- Technical Paper -

EFFECT OF CORROSION-INDUCED CRACK AND CORRODED REBAR PROFILE ON BOND STRESS AND SLIP RELATIONSHIP

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ABSTRACT

This paper investigated individual effect of corrosion-induced crack and corroded rebar profile on bond behavior. Test specimens were corroded by an accelerated electric corrosion method and bond-slip relationship was measured by two ends pull-out test. Under various corrosion degrees, the influence of corrosion crack, shape of corroded rebar and rust around rebar on bond behavior were discussed separately. Moreover, corroded rebar profile was measured by laser meter and correlation between corrosion degree and geometry change was demonstrated. Corrosion crack in concrete was clarified to be more dominant factor than corrosion profile in bond deterioration mechanism.

Keywords: bond-slip relationship, rebar corrosion, corrosion crack, corroded rebar profile, two ends pull-out test

1. INTRODUCTION

Rebar corrosion basically causes bond deterioration between rebar and concrete which would directly affect the serviceability (cracking and deformation) and safety (strength and ductility) of reinforced concrete (RC) structures. Many researchers have studied bond behavior of corroded RC members through experimental study, which revealed the effect of corrosion degree on bond deterioration and established empirical degradation functions of corrosion level [1,2,3]. Moreover, bond deterioration mechanism has been discussed through analytical approach considering change of rebar rib height and confinement of surrounding concrete [4,5]. Previous studies so far concluded that bond behaviors of rebar in concrete subjected to corrosion are influenced by both the surface shape of corroded rebar and the condition of surrounding concrete. Conditions of concrete are affected by corrosion product layer thickness, penetration of corrosion product into pores and corrosion induced cracks etc. Loss of rib height and formation of cracking zone in concrete is the major cause of bond degradation by defecting interlocking force between corroded ribs and cracked concrete. However, experimental studies until now focused more on synthesized effects of corrosion on bond performance than on the individual effects of corroded rebar profile and cracking behavior in concrete. Therefore, the effect of corroded rebar profile and corrosion crack on bond performance should be clarified.

This paper presents an experimental program whereby the bond behavior between deformed rebar and concrete was tested by two ends pull-out test using single rebar embedded in concrete specimen. Rebar were corroded by an accelerated electric corrosion method in laboratory. Test specimens were divided into four groups, including one non-corroded control group. For the normal corrosion group, bond test was conducted directly after the corrosion test, of which the purpose is to evaluate total effect of rebar corrosion such as concrete cracking, corroded rebar profile and rust. In another group, rust was removed from corroded rebar and casted into new concrete to evaluate single effect of corroded rebar profile. Similarly, corroded rebar with rust was casted into new concrete to evaluate the effect of both rebar shape change and rust accumulation. Test series were conducted with several corrosion degrees. Moreover, corrosion degree, corroded rebar shape and internal crack pattern were measured through test. The effects of corroded rebar profile, rust around rebar and crack due to corrosion on bond-slip relationship were clarified.

2. TWO ENDS PULL-OUT BOND TEST OF CORRODED RC SPECIMEN

2.1 Materials

Table 1 shows the mix proportion of concrete. The early strength Portland cement and coarse aggregates having a maximum diameter of 20mm were used. The specimens and test cylinders were cured for 14 days. Based on different casting sequences, compressive strength were 39.0 MPa, 40.0MPa and 35.0 MPa, respectively.

In order to prevent the yielding of rebar before

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Table 1. Mixture proportion of concrete

W/C (%)	s/a (%)	Unit (kg/m^3)				
		W	C	S	G	AE (l/m^3)
56.5	44	166	294	779	990	1.18

Table 2. Mechanical property of rebar

Rebar type	A_s (mm^2)	E_s (MPa)	f_y (MPa)
SD685	201.1	18300	721

bond failure, the rebar with high yielding stress were used. The mechanical property of the high strength rebar is tabulated in Table 2.

