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Corrosion influence on bond in reinforced concrete

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Abstract

The bond between reinforcing steel and the surrounding concrete can be deteriorated by corrosion. Pullout tests were carried out to evaluate the effects of corrosion on bond and bond–slip behavior, for a series of specimens with varying reinforcement corrosion levels between 0% and 9%, and for specimens with and without stirrups that provide confinement. Specimens with both smooth and deformed bars were tested. The tests were designed to provide the data required to assess the bond properties, including the ultimate bond strength and free-end slip for various degrees of corrosion under pullout loads. The specimens were tested in an MTS testing machine on which loads, slips and displacements were recorded. Some conclusions have been reached based on the test results.

Keywords: Reinforcement corrosion; Bond strength; Reinforcement; Concrete

1. Introduction

While it is known that reinforcing steel provides strength and ductility only through bond and anchorage to the concrete, the effectiveness of this connection can be reduced through deterioration of the steel, concrete or both. Therefore, the durability of concrete structures depends on the resistance of the concrete against chemical and physical factors and its ability to protect the embedded reinforcement against corrosion [1]. In view of the fact that a large number of existing structures are being deteriorated with time by reinforcement corrosion due to environmental exposure, corrosion is one of the main causes for the limited durability of reinforced concrete [2]. The corrosion product, rust, resides at the interface between reinforcement and concrete, degrading the bond between rebar and concrete and thus reducing the service life of the structure. The nonuniformity in bond stress distribution causes difficulties in assessment of the effects of corrosion on bond and thus on the structures.

Recently, a number of studies have been undertaken to evaluate the effects of corrosion on the bond strength [3,4,5]. Studies conducted by some researchers suggested that losses in the structural performance of reinforced concrete members with corroded reinforcements are caused by three factors [6–11]: losses in the effective cross-sectional area of concrete due to cracking in the cover concrete, losses in the mechanical performance of reinforcing bars due to the losses in their cross-sectional area and losses in the bond performance of concrete with reinforcements. Studies conducted by Auyeeung [12] have confirmed that the loss of bond strength for unconfined reinforcement is much more critical than cross-section loss; that is, a low percent diameter loss could lead to 80% bond reduction. Auyeeung's study also showed that confinement provides excellent means to counteract the bond loss.

Although numerous research programs have been conducted regarding bond behavior of corroded steel bars and concrete, some aspects regarding different degrees of corrosion of reinforcement in concrete need further study. The objective of this study, therefore, is to evaluate the effect of different degrees of reinforcement corrosion on the bond degradation.

2. Experimental program

2.1. Experimental methods

Two series of tests were carried out, for specimens of different degrees of corrosion under pullout and cyclic loading, respectively. Among the tested specimens, 40 were

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Fig. 1. Bars used as reinforcement.

tested under pullout loading. This study is based on the pullout test results to evaluate the bond properties, including the ultimate bond strength and free-end slip for various corrosion levels.

The specimens, after curing for 28 days, were emerged in a 5% NaCl solution in order for the steel bars to be corroded to different designed corrosion levels under direct electric current. The specimens were then tested for bond strength and slip under pullout loading. It had been noted that the initiation and propagation of corrosion in the specimens depend on many factors, among them are:

(1) Permeability of the concrete matrix;
(2) Cover thickness;
(3) The electric current applied;
(4) Density of the solution used;
(5) The environmental temperature.

Electrolytic corrosion method was used to accelerate the corrosion. In the procedure of reinforcement corrosion, electric current and corrosion time were used as the indications for the designed corrosion levels. The contact resistivity was also recorded together with the corrosion time. The contact resistivity is a quantity that increases monotonically with an increasing amount of interfacial phase (rust), because the interfacial phase has a higher volume electrical resistivity than steel and even likely a higher resistivity than concrete as well. In this study, however, the resistivity was used only as a reference factor for the analysis of the test results rather than to determine the corrosion levels.

