*- Technical Paper -*

# EXPERIMENTAL STUDY ON BOND BEHAVIOR OF STEEL BARS IN CONCRETE IN LOW LEVEL CORROSION

Aris ARYANTO[*1] and Yasuji SHINOHARA[*2]

## ABSTRACT

This paper presents an experimental study of bond behavior, cracking, and tension stiffening on corroded steel bars in concrete subjected to uniaxial load. Seven cylindrical RC tension members were experienced with various corrosion levels. It was found through test that in low level corrosion the average crack spacing decreases with increasing of corrosion level. Moreover, it concludes that the decreasing of this average crack spacing is attributed to the increasing of bond strength and the decreasing of concrete tensile strength, which is caused by crack forming around corroded bar.

Keywords: bond stress, corrosion, crack spacing, and tension stiffening,

## 1. INTRODUCTION

In high risk corrosive region i.e. coastal area, many RC structures experience severe corrosion problems causing the degradation of structural integrity, safety and reduction of service life time. Corrosion of reinforcement influences the behavior of RC structure, because it causes reduction of cross-section area of steel bar, deterioration of bond strength and leading to cover cracking and spalling. It also leads to high cost of maintenance. Therefore, a comprehensive understanding about the effect corrosion of steel bar on mechanical properties of reinforced concrete and on behavior of RC structure is required in order to predict the future structural performance or to assess the existing RC structures.

One of the main aspects which is necessary to be evaluated corresponding to structural capacity of corroded RC structure is bond between steel and surrounding concrete. Regarding to bond behavior between corroded reinforcing bar and concrete, many studies have been undertaken. Al-Musallam et al. [1] and Al-Sulaimani et al. [2] conducted a pull-out test to quantify bond strength of corroded RC in various corrosion levels. Moreover, an experimental work through tensile test was also performed by Amleh et al. [3]. From previously mentioned study, it reported that an increase in corrosion level generates a decrease in bond strength, tension stiffening and an increase of average crack spacing.

Due to high volume of corrosion product compared to original volume of steel bar, corrosion also produces expansion pressure and ring tension stress causing the crack of surrounding concrete, or even more spall of concrete cover. From the experimental and analytical work conducted by Andrade et al. [5] and Shinohara [6] respectively, it shows that crack of concrete cover is generated by 20 to 30 micrometers of corrosion penetration (corrosion rate of 0.4-0.6%).

The main purpose of this experimental test is to gain more knowledge on bond behavior, cracking, and tension stiffening of corroded steel bar in concrete particularly in low level corrosion. Regarding to this, the additional instruments (strain measurement) were attached on embedded steel bar to obtain the actual steel stress distribution and the local bond stress along the bar.

## 2. EXPERIMENTAL PROGRAMS

### 2.1 Specimens and Materials

Seven specimens of tension test were prepared. Each specimen, a deformed bar of 19 mm was installed in the center of a 125 mm diameter concrete cylinder. For placing strain gauges in the reinforcing bar, a machine groove cutting of 3 mm in width, 3 mm in depth, and 840 mm in length was made. This grooving was made to avoid damage in strain gauges during accelerated corrosion process and to prevent the chance on the actual bond behavior. Before and after cutting or grooving the bars, the weight of bar was measured to estimate a reduction rate of sectional area by grooving.

The strain gauges were attached along the bar with 100 mm of interval to measure steel stress (strain) distribution. After attaching strain gauges on the grooving, the strain gauge wires were passed through the grooving and taken out at the end of specimens as shown in Fig. 1. Later, the grooving was filled by waterproofing material to protect the gauges during concrete placing and accelerated corrosion process. At top and bottom of the specimens, a 50 mm of bond

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[*1] Dept. of Environmental Science and Tech., Tokyo Institute of Technology, JCI Student Member
[*2] Associate Prof., Structural Engineering Research Center, Tokyo Institute of Technology, JCI Member

insulation was installed around steel bar to avoid cone damage.

