PREDICTED METHOD FOR BOND STRESS BEHAVIOR DEPENDED ON CRACK WIDTH IN CORRODED REINFORCED CONCRETE

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1. INTRODUCTION

Reinforced concrete can encompass many types of structures and components. At use stage, cracks occur in concrete, and corrosion results in the formation of rust of which volume has two to four times of the original volume. Rust reduces strength capacity as a result of both the reduced cross-sectional area and corrosion cracks in the surface rebar. It is very difficult to accurately estimate the bond stress of cracked reinforced concrete due to the corrosion of rebar, as there are many factors that affect the bond stress. In this paper, corroded specimens with cracks in the concrete cover were tested, and the method for estimating bond stress is suggested. The data shows that it is feasible to estimate the bond stress based on three major factors: corrosion ratio of rebar, corrosion crack width and tensile concrete stress.

2. RELATION BETWEEN INTERNAL STRESS AND BOND STRESS.

In the previous literature [1], a concrete ring model was analyzed. The interaction force makes an angle with the axis of rebar due to the presence of ribs. The interaction force can be resolved into radial (internal stress) and tangential (bond stress) component (see Fig.1). Eq. 1 can be obtained.

$$p_i = \tau \cdot \tan \beta \qquad (1)$$

where,

p_i : internal pressure

β : angle between the surface of rib and the rebar axis

τ : bond stress

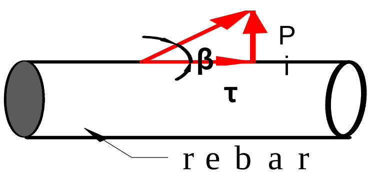

Fig.1 Component of interaction force

3. BOND ACTION OF CORRODED RC

Fig. 2 shows the distribution of radial (purple) and tangential (blue) stress in the horizontal concrete cover (40mm). The dimension of the model, with crack in vertical concrete cover, is 120mm*100mm. Internal pressure of 2.5N/mm^2 is applied on internal surface with diameter 16mm. Positive value denotes tensile stress and negative denotes compressive stress. After cracking, the distribution of stress is more complicated, for the discontinuity of concrete cover.

It indicates that tensile stress is much larger than compressive stress. On this occasion, if the vertical component of internal force exceeds the tensile capacity of concrete cover, failure crack extends along horizontal corrosion crack.

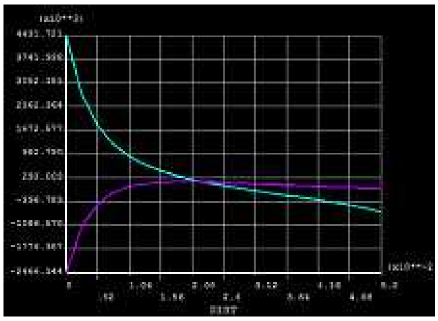

Fig.2 FEA solution at elastic stage

4. BOND MODEL OF CRACKED RC COCRETE

Based on the FEA solution and the experiment, a predicted method for bond stress of cracked RC beams is promoted in both elastic stage and plastic stage.

4.1 IN ELASTIC STAGE

In the elastic stage, the mechanical model can be shown in Fig.3(a). Complementary angle of half of crack can be calculated as follows:

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$$\theta = \pi/2 - S/2c \tag{2}$$

where,

S : width of crack changing with internal pressure

c : concrete cover depth in crack direction

The vertical force acting on concrete with unit length can be calculated as follows:

$$P_V = 2P_{vi} = 2\int_0^{\theta} \sin\theta \cdot p_i \cdot \frac{d}{2} d\theta \tag{3}$$

where,

d : diameter of rebar

p_i : internar pressure

θ :complementary angle of half of crack

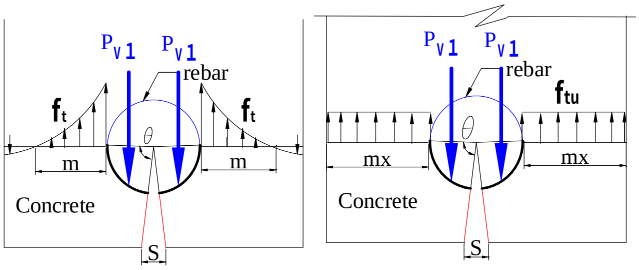
The tensile force acting on concrete with unit length can be calculated as follows:

$$F = 2\int_m f_t(m) \cdot dm \tag{4}$$

where,

$f_t(m)$: tensile stress at point on line m

m : region of integration of tensile stress



(a) Elastic stage (b) Plastic stage

Fig.3 Mechanical mode in elastic stage

Although the shape of the distribution of tangential stress is similar to that of un-cracked thick walled cylindrical mode, the peak stress of cracked model is much higher, compared at the condition with same internal pressure. Based on the balance of force and Eq. 1, bond stress can be calculated as follows:

$$\tau = \frac{2\int_m f_t(m) \cdot dm}{d\{1 - \cos(S/2c)\}\tan\beta} \tag{5}$$

4.2 IN PLASTIC STAGE

In plastic stage, crack will not occur in concrete until every point at the plane of horizontal concrete cover has reached the ultimate tensile concrete stress. At this moment, the bond stress between concrete and rebar can be expressed as