2.2. Test specimens

The design of the specimen conformed to Standard Methods for Testing of Concrete Structures (GB 50152 92, China Standard). The reinforcing steels used for both smooth and deformed bars were hot-rolled Grade I and Grade II bars, respectively, as shown in Fig. 1. The mechanical properties of the reinforcement are shown in Table 1. The reinforcement had a diameter of 20 mm and a length of 420 mm. The length of the main reinforcement bar was kept to 420 mm to facilitate loading of the specimen in an MTS 880 testing machine and measurement of the free-end slip. For those specimens with stirrups, round steel with a diameter of 6 mm was selected for rectangular closed stirrups with a spacing of 40 mm, as shown in Fig. 2. To avoid corrosion of the stirrups, they were isolated from the main bar.

Table 1
Mechanical properties of reinforcement

Material	Yield stress (N/mm^2)	Tensile strength (N/mm^2)	Elastic modulus (N/mm^2)	Elongation (%)
Smooth bar A3 (Grade I)	289.6	440.0	210,000	30.3
Deformed bar 20MnSi (Grade II)	350.9	521.2	200,000	34.0

The bars were descaled and cleaned before casting into the concrete specimens. The embedment length chosen was four times the bar diameter, e.g., 80 mm, as shown in Fig. 2. This short embedment length was selected to avoid yielding of the steel bar under pullout load. To debond the remaining 100-mm length of reinforcement, 50-mm-long PVC conduits that were about the same in diameter as the main reinforcement were used on both ends of the specimen. This arrangement ensured a bar embedment length of 80 mm in contact with the concrete. These debonded zones were also used to protect the reinforcement from the confining pressure of concrete at the supports.

Normal Portland cement, fine aggregate (medium-sized natural sand) and coarse aggregate (crushed limestone) in the ratio of cement/sand/coarse aggregate = 410:658:1120 with the water/cement ratio of 0.44 were used to prepare the concrete mixture.

All ingredients were mixed in a concrete mixer for about 20 min. The concrete mix was then poured into $140 \times 140 \times 180$ mm^3 wooden moulds (see Fig. 3). A steel reinforcement bar was positioned horizontally at the center of

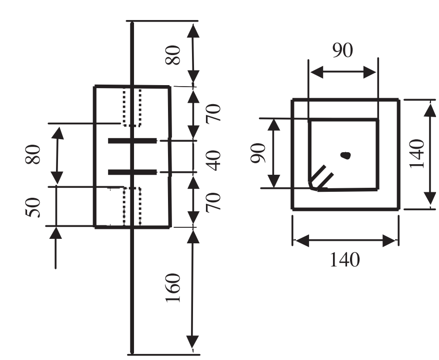

Fig. 2. Geometry of the specimens used in the study. All dimensions in mm.

Fig. 3. Mould for specimens with stirrups.

the mould and held in place by plastic ties. Holes were made in both ends of the mould so that the steel bar could protrude through the specimen for convenience of installation in the testing machine and measurement of free-end slip. The moulds containing the concrete mix were then placed on a vibrator for casting. Five concrete cubes with a dimension of $100 \times 100 \times 100$ mm^3 were also cast for testing the compressive strength of the specimens.

After casting, the concrete specimens, both pullout specimens and cubes for compressive strength, were kept in the moulds and covered with damp polythene at 20 °C for 3 days. They were then demoulded and kept in a standard curing room for 28 days. The 28-day cured specimens had an average measured strength of 52.1 MPa. The specimens were then fully immersed in a 5% NaCl solution. Non-corrosion specimens were immersed in water.

2.3. Corrosion acceleration

To accelerate reinforcement corrosion, direct electric current was impressed on the steel bar embedded in the specimen using an integrated system incorporating a rectifier with a built-in ammeter to monitor the current, and a potentiometer to control the current intensity. The specimens were immersed in NaCl solution for 3 days before the direct current was applied. The specimens were fully immersed in water in a plastic tank. The direction of the current was adjusted so that the reinforced steel bar served as the anode while a stainless steel plate counterelectrode was positioned in the tank to act as a cathode.