The specified compressive concrete strength of 28 days was 48 N/mm$^2$ conforming to Japan concrete code. The concrete proportion/mixing was shown in Table 1. The reinforcing bars used have specified yield strength of 390 N/mm$^2$ (SD390). The average yield strength of reinforcing bar from tests was 435 N/mm$^2$, the tensile strength was 610N/mm$^2$, and the elastic modulus was 1.85 × 10$^5$ N/mm$^2$.

Table 1 Concrete Mixing

| Material | Volume | Remark |
|---|---|---|
| Water | 175 kg/m$^3$ | w/c =0.5 |
| Cement | 350 kg/m$^3$ | |
| Fine Aggregate | 780 kg/m$^3$ | |
| Coarse Aggregate | 968 kg/m$^3$ | |
| Admixture | 0.8% | Air entraining and water reducing |

### 2.2 Accelerated Corrosion

An accelerated corrosion using the electrochemical process was performed after 4 weeks of curing. During electrochemical process specimens were placed in the tank and filled with 3 percent of NaCl solution. The set up was arranged so that the reinforcing bar acted as anode and the copper plate acted as cathode (Fig. 2). Furthermore, a 200mA of current was applied and monitored using a data logger.

### 2.3 Loading and Measurements

A load-controlled tensile test was performed using a 2000kN of Amsler Universal Testing Machine. During the test, the applied load and the displacement were recorded and monitored using an automatic data acquisition system. There were two types of displacement measurement attached into specimens. First, to measure the stress/strain distribution along reinforcing bar a 100mm interval of strain gauge was attached into reinforcing bar. Secondly, the global elongation of specimens was measured using vertical jig attached to the specimen (Fig. 1).

## 3. RESULTS AND DISCUSSIONS

### 3.1 Specimens and Corrosion Level

The specimens were categorized into seven corrosion levels. The specimen No.1 was a healthy specimen which no impressed current applied. The corrosion levels of specimen's No. 2 to No. 7 were gradually increased. The specimen No.7 was mentioned as the highest corrosion level in this experiment.

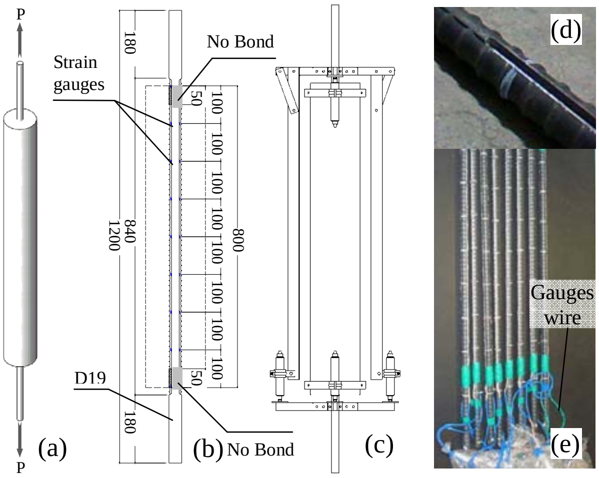


Fig. 1 (a) Typical specimens, (b) Strain gauges location, (c) Jig for vertical displacement, (d) Grooving, and (e) Gauges wire

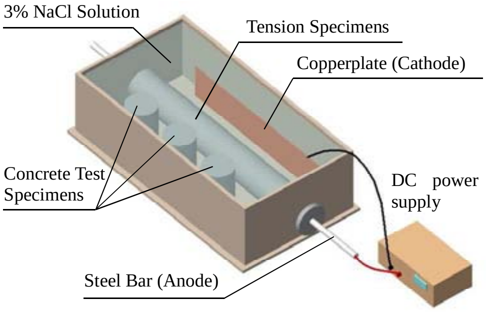


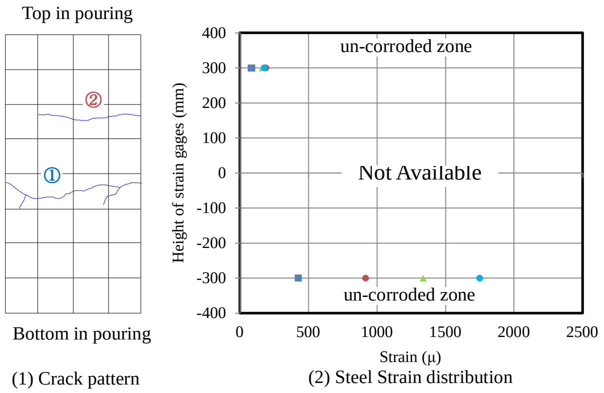
Fig. 2 Overview of electrochemical corrosion test

