D.20

STUDY ON LOCAL BOND BEHAVIOR BETWEEN CORRODED REINFORCEMENT AND CONCRETE

T.Kanakubo[1]- Dr.E . Associate Professor, **M.Oyado[2]-** Dr.E. Senior Research Engineer,

Y.Saito[3]- M.Eng. Design Engineer

[1]Institute of Engineering Mechanics and Systems, University of Tsukuba, Tsukuba-city, Japan

[2]Structures Technology Division, Railway Technical Research Institute, Kokubunji, Japan

[3]Shimizu Corporation, Tokyo, Japan

ABSTRACT*: It is important to confirm the safety performance of existing reinforced concrete (RC) structures, especially when they are damaged by corrosion. It is considered that strength and deformation capacity of RC members decreases due to the corrosion of reinforcements. This paper aims to present the fundamental properties of local bond behavior between corroded reinforcement and concrete. In this study, the concrete block specimen with a bond length of four times of the diameter of reinforcement is used. One deformed steel reinforcement is inserted into the center of the specimen. This specimen is subjected to pullout load in order to determine the local bond performance between reinforcement and concrete. The test parameters are thickness of cover concrete and the level of corrosion. The corrosion level is controlled by the term of electrolytic corrosion.*

From the loading test results, relationships between bond strength and weight reduction ratio of reinforcement up to 7% can be recognized. The internal cracks which occur due to corrosion are evaluated by photographic analysis. It is considered that the internal cracks make bond strength lower in case of splitting failure of concrete.

KEYWORDS: reinforced concrete, corrosion, internal crack, rust, bond splitting.

1. INTRODUCTION

It is important to confirm the safety performance of existing reinforced concrete (RC) structures, especially when they are damaged by corrosion. It is considered that strength and deformation capacity of RC members decreases due to the corrosion of reinforcements. Until now, many researches have been carried out for evaluating structural performance of non-corroded RC structures. However, no evaluating method or assessment procedure has been proposed to the corroded RC members because of the lack of experimental data and related information. This paper aims to present the fundamental properties of local bond behavior between corroded reinforcement and concrete.

Bond behavior between reinforcement and concrete has a large influence to structural behavior of RC. The reduction of bond capacity causes decrement of load capacity, deformation capacity and energy absorption behavior for RC member. It has been considered that the corrosion of reinforcement causes cracks of concrete around reinforcement and peeling down of cover concrete. Lots of previous studies concerning bond behavior between corroded reinforcement and concrete had been carried out [1]. These studies had reported two typical experimental results.

The first one is the case that bond strength increases with the corrosion occurrence, and the other is the case that the strength decreases with large level of corrosion. It has been considered that production due to rust causes volume expansion and then confinement effect increases bond strength in the case of low level corrosion. In the case of high level corrosion, cracks around the reinforcement occur and these cracks and volume reduction of reinforcement itself cause the decrement of bond strength.

In this study, the fundamental properties of local bond behavior between corroded reinforcement and concrete are investigated using the concrete block specimen with a bond length of four times of the diameter of reinforcement. The corrosion of reinforcement is introduced by electrolytic corrosion process.

2. TEST OUTLINE

2.1. Specimen

The specimen is shown in Fig.1. The specimen with the bond length of four times of the diameter of reinforcement (d_b) is concrete block inserted one reinforcement. The dimensions of specimen are $14d_b$ x $14d_b$ x $7d_b$ in rectangle. To represent concrete cover, the slits are inserted at both sides of concrete block. The cover thickness (C) is controlled by the width of slits. The test parameters are thickness of cover concrete and level of corrosion. The thickness is set to 1.5, 2.5 and 3.5 times of reinforcement diameter (C/d_b=1.5, 2.5, 3.5).