Fig. 4 shows schematically the electrochemical system used. A potentiostat was set to let the reinforcement act as an anode; the stainless steel cylinder immersed in the solution was used as the counterelectrode, the cathode. An electric wire was soldered to the main reinforcement to impress the electric current. The stainless steel cylinder that served as the cathode consumed the excess electrons given off by the reinforcement during the corrosion process. Power supplies with adjustable voltage and current (from 0 to 2 A) were chosen for the electrolyte corrosion process. The positive terminal was connected to the steel bar and the negative terminal was connected to the stainless steel cylinder.

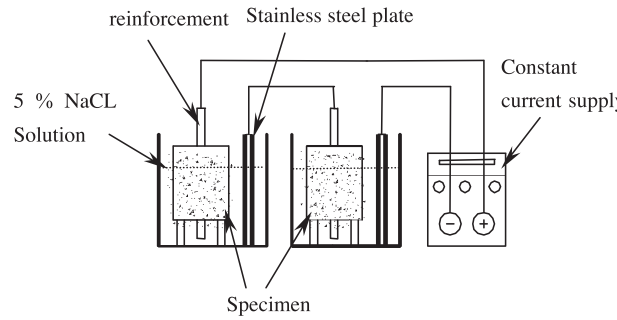

Fig. 4. Schematic representation of the electrochemical system.

To ensure that only the bonded zone would be corroded, one end of the steel bar was insulated during the corrosion. The lower part of the steel bar was coated with paraffin, and wrapped with insulated plastic membrane, as shown in Fig. 5.

After the power supply was turned on, the current was adjusted and fixed to a volume, and the voltage was adjusted automatically by the constant current supply. Both voltages and resistivity were recorded at 6-h intervals. The appearance of the first crack was monitored carefully as this formed a reference time for selecting pre- and post-cracking levels of corrosion. The current was impressed to accelerate the reinforcement corrosion process and meet the objectives of this study within a reasonable period of time.

To establish different corrosion levels of reinforcement corrosion, tables showing durations of impressed current and the corresponding degree of corrosion were prepared according to Faraday's law that states: the amount of corrosion is a function of voltage, amperage and time. The designed amount of corrosion was calculated according to the designed degree of corrosion and the weight of the reinforcing bar along the bond length, based on the unit length of the reinforcing bar. On the other hand, the designed amount of

Fig. 5. Insulated end of steel bar during corrosion.

corrosion, in terms of the mass loss of reinforcing steel due to corrosion can be estimated by the following equation:

$$m_t = \frac{t \times \bar{I} \times 55.847}{2 \times 96487} \quad (1)$$

where t is the duration of exposure and $\bar{I}$ is the average current over the duration which the reinforcement was exposed to. Therefore, the designed degrees of corrosion were used to calculate the electric current and the time of corrosion.

It should be noted that the designed degrees of corrosion as well as the corresponding amounts of corrosion (Eq. (1)) were used only to roughly control the electric current and the time of corrosion in the corrosion procedure. A small amount of NaCl was added to the concrete mix before casting, to reduce the degree of nonuniformity of corrosion along the length of the rebar. The actual amount of corrosion of the reinforcing bar was measured as the loss in weight of the reinforcement steel bar. The actual degree of corrosion, or corrosion level, was accordingly measured as the loss in weight of the reinforcement steel bar to that of the bond length before corrosion, and thereby representing an average corrosion level along the bond length (see Eq. (2)). Before being placed into the moulds, the reinforcing bars were cleaned with a 12% hydrochloric acid solution, then cleaned by pure water, and neutralized by calcium hydroxide solution before being cleaned by pure water again. The steel bars were then dried for 4 h in a dryer chamber. Thereafter, the treated bars were weighed for the original weight (accurate to 0.1 g). Upon completion of bond tests, the specimens were photographed and scanned for cracks. The corroded steel bars were then removed from the specimens, and treated the same way as that for obtaining the original weight.

The corrosion level was expressed using the following equation:

$$C_{\mathrm{R}} = \frac{G_0 - G}{g_0 l} \times 100\% \quad (2)$$

where G_0 is the initial weight of the reinforcement before corrosion, G is the weight of reinforcement after removal of the corrosion products, g_0 is the weight per unit length of the reinforcing bar, and l is the bond length.