In order to determine the corrosion level during accelerated corrosion process, the prediction from the relationship between the duration of the impressed current and the corresponding degree of corrosion was studied. The corrosion rate of the reinforcing bar was calculated by a Faraday's law of electrolysis from the electric flow measurement. The corrosion rate was measured as loss in weight of the reinforcing bars divided by original bar weight. To measure the corrosion weight, after the completion of loading test, a corrosion section of 700mm was taken out to calculate the actual value of the corrosion rate by a mass measurement (Table 2). The corrosion efficiency by the electrolytic corrosion considerably varies from 30% to 60% from the mass measurement, except for specimen No.2.

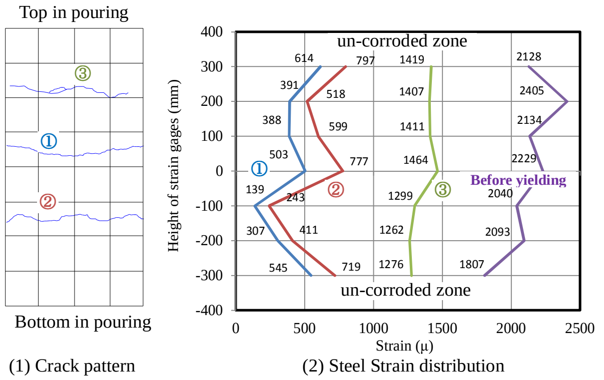
Table 2 Corrosion Rate in Mass loss

| Specimens | Estimated by Faraday's Law (g) | Determined by Measurement (g) |
|---|---|---|
| No.1 | - | - |
| No.2 | 9.54 (0.72) | 9.60 (0.72) |
| No.3 | 30.18 (2.26) | 11.70 (0.88) |
| No.4 | 39.74 (2.97) | 14.00 (1.05) |
| No.5 | 50.36 (3.77) | 14.90 (1.12) |
| No.6 | 73.37 (5.49) | 36.30 (2.27) |
| No.7 | 90.94 (6.78) | 52.90 (3.95) |

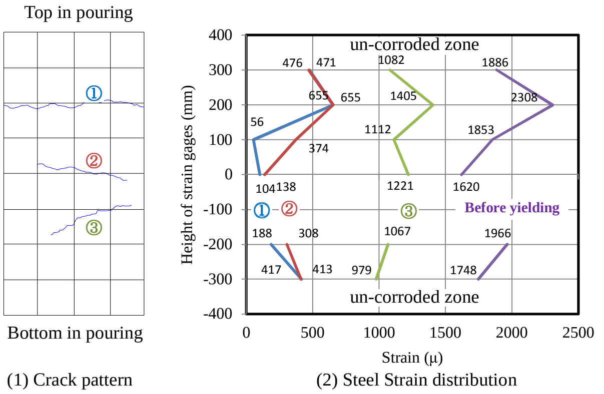
Note: number in the parenthesis shows percentage of mass loss