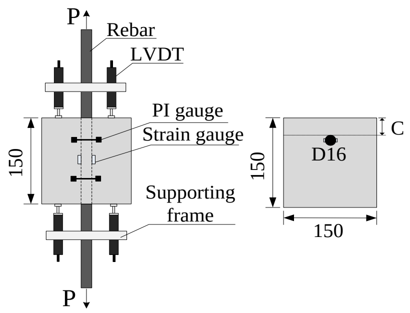
2.2 Test Series

Two ends pull-out specimens were designed as shown in Fig.1(a). Size of specimens was 150×150×150mm and a deformed D16 rebar was embedded at 30mm cover thickness as tabulated in Table 3. The length of specimen was chosen to avoid the formation of a transverse crack in the concrete. The specimen surface with minimum cover thickness was located at bottom surface when concrete was casted. In order to calculate bond stress, steel strain at the center of rebar was measured. The strain gauges were attached to the surface of horizontal ribs of rebar. VM tape was wrapped on rebar where attached strain gauge to prevent the corrosion of strain gauges. The embedment length of rebar for the bond test was set as 150mm.

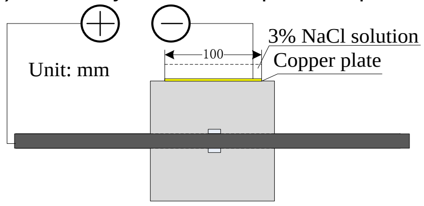
Four test groups were fabricated with different corrosion conditions. nine uncorroded specimens in Group I were used as control group corresponding to different casting sequence. Specimens in Group II-IV were corresponding to corroded rebar with rust in cracked concrete, corroded rebar without rust in non-corroded concrete and corroded rebar with rust in non-corroded concrete.

2.3 Accelerated Corrosion Method and Pull-out Test

The specimens were corroded to objective corrosion level by using accelerated electric corrosion method. Fig.1(b) shows the corrosion test set up. A salt water pool was placed on the top surface of specimen, the copper plate was immersed in 3% NaCl solution to serve as cathode. The part of rebar outside concrete was coated by anti-corrosion epoxy. The current density was chosen as 900μA/cm^2 and objective current flow was 28.1A.hr and 56.1A.hr by



(a) Geometry of two ends pull-out specimen



(b) Accelerated corrosion method

Fig.1 Details of test specimen (unit: mm)

Faraday's law. Corrosion degree X_p defines as percentage weight loss of rebar within embedded length. The target corrosion degrees were 5.0 and 10.0%. The actual corrosion degree was determined by measuring the weight loss of the rebar after removing the rust with 10% diammonium hydrogen citrate.

As corrosion test completed, pull-out test of specimens in Group II were conducted. In Group III and IV, rebar were taken out from concrete. Rust on the rebar was removed in group III while rust remained on rebar in group IV, then casted into new concrete before pull-out test.

Tensile loading at the end of rebar was applied by universal test machine till the rebar yielded. The loading speed was around 100N/sec. The slip of rebar was measured by four LVDTs installed on the supporting frame by bolts as shown in Fig.1(a).The surface crack opening of corroded specimen during loading was measured by two PI gauges installed on the concrete surface with smallest cover thickness.
Average bond stress τ from the rebar loading end to center of specimen based on the steel stress distribution was calculated by Eq.(1) [6].

$$\tau = A_s(\sigma_{s1} - \sigma_{s0})/ul \qquad (1)$$

where A_s is the nominal cross-sectional area of rebar, u is the nominal rebar perimeter, σ_{s0} and σ_{s1} is the steel stress at the center and loading end, l is the embedded length of half specimen (75mm).

Table 3. Test specimens

Group	Corrosion condition	Rebar diameter (mm)	C (mm)	Corrosion degree X_p(%)	$f'c$ (MPa)	Specimen number
I	Non-corroded	D16	30	0.0	35,39,40	9
II	Normal			5.0, 10.0	35,39	5
III	Corroded rebar without rust			5.0, 10.0	35,40	8
IV	Corroded rebar with rust			5.0, 10.0	35,40	6

The slip of rebar is calculated by Eq.(2).

$$S = S_{LVDT} - \Delta l \qquad (2)$$

where S_{LVDT} is the measured slip by LVDT and Δl is the rebar elongation which is calculated by rebar strain obtained from load value and the length from the support frame to concrete surface.