3. Pullout tests

The concentric pullout test is widely used due to its simplicity. In this test, a steel bar is embedded in a rectangular concrete beam specimen. The bond tests were carried out on an MTS 880 testing machine that had a capacity of 50 kN, as shown in Fig. 6. A specially designed loading frame was used for the tests under pullout loading, as shown in Fig. 7. To measure the slip more accurately, one COD gauge, as shown in Fig. 8., was used when the slip was small, i.e., less than or equal to 2 mm, while the MTS built-in LVDT (not shown) was used to measure the displacement from the beginning up to the completion of the loading. The outputs from the COD and the LVDT as well as the loading system of the testing machine were connected to a computer. The load, slip and displacement readings were displayed on and recorded automatically by the computer. All the loads were applied through the computer, using displacement control. The loading speed was 0.004 mm/s when slip was not greater than 2 mm, and 0.02 mm/s when slip was greater than 2 mm. For all the tests, the strain in the steel bars was very low and yielding of the steel bars was not observed.

Fig. 6. Pullout test system.

4. Test results and discussions

To obtain the bond properties between corroded reinforcement and concrete, the test results were analyzed for the following major parameters:

(1) Comparison between theoretical and actual degree of corrosion;
(2) Load–slip behavior and slip at failure at different corrosion levels;
(3) Effects of corrosion level on the bond strength.

The theoretical corrosion levels were first designed and the corresponding corrosion amounts were computed using Eq. (1). The actual corrosion levels were estimated through measurements using Eq. (2). The two results differed (see Table 2) which shows both theoretical and measured values of some specimens.

From Table 2, it can be seen that the measured corrosion levels were generally lower than the designed ones. The difference in results indicates that the permeability of

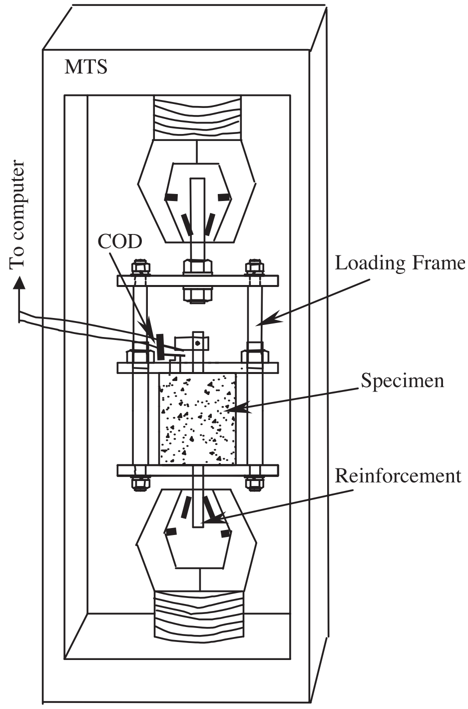

Fig. 7. Test setup.

concrete plays a role in the magnitude of actual corrosion; the permeability of the concrete was not included in the equations for the theoretical calculation of corrosion amounts. Although the specimens were immersed in the NaCl solution, it would have taken a period of time for the solution to reach the reinforcement through the concrete cover. Another factor that affects the corrosion may be the heterogeneity of the coarse aggregate within the specimen. Generally, the longer the specimen was immersed in the salt solution, the less the difference between the measured value and the designed one. Furthermore, it was observed that the corrosion speeded up after the cracking of the specimen.

It was observed in the corrosion process that the electrical resistivity increased quickly during the beginning period of the corrosion process, and then increased more slowly for a relatively long time until it stopped increasing and began to

Fig. 8. COD setup.