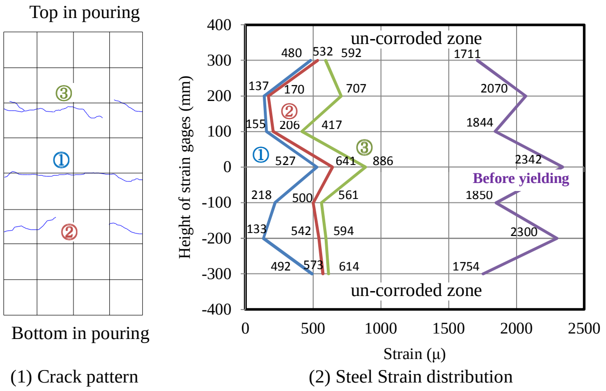
(a) Specimen No.1



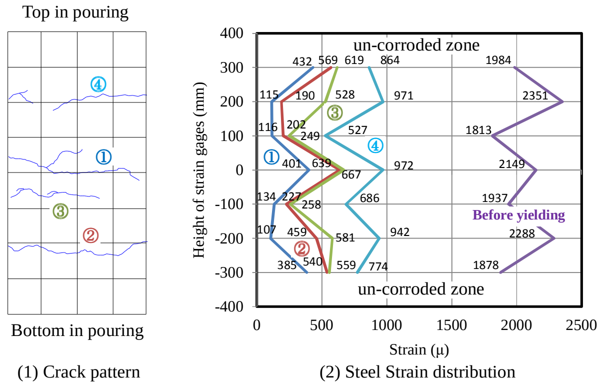
(b) Specimen No.2



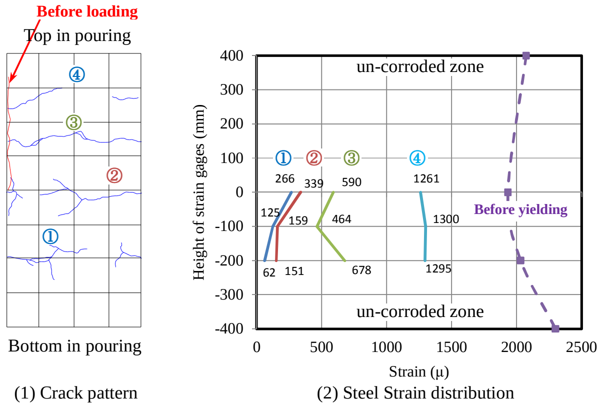
(c) Specimen No.3



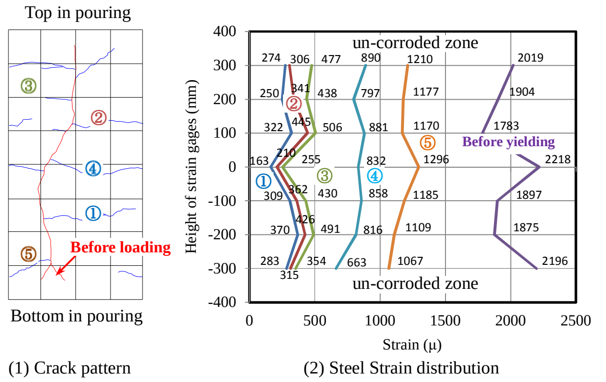
(d) Specimen No.4



(e) Specimen No.5



(f) Specimen No.6



(g) Specimen No.7

Fig.3 Specimen's crack pattern and steel strain distribution

## 3.2 Steel Stress Distribution and Crack Pattern

The specimen's crack pattern after yielding of steel bar and steel strain distribution of each specimen are shown in Fig. 3. The number inside the circle in Fig. 3 indicates the order of cracking occurrence. From the figure, it obviously shows that the stress distribution of steel bar varies along the bar. Clearly, when crack is forming in the specimen, the steel stress at crack location becomes higher. It means that steel carried most of the applied load. However, because more than a half of attached strain gauges were damage in specimen No. 1 and No.6, the strain distribution of them cannot be presented. Therefore, the strain gage's measurement results of specimen No. 1 and No.6 were not considered in bond stress calculation on subsequent section.

### 3.3 Tension Stiffening

Fig. 4 shows the load-strain relationship of specimens No.2 to No.7 compared to bare bar and healthy specimen (Specimen No.1) under tensile loading. The actual global elongation is measured over the gauge length of 840 mm. However, in the Fig. 4, the average strain is determined from the effective bond length of 700 mm. It is obtained from the actual global elongation reduced by strain elongation of 140 mm of unbonded or bare bar from both ends of specimens.