The corrosion is introduced by electrolytic accelerated corrosion process using DC power supply as shown in Fig.2. The specimen is put into the water tank filled with 3% NaCl solution and reinforcement is connected with the anode of the power supply. The copper plates which are inserted into the water tank are connected with the cathode. The level of corrosion is controlled by the term of electricity time under 0.03A constant current. The lowest level of corrosion (L1.0) is given by 116 hour electricity time and the upper levels of corrosion (L1.5 – L4.0) are set by 1.5 to 4 times of electricity time of L1.0 corrosion. The bottom of reinforcement is not to be contact with solution by clay as shown in Fig.2. When the bond test is terminated, the level of corrosion is estimated by the weight reduction ratio to its original weight of reinforcement.

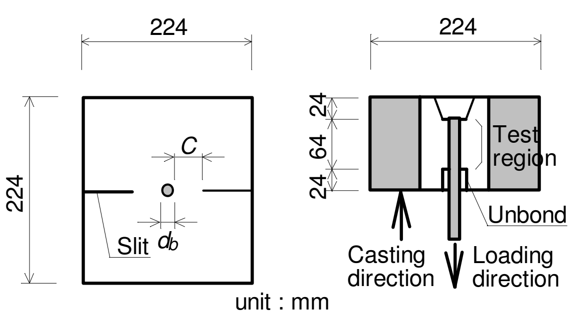

Fig.1- Bond specimen

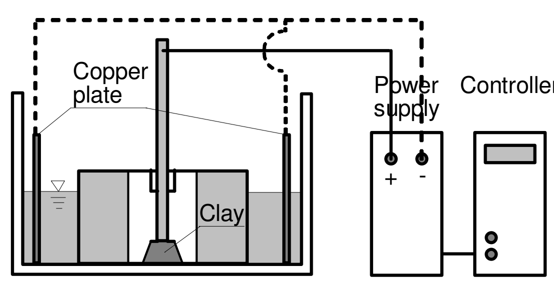

Fig.2- Electrolytic accelerated corrosion process

2.2. Materials

The deformed steel bar with the specific diameter of 16mm (D16) is used for reinforcement. The yield strength and elastic modulus of D16 is 383MPa and 180GPa, respectively. Normal concrete with the target compressive strength of 27MPa is utilized. The compression test results of test pieces (100ϕ-200mm cylinder) at the age of bond test show 30.9MPa of compressive strength and 2.40MPa of tensile splitting strength.

2.3. Loading and measurement

The specimen after electrolytic accelerated corrosion process is provided to bond test. The loading and measurement method is shown in Fig.3. The reinforcement is subjected to monotonic pullout loading. The specimen is set on the Teflon sheets and the loading plate on which the hole with same diameter corresponding to concrete cover not to restrict the lateral deformation of concrete. The measurement items are pullout load and slippage of reinforcement at the free end by LVDT.

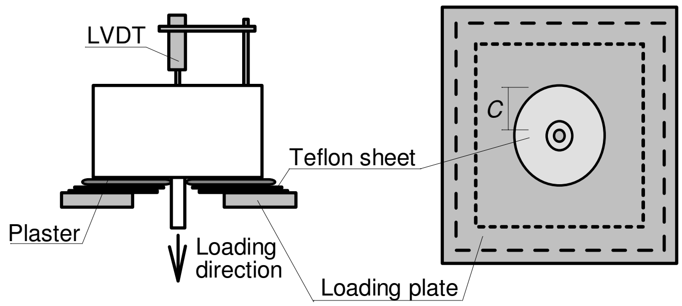

Fig.3- Loading method

3. TEST RESULTS

3.1. Electrolytic corrosion process

In the electrolytic corrosion process, occurrence of rust from the bottom of specimen and the top part of reinforcement was observed. Also cracks took place from the reinforcement to the position of slit at the concrete surface. Fig.4 shows examples of the splitting surface after bond test. The rust can be observed on the splitting surface position by position. However, it can not be recognized any relationship between the level of corrosion or thickness of cover concrete and the penetration of rust into splitting surface.

The ratio of weight reduction to the original weight of reinforcement (*R*) is determined by the weight measurement after bond test. The results are summarized in Table 1. It is generally recognized that weight reduction ratio (*R*) becomes larger as the level of corrosion (electrolytic corrosion time) increases.