$$\tau = \frac{2 f_t \cdot m_x}{d\{1 - \cos(S/2c)\}\tan\beta} \tag{6}$$

where,

f_t : ultimate tensile stress of concrete

m_x : length of concrete cover in horizontal direction

5. EXPERIMENT

5.1 Specimens

In order to investigate the predicted method, the previous experiment of reinforced concrete beam [2] and pullout test are cited. The schematic of specimens are shown in Fig. 4. Moreover, in order to prevent strain gauges from corrosion, they are set inside one tensile rebar, with spacing of 48mm. In order to identify the rebar, two outside tensile rebar are named L and R, and middle rebar, if any, is named M. (See Fig. 4). The concrete covers depth of all the specimens are 40mm.

The beam specimens are monotonically tested until failure with four-point flexural loading, under displacement control at a velocity of 0.5mm/min. With regard to pullout test, tensile force applied on rebar increased at the speed of 9.8kN/min.

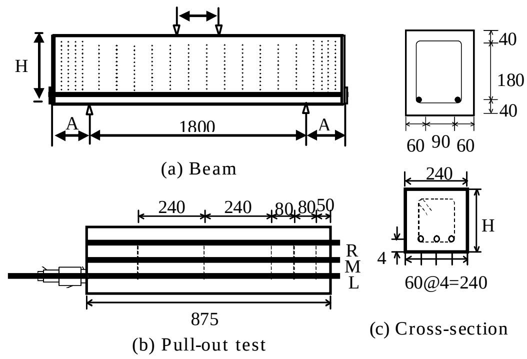


Fig.4 Schematic of specimens

5.2 Corrosion cracks

Corrosion crack occurred along two outside rebar, and partly occurred along rebar M in concrete cover. The width of corrosion crack in concrete cover can be measured directly. Take corrosion crack of one pullout specimen for example, shown in Fig. 5. But the length of corrosion crack at horizontal direction in the concrete cannot be measured which will be discussed in next section.

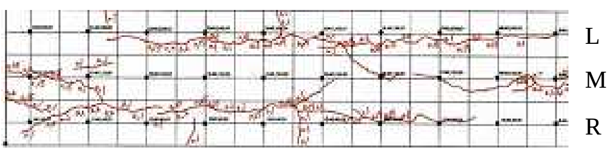
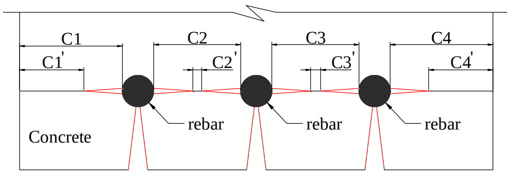


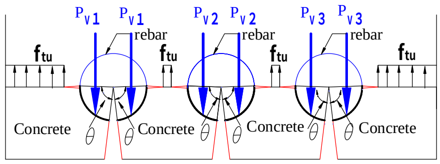
Fig. 5 Corrosion crack in concrete cover B-LM-0-20

5.3 Data analysis

Each of the specimens has two or three main rebar. However, the effect of internal pressure of each rebar was ignored. Based on the corrosion cracks of these beam, not only the corrosion crack at bottom surface, but also the corrosion cracks in horizontal direction are taken into account. The corrosion crack model and mechanical mode are shown in Fig.6. With regard to the corrosion cracks in the concrete cover, the width at failure stage should be used based on the estimated model. As there is no such data, the width of corrosion cracks is used in the next calculation. In this section, parameters affect the bond stress will be discussed.



(a) Model of corrosion crack propagation



(b) Mechanical model

Fig. 6 Corrosion crack and mechanical model

(1) Region for calculation

The beams adopt performed bond failure, as the bond stress in anchorage reached the maximum. With regard to pullout specimen, the computed region is from one gauge, at which rebar has yielded or the bond reached maximum, to another gauge, of which the strain is zero.

(2) Ultimate tensile stress at bond splitting failure

Both the effects of concrete and the stirrups are taken into account. The part of concrete is evaluated with ultimate tensile stress of concrete by splitting tension test. With regard to the part of stirrups, both residual mass ratio and number of stirrups are taken into account, which can be expressed as follows:

$$f_{st}/f_t = \gamma \cdot n \tag{7}$$

where,

f_{st} : increcement of tensile strength due to confined effect of stirrups

f_t : tensile strength of concrete

γ : residual mass ratio of stirrups

n : number of stirrups in unit calculated region

Hence the proposed equation for estimated tensile strength of specimen f_{tu} can be expressed as below.

$$f_{tu} = f_t + f_{st} = f_t \cdot (1 + \gamma \cdot n) \tag{8}$$

(3) Effective width of concrete

With corrosion, the corrosion cracks propagate at horizontal direction. Therefore, the effective width of concrete becomes shortened. Here define effective width of concrete to denote the width of concrete where cracks, horizontal direction, have not occurred. Moreover the concrete located between two rebar is affected by individual two rebar, and the corrosion crack is longer. For simplify, coefficient 0.5 is multiplied. Eq. 9 Shows the calculation of specimens with three rebar.

