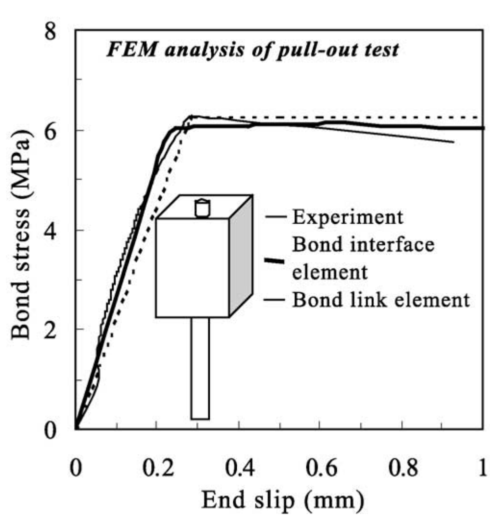

Fig. 10. Bond stress–end slip curves (FEM analysis).

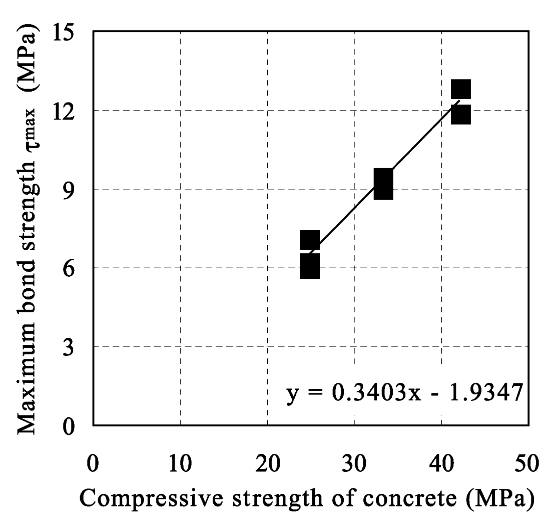

Fig. 12. Relationship between compressive strength of concrete and the maximum bond strength (sound specimen).

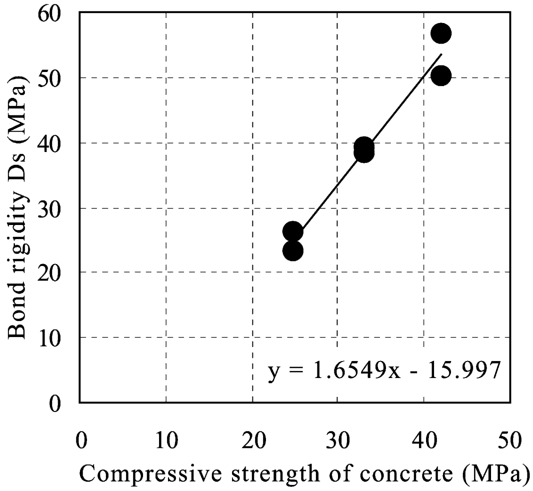

Fig. 13. Relationship between compressive strength of concrete and bond rigidity (sound specimen).

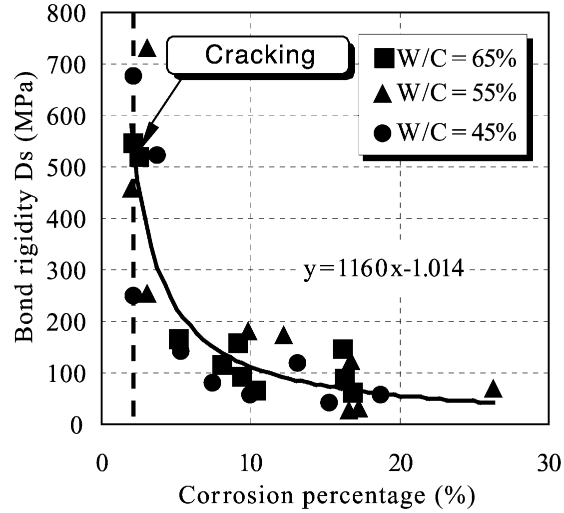

Fig. 15. Relationship between corrosion percentage and bond rigidity (corroded specimen).

agreed well with the results of the experiment. It was found that there was no difference between bond link element and bond interface element.

In order to conduct an FEM analysis of RC members using the changes of bond properties due to reinforcement corrosion, the pullout test was back-analyzed by the FEM using a bond interface element. Fig. 11 shows the results of FEM analysis using τ_{max} and D_s obtained from the experiment. The FEM analysis results agreed well with the results of the experiment. Thus, the optimum values of τ_{max} and D_s can be obtained by FEM analysis.