The reason that there is no direct relation between weight reduction ratio and penetration situation of rust into splitting surface would be considered that corrosion of reinforcement proceeds at the local area of reinforcement. Fig.5 shows the example of the reinforcement after removing rust. Localized corrosion can be observed at the top of the concrete surface.

Table 1- Weight reduction ratio

Specimen Corrosion level – Cover concrete	Weight reduction	Specimen Corrosion level – Cover concrete	Weight reduction	Specimen Corrosion level – Cover concrete	Weight reduction
L1.0-C1.5	2.48%	L1.0-C2.5	3.40%	L1.0-C3.5	1.87%
L1.5-C1.5	4.54%	L1.5-C2.5	4.95%	L1.5-C3.5	4.62%
L2.0-C1.5	7.08%	L2.0-C2.5	5.06%	L2.0-C3.5	4.14%
L3.0-C1.5	12.11%	L3.0-C2.5	11.57%	L3.0-C3.5	8.46%
L4.0-C1.5	13.22%	L4.0-C2.5	12.90%	L4.0-C3.5	10.02%

L1.0 L1.5 L2.0 L3.0 L4.0

Fig.4- Examples of splitting crack (C/d_b=1.5)

Fig.5- Localized corrosion

3.2. Pullout bond test

All specimens failed by bond splitting due to cracks between reinforcement and slits. Bond stress versus free end slippage relationships are shown in Fig.6. The bond stress is calculated from pullout load divided by surface area of reinforcement which is multiplication of bond length (64mm) and specific perimeter (50mm). The maximum bond stress is shown in Table 2. The maximum bond stress is standardized by calculated bond splitting strength reported in previous study [2] as non-corroded specimen using Eq.(1).

$$\tau_{b,\max} = 0.601 \cdot \sigma_t \cdot \frac{r_u}{d_b} \cdot \cot \alpha \tag{1}$$

Where, $\tau_{b,max}$: bond splitting strength, σ_t : splitting tensile strength of concrete, r_u : $C+d_b/2$, d_b : diameter of reinforcement, C : thickness of cover concrete, α : angle between longitudinal axis and splitting force (=34 degree).

Bond stress – slippage relationships have a tendency that decrement of bond stress after maximum becomes mild in case of high level of corrosion. In some specimens, maximum bond stress is observed at the slippage around 1mm. It would be considered that rust production exists around the reinforcement and bearing force occurs after certain slip of reinforcement.

Table 2- Maximum bond stress

Specimen Corrosion level – Cover concrete	Experi-ment (MPa)	Exp. / Cal.	Specimen Corrosion level – Cover concrete	Experi-ment (MPa)	Exp. / Cal.	Specimen Corrosion level – Cover concrete	Experi-ment (MPa)	Exp. / Cal.
L0.0-C1.5	6.77	1.61	L0.0-C2.5	9.90	1.57	L0.0-C3.5	10.73	1.27
L1.0-C1.5	4.40	1.05	L1.0-C2.5	5.60	0.89	L1.0-C3.5	5.53	0.66
L1.5-C1.5	2.24	0.53	L1.5-C2.5	5.21	0.83	L1.5-C3.5	2.26	0.27
L2.0-C1.5	1.43	0.22	L2.0-C2.5	2.19	0.35	L2.0-C3.5	3.27	0.39
L3.0-C1.5	2.35	0.56	L3.0-C2.5	1.21	0.16	L3.0-C3.5	3.50	0.42
L4.0-C1.5	2.49	0.59	L4.0-C2.5	2.53	0.40	L4.0-C3.5	3.19	0.38