$$\begin{cases} C_1' = (1-\lambda)\cdot C_1 \\ C_2' = \dfrac{1}{2}(1-\lambda)\cdot C_2 \\ C_3' = \dfrac{1}{2}(1-\lambda)\cdot C_3 \\ C_4' = (1-\lambda)\cdot C_4 \end{cases} \tag{9}$$

where,

λ : coefficient of crack propagation

C_1, C_2, C_3 : width of concrete before corrosion

C_1', C_2', C_3' C_4' : effective width of concrete

(4) Function of λ

It is difficult to measure the length of corrosion cracks occurring in horizontal direction, as they are invisible. For simplicity, we assume that coefficient of crack propagation is determined by corrosion ratio of rebar. When the corrosion crack occurs in the side surface of specimen, equation $\lambda = 1$ is obtained. In this experiment, the local corrosion ratio of rebar L or R reached to 25%, corrosion crack appeared on the side surface of specimens. If assume is proportional to $\alpha^{2/3}$, then it can be expressed as following.

$$\lambda = 2.4\alpha^{2/3} \tag{10}$$

where,

α : corrosion ratio of rebar

(5) Tensile force of concrete

As the changing of corrosion cracks were not measured during load test, only bond stress in plastic stage will be investigated in this paper. The tensile force of concrete per unit length at failure stage can be expressed as Eq 11.

$$F_t = f_t \cdot \sum_{i=1}^{4} C_i' \tag{11}$$

(6) Vertical force acting on concrete by rebar

The vertical force applied on the surface of bottom concrete by rebar can be expressed as Eq 12.

$$P_V = 2\sum_{i=1}^{3}\int_0^{\theta_i} \sin\theta \cdot p_i \cdot \frac{d_i^{'}}{2} d\theta = \sum d_i^{'} p_i (1-\cos s/2c) \qquad (12)$$

where,

$d^{'}$:diameter of rebar after corrosion

p_i : internar pressure

s : width of corrosion crack

c : concrete cover in crack direction

Assuming that the bond stresses of rebar are the same, the Eq. 13 can be obtained

$$P_V = p\sum_{i=1}^{4} d_i^{'}\{1-\cos(s/2c)\} \qquad (13)$$

(7) Angle β

In reality, the angle between rib and the axis of rebar is changing during corrosion. Assuming the angle becomes larger with corrosion and expressing it as below:

$$\beta = 45° + \alpha^{1/3} \qquad (14)$$

where,

α : corrosion ratio of rebar

(8) Bond stress

Based on equilibrium at failure stage, $F_t = P_V$, and equation $p_i = \tau \cdot \tan\beta$, the estimated equation of bond stress can be established as Eq. 15.

$$\tau = \frac{f_t \cdot \sum_{i=1}^{3} C_i^{'}}{\sum_{i=1}^{4} d_i^{'}\{1-\cos(s/2c)\}\tan\beta} \qquad (15)$$

(9) Experimental mean bond stress

The experimental value of local bond stress is calculated by Eq. 16.

$$\tau_{loc} = -\frac{1}{\pi\sqrt{1-\alpha_{loc}} \cdot d}\frac{dP_s}{dx} \qquad (16)$$

Where,

τ_{loc} : local bond stress

p_s : axial force of tensile rebar

α_{loc} : local corrosion ratio of rebar

d : diameter of tensile rebar

x : position of strain gauge

In calculating the axial force of rebar, the degradation of yield strength due to corrosion was taken into account, and the local yield strength was calculated by Eq. 17.[3]

$$f_{sc} = f_{so} - 2.4303 \cdot \alpha_{loc} \qquad (17)$$

where,

f_{sc} : yield strength after corrosion

f_{so} : nominal yield strength

α_{loc} : local corrosion ratio of rebar

5.4 Comparison

The value of both experimental and estimated maximum bond value is shown in Fig. 7, which indicates that the many of the data is in ±30% region. It is reasonable to simplify the mechanical model as shown in Fig. 7, and it is feasible to estimate the maximum mean bond stress by promoted method in this paper.

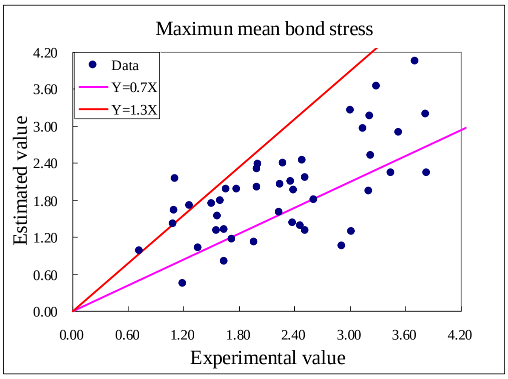


Fig. 7 Experimental and estimated bond stress

6. CONCLUSIONS

1) The internal bond stress of cracked reinforced concrete can be estimated by corrosion ratio of rebar, corrosion crack and tensile strength of concrete.

2) The maximum bond stress of cracked reinforced concrete can be estimated by internal stress.

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