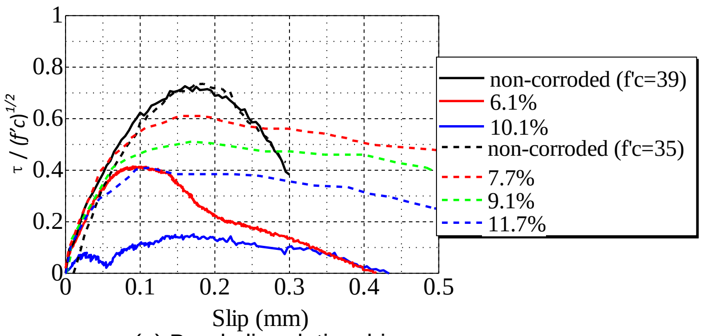
3. TEST RESULTS

3.1 Bond-slip Relationship of Normal Corroded Specimen

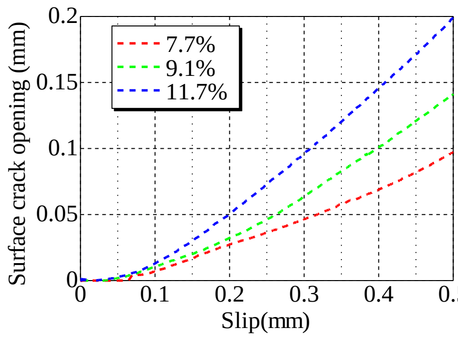
The bond-slip relationship and surface crack opening-slip relationship of corroded specimens in Group II are shown in Fig.2. In order to eliminate the influence of concrete strength at different casting sequences, bond stress of each specimen is normalized by being divided by $(f'c)^{1/2}$, because bond strength of non-corroded concrete proposed by Iizuka et al. [6] is the function of $(f'c)^{1/2}$. In Fig.2(a), bond-slip relationships of non-corroded specimens are the averaged curve of specimens with same concrete compressive strength. The shape of non-corroded bond-slip relationship is parabolic. Compared with non-corroded case, normal corroded specimen shows relative lower ultimate bond strength τ_{max} and smaller slip at ultimate strength with the increase of corrosion degree. Internal crack patterns are shown in Fig.3. Actual corrosion degree is shown in the figure. The photos are cross-sectional crack pattern at position of 1/4 length of specimen, which were observed by cutting specimen after corrosion test and after pull-out test. Specimens cut after corrosion test was prepared in same corrosion series. Internal crack pattern shows one vertical and two horizontal corrosion crack, which in agreement with crack pattern under same concrete cover thickness to rebar diameter ratio C/D observed in previous studies [7]. Comparing internal crack pattern formed by rebar pull-out with corrosion crack of specimens, it can be observed that splitting cracks propagate longer and turn into diagonal direction at higher corrosion degree. It is confirmed that splitting crack develops along the initial corrosion crack.

According to surface crack opening behavior shown in Fig.2(b), gradient change of the crack widths along the slip happens when bond-slip curve enters non-linear stage. With the increase of corrosion degree, crack opening initiate earlier and develops faster with pull-out of rebar. As a result, mechanical interlocking between rebar ribs and cracked concrete proportioned to crack opening gradually deteriorates and yields to a lower bond strength and slip.