4.4. Relationship between the bond properties (τmax and Ds) and the corrosion percentage (Δw)

Fig. 12 shows the relationship between compressive strength of concrete and the maximum bond strength in the case of sound specimen ($\Delta_w = 0$) with no lateral reinforcement. Also, Fig. 13 shows the relationship between compressive strength of concrete and the bond rigidity in the case of sound specimen. As the compressive strength of concrete increased, the maximum bond strength and bond rigidity increased. Also, there were very high correlations between compressive strength of concrete and bond properties.

Fig. 14 shows the relationship between the corrosion percentage of corroded reinforcement and the maximum bond strength in case of no lateral reinforcement. Also, Fig. 15 shows the relationship between corrosion percentage of corroded reinforcement and bond rigidity. As the corrosion percentage increased, the maximum bond strength decreased. Also, as the corrosion percentage increased, the bond rigidity decreased rapidly. The corrosion percentage correlated well with the maximum bond strength and the bond rigidity. Accordingly, the maximum bond strength and the bond rigidity necessary for an FEM analysis of RC members with corroded reinforcements can be calculated using Table 5 only by measuring the corrosion percentage of corroded reinforcement.

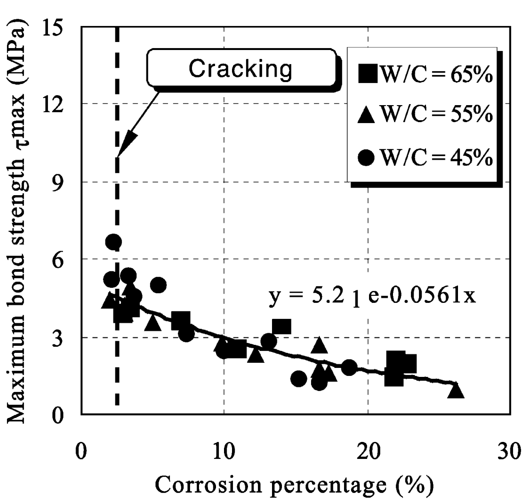

Fig. 14. Relationship between corrosion percentage and maximum bond strength (corroded specimen).

Table 5
Equations for bond properties of reinforcement as function of corrosion percentage

Corrosion percentage (%)	Maximum bond strength (τ_{max}) (MPa)	Bond rigidity (D_s) (MPa)
$\Delta_w < \Delta_{wc}$	$\tau_{max} = 0.34\sigma_B - 1.93$	$D_s = 16.5\sigma_B - 160$
$\Delta_w \geq \Delta_{wc}$	$\tau_{max} = 5.21e^{-0.0561\Delta w}$	$D_s = 1160\Delta_w^{-1.014}$

σ_B: Compressive strength of concrete.
Δ_{wc}: Corrosion percentage at cracking (%).
Δ_w: Corrosion percentage (%).

5. Conclusions

In order to investigate the effect of reinforcement corrosion on the bond properties, the maximum bond strength (τ_{max}) and bond rigidity (D_s), between concrete and reinforcement, the pullout tests were conducted using reinforcements embedded in concrete specimens. The results obtained from these experiments and FEM analyses are as follows:

(1) Whereas the specimens with no lateral reinforcement incurred brittle failure from increasing of cracks due to reinforcement corrosion, the specimens with lateral reinforcement were fractured by slipping of reinforcement because of confinement effect.

(2) It was found that there was no difference between bond link element and bond interface element in the analysis of pullout test by FEM analysis.

(3) From back-analyzed pullout test by the FEM using bond interface element, the FEM analysis results agreed well with the results of the experiment. Thus, the optimum values of the maximum bond strength (τ_{max}) and the bond rigidity (D_s) can be obtained by FEM analysis.

(4) As the compressive strength of concrete in case of sound specimens increased, the maximum bond strength (τ_{max}) and bond rigidity (D_s) increased. Also, there were very high correlations between compressive strength of concrete and bond properties.

(5) In the pullout tests of corroded specimens, the maximum bond strength (τ_{max}) and the bond rigidity (D_s) of specimens decreased in proportion to the increase of corrosion percentage (Δ_w), respectively.

(6) The corrosion percentage (Δ_w) correlated well with the maximum bond strength (τ_{max}) and the bond rigidity (D_s). Accordingly, the maximum bond strength (τ_{max}) and the bond rigidity (D_s) necessary for an FEM analysis of RC members with corroded reinforcements can be calculated using the Table 5 only by measuring the corrosion percentage (Δ_w) of corroded reinforcement.

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