Table 2
Comparison between designed and measured corrosion level for some specimens

Specimen number	Specimen type[a]	Designed corrosion (%)	Measured corrosion (%)	Corrosion time (h)	Time of cracking (h)
1	D1	3.0	2.01	92.95	No crack
2	D1	7.0	4.29	219.16	120
3	D1	10.0	9.02	324.36	106.5
4	D2	3.0	1.00	92.95	No crack
5	D2	10.0	3.84	324.36	252
6	D2	7.0	6.01	219.16	72
7	S1	3.0	3.28	92.95	81.8
8	S1	10.0	6.77	324.36	226
9	S2	3.0	3.02	92.95	81.8
10	S2	7.0	4.74	219.16	154

[a] In all figures, D1: deformed without stirrups; D2: deformed with stirrups; S1: smooth without stirrups; S2: smooth with stirrups.

decrease (see Fig. 9). Surface fine cracks could be observed a short time after the resistivity began to decrease. With the fine cracks growing, the value of resistivity decreased quickly to a constant value.

The load and free-end slip were recorded automatically by the computer for each loading. The bond stress was calculated from the external loads on the reinforcement and surface area of the embedded portion of the reinforcement, thus expressing an average stress along the bonded length of the reinforcement.

Fig. 10 shows load versus free-end slip relationships for different corrosion levels for deformed reinforcement bars without stirrups. The corrosion levels for the three specimens were 0%, 4.0% and 9.0%. Substantial degradation was observed as the corrosion level increased. The ultimate load decreased from 110 to 60 kN as the degree of corrosion increased from 0% to 4.0%, and then even further to 9.0%. The corresponding free-end slip at the ultimate load decreased from 0.56 through 0.097 mm and then to 0.064 mm.

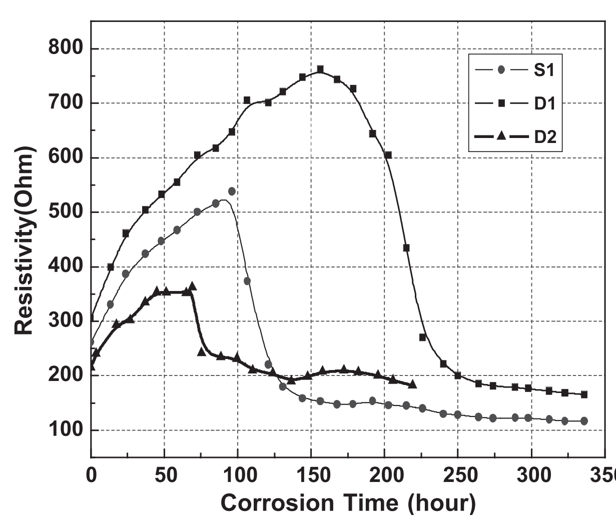

Fig. 9. Relationship between resistivity and corrosion time.

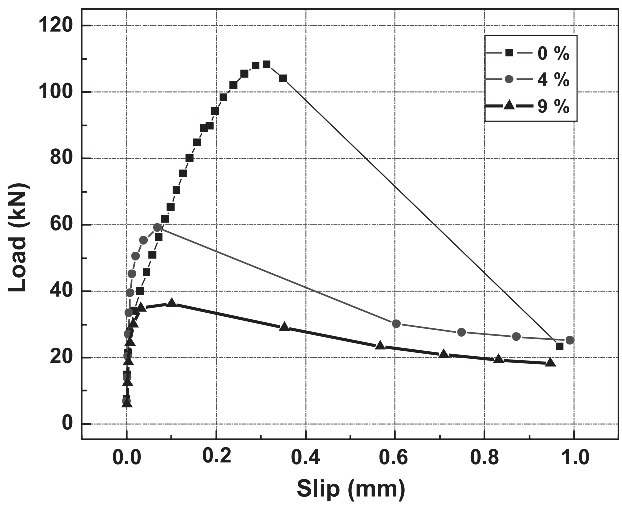

Fig. 10. Relationship between load and slip for test of deformed reinforcing bar without stirrups.