Moreover, initial stiffness at elastic stage of bond-slip relationship does not show obvious degradation. In this stage, bond force is only contributed by cementation action. It is confirmed that rebar corrosion does not severely affect the adhesive force between rebar and concrete interface. It is noted that gradient of softening curve of corroded specimens except 6.1% corrosion case appears different with non-corroded case. For non-corroded case, abrupt descending segment in the primary stage corresponds to the process of interlocking action

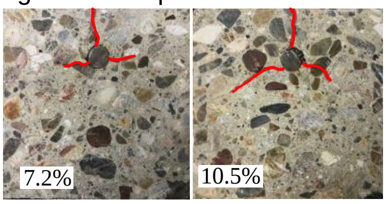


(a) Bond-slip relationship

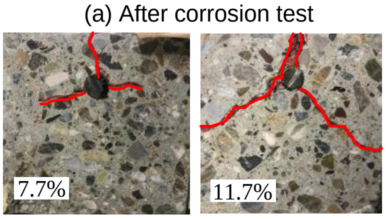


(b) Surface crack opening-slip relationship

Fig.2 Bond-slip and surface crack opening-slip relationship of normal corrosion specimen



(a) After corrosion test



(b) After pull-out

Fig.3 Crack pattern of corroded specimen

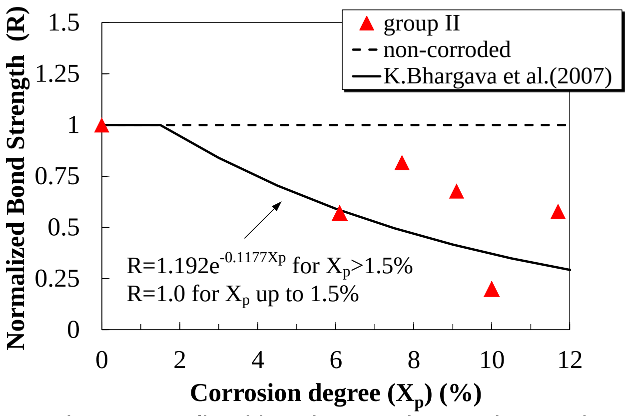


Fig.4 Normalized bond strength R and corrosion degree relationship of normal corrosion specimen

being rapidly destroyed. On the contrary, for corroded specimen, a more gradual descending was obtained. It is because of some energy has already released due to the existence of corrosion crack before pull-out hence shows a mild softening stage. The decrease of softening gradient with the extent of rebar corrosion was also reported in previous researches [1,2,3].

The relationship between normalized bond strength R and corrosion degree are shown in Fig.4. Bond degradation from non-corroded case is in good agreement with empirical model proposed by Bhargava et al. [5], as the function of corrosion degree.

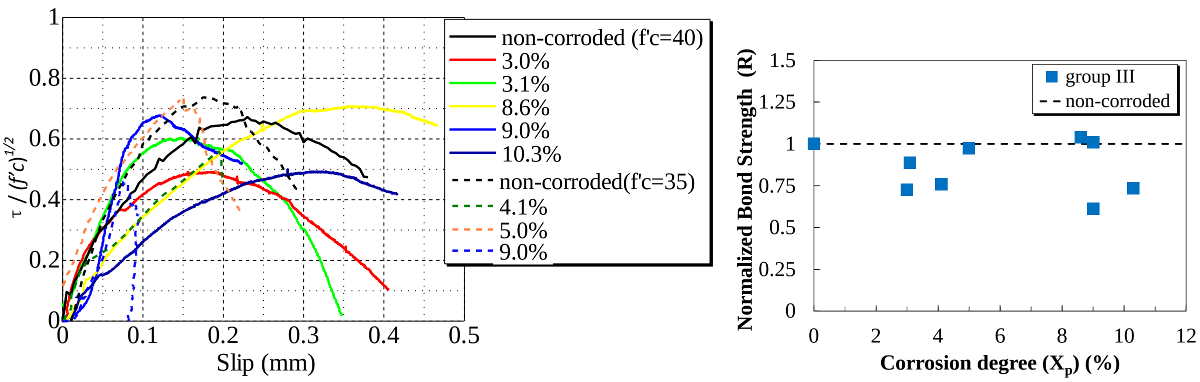
3.2 Bond-slip Relationship of Corroded Rebar without Rust in Non-corroded Concrete