Note : Specimen ID L0.0 means non-corroded specimen

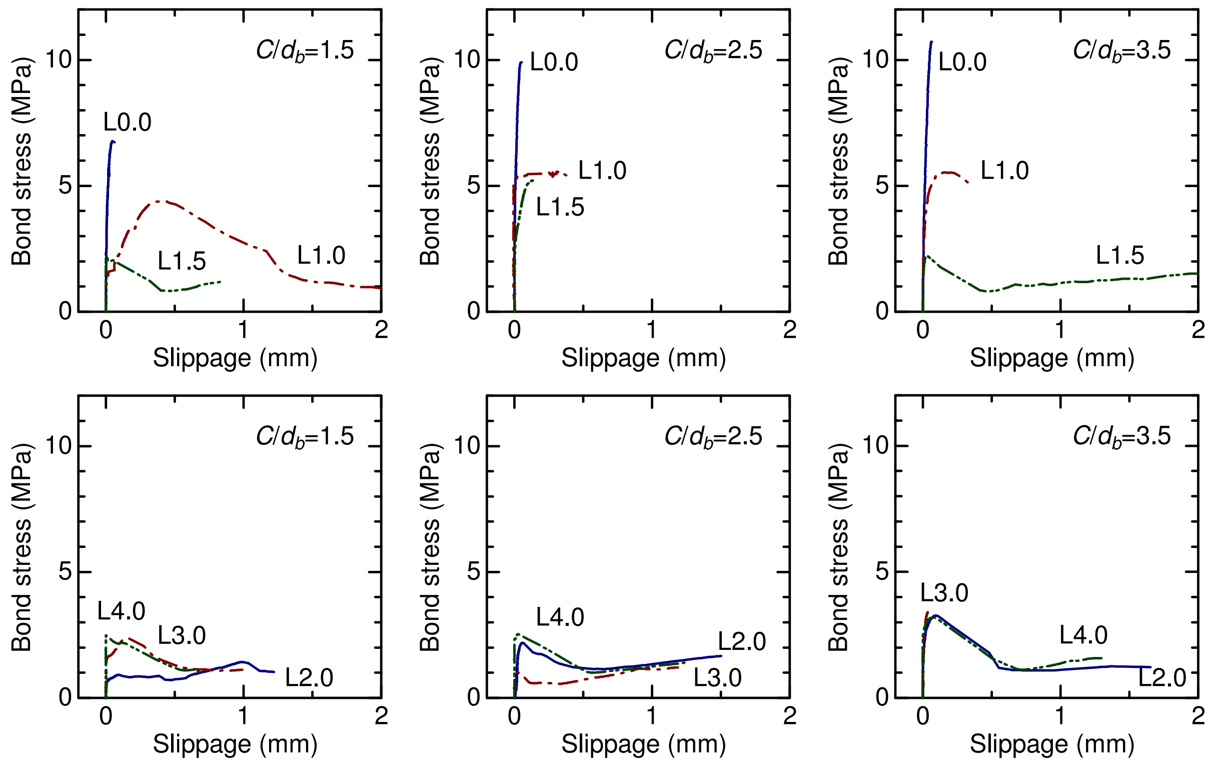

Fig.6- Bond stress – slippage relationship

Maximum bond stress generally decreases as the level of corrosion increases. Fig.7 shows the relationship between standardized maximum bond stress and weight reduction ratio. Up to 7% of weight reduction ratio, maximum bond stress decreases in linear sense with weight reduction ratio. From the regression analysis, the formula shown in the figure can be obtained. However, in the specimen with over 7% weight reduction ratio, no relationship is recognized.