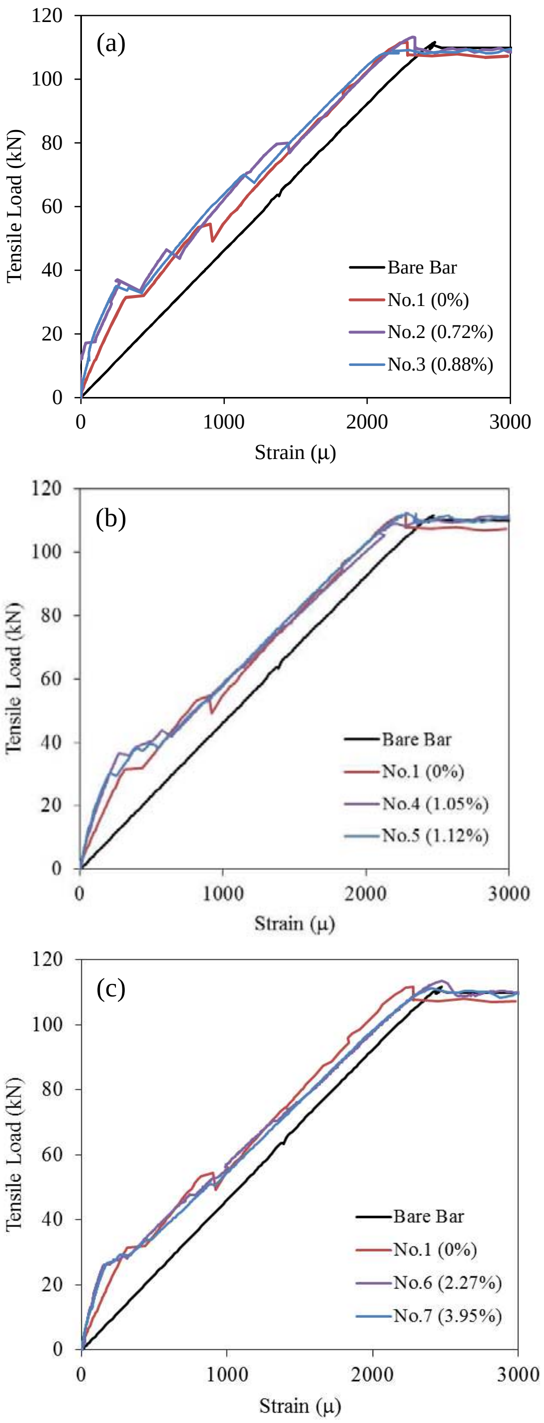


Fig.4 Load – strain curves

Because concrete shares tension, the specimen's tensile load generates a larger value than the bare bar until yielding of the reinforcing bar. Generally, as shown in the Fig. 4 tensile forces of specimens No.1 to No.7 produce larger value than tensile force of bare bar before steel bar yields. If specimen No.2 and specimen No. 3 are compared with healthy specimen, they slightly produce higher tension stiffening as shown in Fig. 4. For specimen No.4 and No.5, higher corrosion levels, produce almost same tension stiffening level as specimen No.1. However, for specimen No.6 and No.7, where the longitudinal corrosion cracking appeared before tensile test, the tension stiffening is slightly lower than specimen No. 1.

From Fig. 4 there is no significant reduction in the yield load within the increasing corrosion level up to 4%. The maximum yield load produced seems have a small different compared to maximum yield load of bare bar. This indicates that the applied corrosion level not significantly influence the yield strength of RC members.