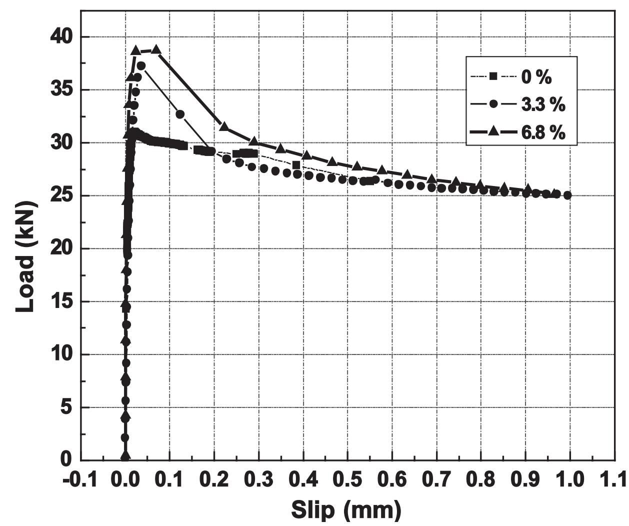

Fig. 12. Relationship between load and slip for smooth reinforcing bar without stirrups.

All the corroded specimens shown in Figs. 10–13 had longitudinal corrosion-induced cracks. Figs. 10–13 reveal that as the corrosion level increased, bond strength of deformed reinforcing bar specimens decreased, whereas that of smooth bar specimens increased. Fig. 11 shows that as the degree of corrosion increased, there was no substantial degradation in bond strength for deformed reinforcing bar with stirrups. In terms of bond strength of corroded specimens when compared to bond strength of noncorroded specimens, when the degree of corrosion was 6.0%, the bond strength only decreased 12%. An explanation may be that although corrosion had caused fine cracks in the specimen, the stirrups provided enough confinement. When a pullout load was applied to the specimen, the bearing action of the ribs of the deformed sled bars against the concrete caused horizontal bearing stresses as well as hoop stresses. Due to the corrosion cracks, the tension in the specimen was reduced and therefore the confinement was reduced and the slip increased which finally resulted in bond failure of the specimen. For the corrosion levels in this range, bond failure usually was the result of splitting of the specimen along the corrosion cracks. For this type of failure, the corrosion-induced cracks had already weakened the concrete.

At higher levels of corrosion, a postpeak plateau or residual bond strength was observed for deformed reinforcing bar specimens with stirrups. For the control specimen (no corrosion) with deformed bar, the load–slip curve usually had a sharp decrease. For samples with higher corrosion levels, this decrease was more gradual. A possible explanation is that corrosion-induced cracks on the specimen had already released some energy before loading. For deformed bar specimens, slip at ultimate bond load tended to decrease as the corrosion level increased.

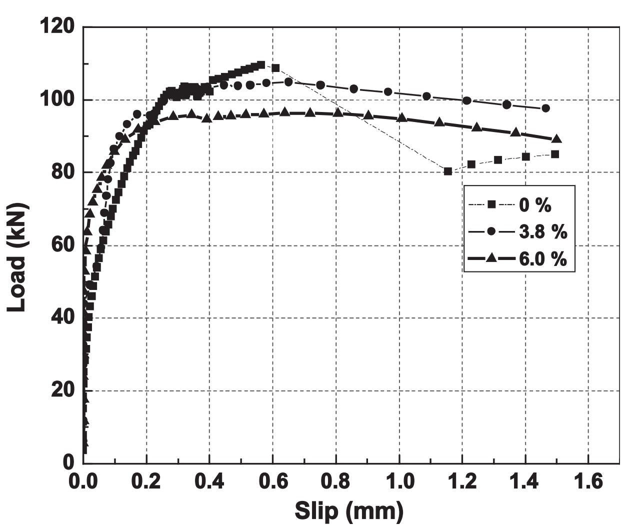

Fig. 11. Relationship between load and slip for test of deformed reinforcing bar with stirrups. Corrosion levels are 0–6%.

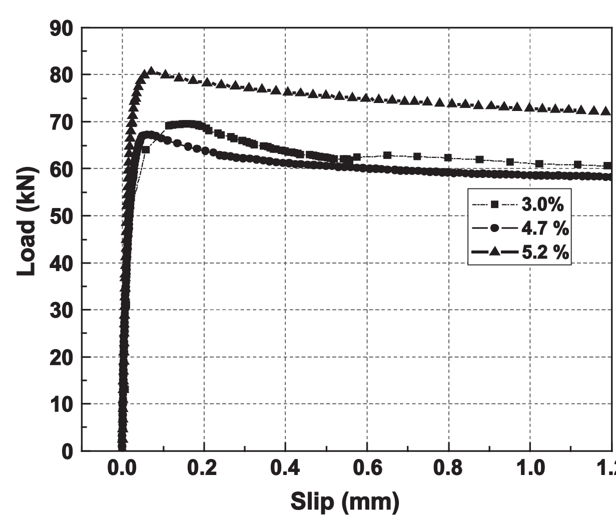

Fig. 13. Load versus free-end slip relationships for different corrosion levels for smooth reinforcing bars with stirrups.