In order to evaluate the single effect of rebar profile change subjected to corrosion, the influence of corrosion crack and generation of corrosion product is excluded. Bond-slip relationships of specimens in group III are demonstrated in Fig.5(a). Correspondingly, relationship between normalized ultimate bond strength R and corrosion degree is summarized in Fig.5(b). Ultimate bond strength τ_{max} and slip at τ_{max} do not show strong dependency on corrosion degree. However, the values are smaller than the non-corroded specimen. Initial stiffness of bond-slip relationship does not decrease until the corrosion level is higher than 8%. Adhesive force enveloping around rebar tends to become weaker of rebar without rust at high corrosion degree. For all specimens, comparing to non-corroded case, softening stage of bond-slip curve shows similar or steeper gradient, which appears different tendency with normal corrosion case. This inconsistency can be attributed to the absence of initial corrosion crack and the reduction of friction force due to geometry change.

Compared to Fig.4, normalized bond strength shows a higher value at similar corrosion level than normal corrosion case, the difference mainly comes from the absence of corrosion-induced crack.

3.3 Bond-slip Relationship of Corroded Rebar with Rust in Non-corroded Concrete

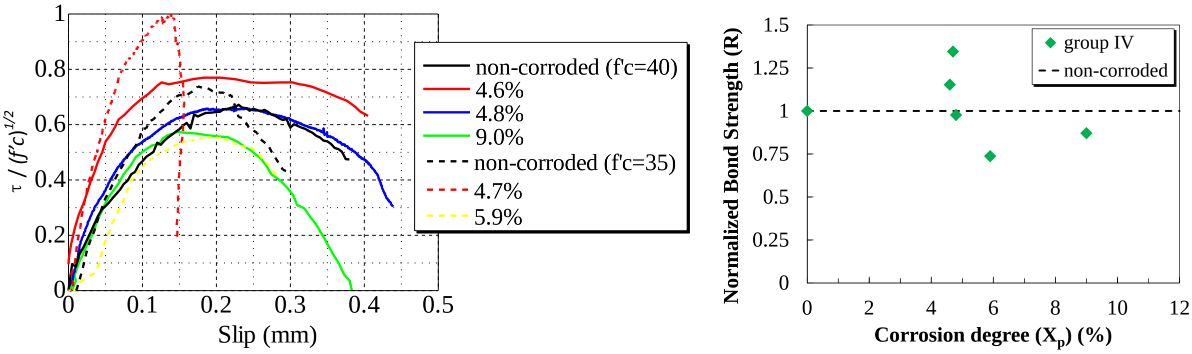
In group IV, the influence of corrosion crack is excluded to clarify the effect of accumulated corrosion product on the rebar surface on bond behavior. Bond-slip relationships of rebar with rust in non-corroded concrete are shown in Fig.6(a) and relationship between normalized ultimate bond strength and corrosion degree is shown in Fig.6(b). With increase of corrosion degree, an increase of ultimate bond strength τ_{max} is observed at around 5% corrosion, while a decrease can be seen at a high corrosion level. Geometry change of corroded profile due to accumulation of rust thickness and corrosion depth can be the major factor to explain this phenomenon. Moreover, slip at τ_{max} does not show obvious degradation with corrosion degree. At elastic



(a) Bond-slip relationship

(b) Normalized bond strength R and corrosion degree relationship

Fig.5 Bond of corroded rebar without rust in non-corroded concrete



(a) Bond-slip relationship

(b) Normalized bond strength R and corrosion degree relationship

Fig.6 Bond of corroded rebar with rust in non-corroded concrete stage of bond-slip relationship, an increase of initial stiffness is captured corresponding to the increase of bond strength. The reason might be the adhesive bonding force between concrete and rust layer become larger, result in stronger cementation action. In all specimens, softening behavior shows similar tendency as rebar without rust case and differs to normal corrosion case. On the basis of softening behaviors of group III and IV, gradient reduction at softening stage in normal corrosion specimen can be concluded as the result of formation of corrosion crack.