### 3.4 Crack Load and Crack Spacing

Fig. 5 shows the first crack load corresponding to corrosion rate of each specimen. Specimen No.1 produces slightly lower than Specimen No.2 to No.4 which have higher corrosion rate. The highest crack load was Specimen No. 4 (corrosion rate 1.05%). The higher cracking load indicates higher tension stiffening (Fig. 4). However, Specimens No.5, No.6, and No.7 produce slightly lower cracking load than Specimens No.1 to No.4. This can be generated by the increasing of radial cracks around the bar due to corrosion. In addition, for specimens No 6 and No7, the longitudinal crack appears in concrete surface during accelerated corrosion before the tensile test as shown in Fig. 3(f) and Fig. 3(g) respectively. This longitudinal crack contributes to the reduction of concrete confinement through reduction of contact area due to longitudinal crack widening. As a result, the bond and tensile strength decrease in high corrosion level.

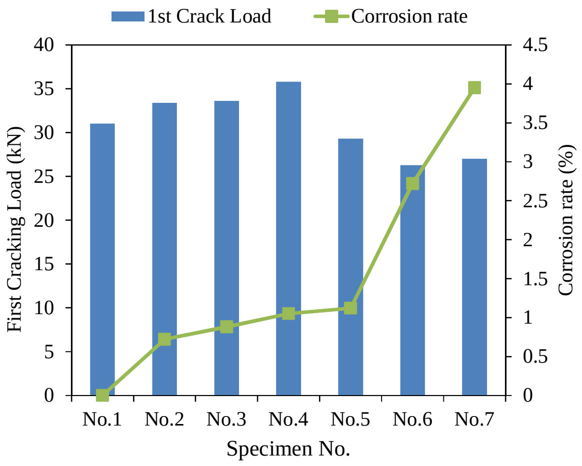


Fig.5 First cracking load

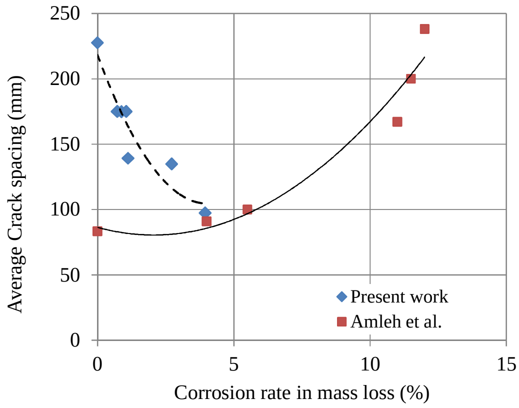


Fig.6 Ave. crack spacing – corrosion rate curves

Fig. 6 presents the relationship between average transverse crack spacing and corrosion rate of the present and the Amleh's work [3]. From the figure it shows that in low level corrosion for the present work, an increase in corrosion level generates a decrease of average crack spacing. This is an indication of the increase of bond stress between steel and surrounding concrete which produces lower transmission length to generate crack in concrete.

## 3.5 Bond Stress

In a typical tension member as shown in Fig. 7, at the main crack, all loads are carried entirely by steel bar $f_s = P/A_s$. Between adjacent cracks, a portion of tensile force is transmitted to surrounding concrete by bond over the transmission length $L_t$, which is half of crack spacing $S_{cr}$, causing stress distribution on steel bar and concrete. If the bond stress distribution along the bar between two adjacent cracks is defined as steel stress variation at certain length, the relationship between local bond stress and steel stress variation at certain length can be expressed as follows:

$$\tau_b = \frac{(\sigma_1 - \sigma_2)A_s}{\Delta x \phi_s} = \frac{(\sigma_1 - \sigma_2)}{\Delta x}\frac{d}{4} \tag{1}$$

where $\tau_b$ is the local bond stress over the length of $\Delta x$; $\sigma_1$ and $\sigma_2$ are steel stress between $\Delta x$; d, $A_s$ , $\phi_s$ is diameter, area and perimeter of steel bar, respectively; and $\Delta x$ is specified length along the bar or in this case is the interval length of strain gauges. In this case the bond stress is assumed to be constant $\tau_m$ along the transmission length using the maximum local bond stress. Therefore, the average bond stress $\tau_m$ can be given by

$$\tau_m = \frac{(\sigma_1 - \sigma_2)}{L_t}\frac{d}{4} \tag{2}$$

The tension force carried by concrete which is transmitted by bond along the transmission length can be described by

$$F_\tau = \tau_m \phi_s L_t \tag{3}$$

The maximum tensile strength of concrete to provoke cracking is given by

$$F_c = f_{ct} A_c \tag{4}$$

where $f_{ct}$ is mean value of concrete tensile strength when crack appeared in concrete and $A_c$ is effective area of concrete.