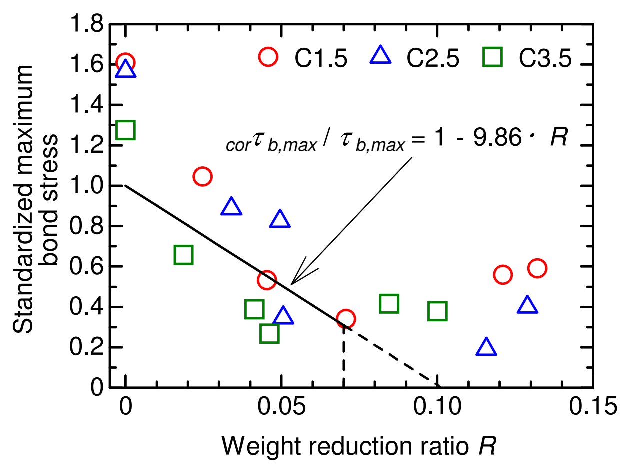

Fig.7- Relationship of weight reduction ratio and maximum bond stress

4. EVALUATION OF BOND STRENGTH BY SPLITTING AREA

4.1. Photographic analysis

As shown in Fig.4, corrosion of reinforcement causes internal cracks of surrounding concrete. It can be considered that splitting surface colored by rust (here after called as "rusted surface") is due to corrosion. In this section, photographic analysis is conducted based on the assumption that bond splitting strength can be estimated by the replacement of cylinder subjected to internal pressure [3].

In non-corroded reinforced concrete, splitting of concrete occurs by ring tension (Fig.8). Bond stress can be estimated by Eq.(2). The maximum value of Eq.(2) is given by Eq. (1) when the value of r_i is equal to $0.486r_u$.

$$\tau_b = \sigma_t \cdot \frac{2r_i}{d_b} \cdot \frac{r_u^2 - r_i^2}{r_u^2 + r_i^2} \cdot \cot\alpha \tag{2}$$

Where, τ_b : bond stress, σ_t : splitting tensile strength of concrete, r_i : internal radius of cylinder, r_u : outer radius of cylinder, d_b : diameter of reinforcement, α : angle between longitudinal axis and splitting force (=34 degree).

It is considered that corrosion of reinforcement already causes internal cracks as shown in Fig.9. So the radius of cylinder which can carry the ring tension has been changed after corrosion. The size of changed radius could be estimated by the size of rusted surface. The size of rusted surface is measured by photographic analysis of splitting surface.

Fig.10 shows the process of the photographic analysis. After the bond test, total of 4 splitting surfaces can be obtained per one specimen. The splitting surfaces are taken by digital camera and the photographs are processed to have two values of RGB in order to distinguish the rusted surface and the other part. The 4 surfaces are summed up and the size of changed radius is estimated by the size of pixels. In this study, the size of one pixel corresponds to 0.1mm. The changed outer radius, r_u' is substituted for r_u of Eq.(1) in the case of $d_b'/2 < 0.486r_u'$. In the case of $d_b'/2 > 0.486r_u'$, r_u' and $d_b'/2$ is substituted for r_u and r_i of Eq.(2), respectively. Then maximum bond stress can be calculated by using changed radius. The size of rusted surface varies along longitudinal axis for one specimen, so the maximum bond stresses calculated by each analyzed pixel line are averaged to express the bond strength of the specimen.