Compared to Fig.4 and Fig.5(b), normalized bond strength in group IV shows a relatively higher value than normal corrosion case and rebar without rust case at similar corrosion level. As a result, the influence of corrosion crack on bond deterioration appears to be more dominant than accumulation of corrosion product and change of rebar profile.

4. GEOMETRIC PARAMETER OF CORRODED REBAR

4.1 Introduction of Laser Scanning and Measurement Method

In order to clarify the geometry change of rebar subjected to corrosion accurately, measurement of rebar profile was conducted by laser scanning test. The measuring instrument setup is shown in Fig.7. Rebar was anchored on a mobile track, which moves along horizontal direction to laser meter, it scanned the height of rebar surface with 0.05mm interval at rebar axial and radial direction. The measured length between two anchors included 150mm corrosion part and 50mm non-corroded part.

Six rebar in group III and five rebar in group IV were measured. Rebar longitude profile was reconstruct and height difference induced by corrosion within corrosion length was compared with non-corroded part.

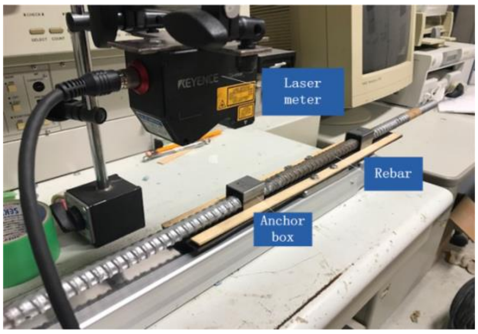


Fig.7 Measuring instrument of rebar profile

4.2 Parametric Analysis of Rebar with and without Rust

Geometric parameter of corroded rebar was studied by analyzing profile height distribution along rebar axial direction, which defines as profile line. Based on observation of corroded rebar and corrosion status in previous research using similar corrosion method [7], corrosion area is highly concentrated on upper quarter of rebar cross-section with minimum cover thickness. Thus profile lines were taken from the assumed quarter area and the averaged profile line was utilized for parametric analysis.

In this investigation, profile characteristic of corroded rebar is represented by three indexes referred to standards of surface characterization [8]: mean rib height of corroded rebar R_h, root mean square deviation of profile line R_q which descripts height deviations, skewness of profile line R_{sk} which is sensitive on occasional deep pitting or high peaks. Profile indexes are calculated by Eq.(3)-(5) basing on height function shown in Fig.8. Corroded area in the concrete and non-corroded area were calculated separately.

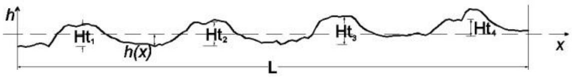


Fig.8 Height function of corroded rebar profile

$$R_h = \frac{\sum_1^N Ht_N}{N} \tag{3}$$

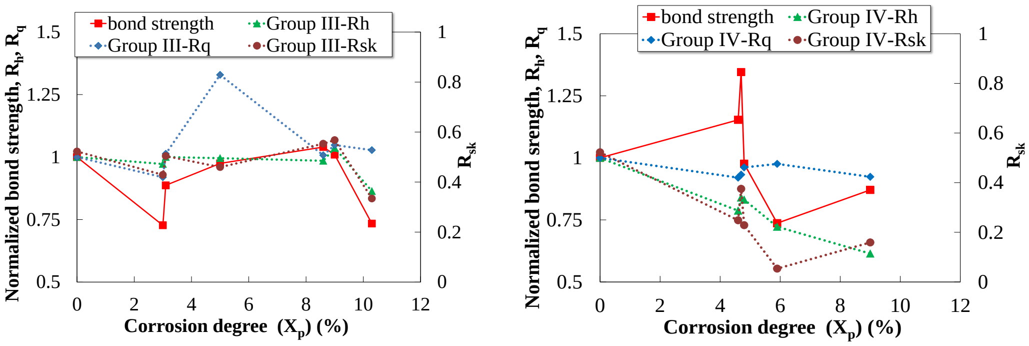
$$R_q = \sqrt{\frac{\sum_1^n h(x)^2}{n}} \tag{4}$$