When $F_\tau = F_c$ , a transverse crack occurs on tension member. Therefore, from equation (3) and (4), it can be derived for the transmission length

$$L_t = \frac{f_{ct} A_c}{\tau_m \phi_s} \tag{5}$$

Equation (5) indicates that the transmission length $L_t$ will decrease if there is an increasing of bond stress $\tau_m$ or a decreasing of concrete tensile strength $f_{ct}$ .

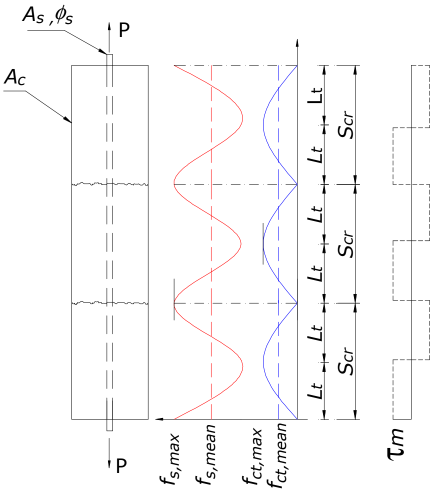


Fig.7 Stress distribution on tension member

By using equation (1) to (5), the maximum local bond stress and concrete tensile strength are summarized in Table 3. From this table, it shows that for corrosion level up to 1 % with the increasing of corrosion level, the local bond stress is increasing, but the concrete tensile strength is not so changed. One of the possible reasons of increasing bond stress is that the interface between concrete and reinforcing steel filled with corrosion product so will increase the mechanical properties of interface.

Table 3 Maximum Local Bond stress and Concrete Tensile Strength

| Specimens | Loss of Weight (%) | Maximum Local Bond Stress (MPa) | Concrete Tensile Strength *fct* (MPa) |
|---|---|---|---|
| No.1 | 0 | N/A * | 2.30** |
| No.2 | 0.72 | 4.15 | 2.04 |
| No.3 | 0.88 | 4.65 | 2.33 |
| No.4 | 1.05 | 3.64 | 1.73 |
| No.5 | 1.12 | 3.44 | 1.72 |
| No.6 | 2.72 | N/A * | |
| No.7 | 3.95 | 1.89 | 1.34 |

Note:

*specimen No.1 and No.6 is not available (N/A) caused by the damage of attached strain gauges

** based on AIJ code

The increasing of bond strength has been reported by Al-Musallam et.al [1] and Al-Sulaimani et.al [2] and from experimentally pull-out test on embedded corroded bar approximately up to 1 percent of corrosion rate. The change of roughness in the interface of concrete and steel due to corrosion leading to the increasing of mechanical interlocking or friction by corrosion products is mentioned as mainly cause of increasing of bond strength.

From Table 3, in corrosion level above 1%, the local bond stress and the average concrete tensile strength decrease. The decrease in local bond stress and tensile strength can be mainly caused by reduction of contact area in bar and concrete interface due to radial cracking around bar surface and widening of initial longitudinal crack resulting from corrosion expansion product.

## 4. CONCLUSIONS

From the experimental results of corroded RC tensile members, the following conclusions can be made.

(1) The local bond stress increases for corrosion level up to 1%.

(2) The average crack spacing decreases with increasing of corrosion level due to the increasing of bond stress for the small corrosion levels.

(3) The average crack spacing also decreases for higher corrosion levels. This is mainly attributed to the decreasing of concrete tensile strength caused by cracks around corroded bar, which is generated by corrosion product expansion for the large corrosion levels.

(4) The longitudinal/splitting crack appeared before applied load contributes in a decrease of bond stress and tension stiffening.

## ACKNOWLEDGEMENT

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