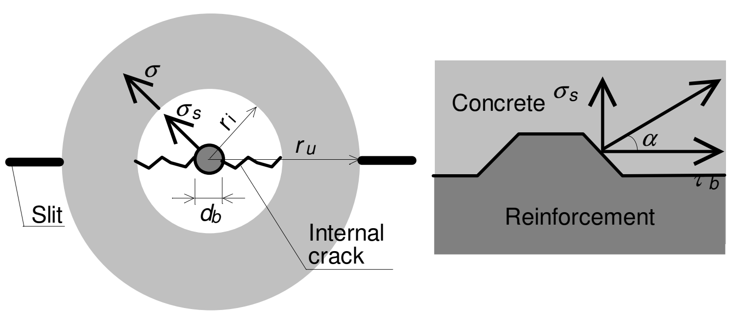

Fig.8- Replacement of cylinder for bond splitting

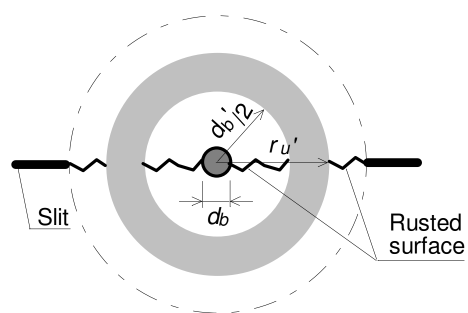

Fig.9- Internal crack by corrosion

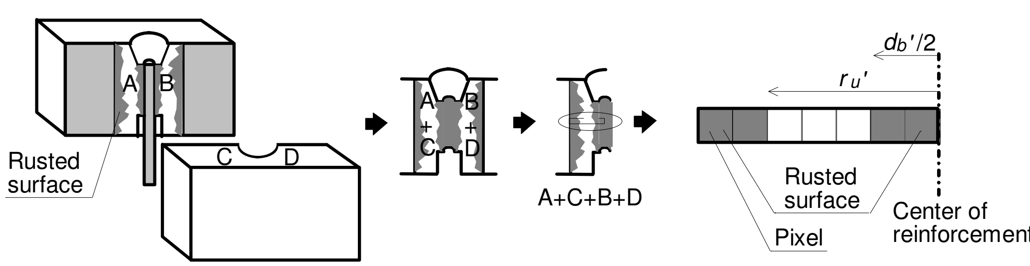

Fig.10- Photographic analysis of splitting surface

4.2. Comparison of experimental bond strength

Fig.11 shows the relationship between experimental maximum bond stress standardized by calculated value and weight reduction ratio. It is shown that the upper limit of the ratio of experimental bond strength to calculated one is almost 1. It could be considered that decrement capacity of bond strength is estimated by considering the concrete splitting area due to corrosion of reinforcement. However, specimens which have the ratio of under 0.6 show no relation between bond strength and weight reduction ratio. The bond stress – slippage relationships of these specimen show different tendency from other specimen. The bond stress increases again after the maximum stress. It is considered that failure mechanism of these specimen differ from bond splitting mechanism. The further studies would be necessary.

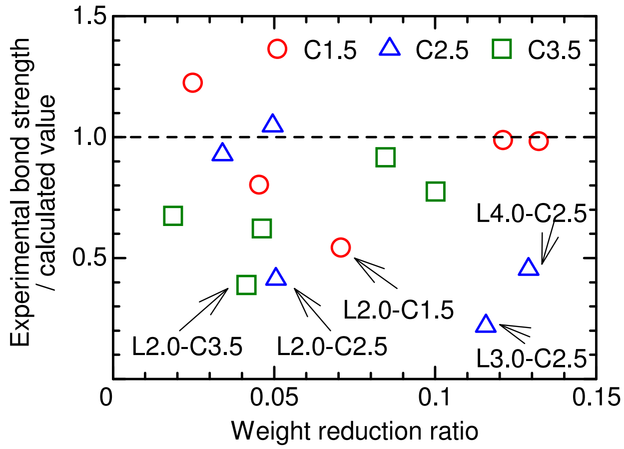

Fig.11- Comparison of maximum bond stress

5. CONCLUSIONS

The concrete block specimens with a bond length of four times of the diameter of reinforcement are subjected to pullout bond test after electrolytic corrosion process. The followings are concluded from the test results.

1. The internal cracks of surrounding concrete occur by corrosion of reinforcement.
2. The relationships between bond strength and weight reduction ratio of reinforcement up to 7% can be recognized.
3. The size of internal cracks are evaluated by photographic analysis. It is considered that the internal cracks make bond strength lower in case of splitting failure of concrete.
4. Calculated bond strength considering internal cracks shows upper limitation of bond strength.

REFERENCES

1. Japan Concrete Institute, (1988), *Report of the Technical Committee on the Rehabilitation of Concrete Structures*, Technical Committee Report, JCI, Tokyo, Japan (in Japanese).
2. Yasojima, A., Kanakubo, T. (2005), *Bond Splitting Strength of RC Members Based on Local Bond Stress and Slip Behavior*, 11th International Conference on Fracture, Proceedings CD-ROM, No.4486
3. Tepers, R. (1982), *Lapped Tensile Reinforcement Splices*, ASCE, Journal of Structural Division, Vol.108, No. ST1, pp.283-301