$$R_{sk} = \frac{1}{Rq^3}\left[\frac{\sum_1^n h(x)^3}{n}\right] \tag{5}$$

where Ht_N is the corroded rebar rib height, represents the height difference between adjacent center of rib and body part, N is the number of rib in measured length L (150mm), $h(x)$ is the relative height of data point subtracting the mean height calculated on measured length, n is the number of data points in measured length.

4.3 Influence of Rebar Geometric Parameters on Bond Strength

The profile index R_h and R_q were normalized by non-corroded region from same rebar while absolute value of R_{sk} was used because skewness is a high-mode unit-less parameter which rises difficulty in normalization. Profile indexes were compared with corresponding bond strength. Fig.9 shows normalized bond strength and profile indexes under various corrosion degrees in group III and IV. For rebar without rust case, with increase of corrosion level, R_h shows a mild descending from non-corroded case till 9.0% corrosion, after that, an obvious decrease is observed at 10.3% corrosion. Comparing to bond strength, the degradation level shows similar tendency and magnitude after 4% corrosion. It is because that interlocking force between rib part and concrete is the dominant factor of bond capacity. In rebar without rust case, profile height at rib part and rebar body part both reduced from non-corroded profile and loss of rebar part become more dominant than body part with the increasing of corrosion degree. Hence, degradation of R_h is small at low corrosion level and develops faster at high corrosion level. For rebar with rust case, degradation of R_h is severer than rebar without rust case and shows a faster decrease than the bond strength deterioration. Profile height of



(a) Rebar without rust (b) Rebar with rust

Fig.9 Normalized bond strength, R_h, R_q and R_{sk} -corrosion degree of rebar with and without rust in non-corroded concrete

rib part reduces along the increase of rust height on the body part, result in obvious descending of rib height with increase of corrosion degree.

Height deviation index R_q is more sensitive to the change of rebar shape. For rebar without and with rust case, a mild reduction of R_q is observed at around 4% corrosion and reaches similar value as R_h and bond strength. At high corrosion degree, degradation of the R_q is smaller than R_h while a certain correlation with bond strength is shown at 9% corrosion in both cases. This is because R_q not only considers the profile change at rib part, but also includes height variations at body part, which tends to become rougher due to the formation of pitting and accumulation of rust.

Skewness of profile line R_{sk} has the highest sensitivity with the change of surface roughness among these indexes. In rebar without rust case, R_{sk} value shows a positive value and similar tendency with bond strength degradation which represents the geometry of corroded rebar remains the characteristics as non-corroded rebar with distinguished ribs and flat body. While in rebar with rust case, deterioration of R_{sk} is larger than bond strength and approaches to negative value. This describes the accumulation of rust at body turning the profile shape into lack of high peaks.

5. CONCLUSIONS

(1) With the increase of corrosion degree, normal corroded specimen shows relatively lower ultimate bond strength and smaller slip. Corroded rebar with or without rust in non-corroded concrete shows relative independency of ultimate bond strength and slip at ultimate bond strength.

(2) Rebar corrosion does not severely affect the adhesive force between rebar and concrete, therefore initial stiffness of bond-slip relationship does not show obvious degradation.

(3) In normal corrosion case, gradient of bond-slip curve at softening stage shows a tendency of reduction with increase of corrosion degree, while with the absence of corrosion crack, softening behavior shows similar tendency as non-corroded case.

(4) Results of geometric study of corroded rebar profile have shown certain correlation between geometric parameters and bond strength.

(5) Effects of corrosion crack, corroded rebar shape and corrosion product on bond deterioration have been examined. Corrosion-induced crack in concrete was clarified to be more dominant than corrosion product and change of rebar profile in bond deterioration mechanism.

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