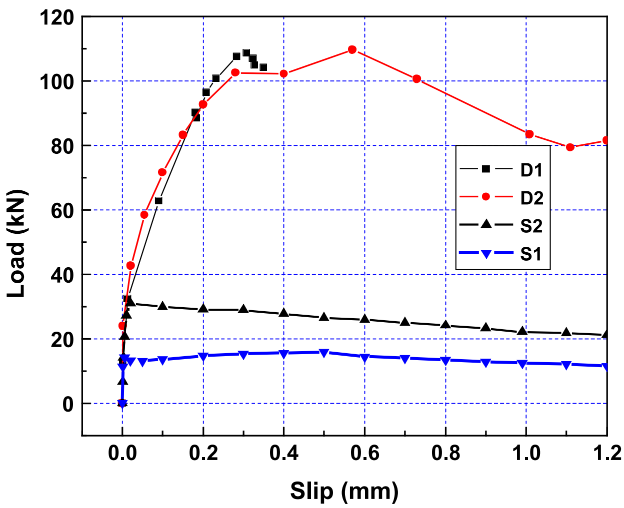

Fig. 14. Effects of rib profile and stirrup on slip for noncorroded specimens.

For smooth reinforcing bar specimens, at low to medium corrosion levels (longitudinal fine cracks were observed), bond strength increased as the corrosion level increased (see Figs. 12 and 13). When comparing these figures, without and with stirrups, bond strength increased as the corrosion level increased from around 3% to a value of more than 5%. It is interesting to note that, for smooth bar with stirrups, bond strength for a corrosion level of 5.2% is about 20% higher than that of a corrosion level of 3.0%, as shown in Fig. 13. This can be attributed to an increase in confinement of the bar in the concrete, as the amount of corrosion product increases and develops an expansive mechanical pressure on the surrounding concrete. Another factor for the increase of bond strength is that, in the initial stages of corrosion, the roughness of the reinforcing bar increases and thus enhances the friction between the bar and the surrounding concrete. Both these effects increase the bond resistance and decrease the slip of the bar [13].

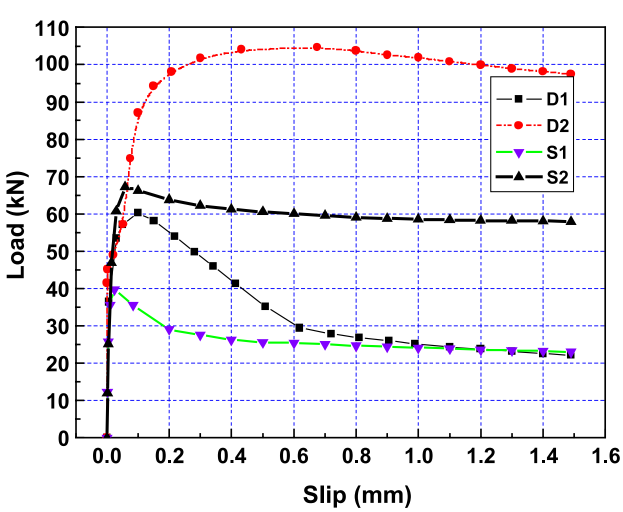

Fig. 15. Effects of steel bar profile and stirrups on slip with a corrosion level of around 3%.

Figs. 14 and 15 show bond–slip relationships for different rib profiles with and without stirrups, for noncorroded and for a corrosion level of around 3%, respectively. It can be seen from Fig. 14 that the bond strength of the deformed reinforcing bar specimen is much higher than that of the smooth bar

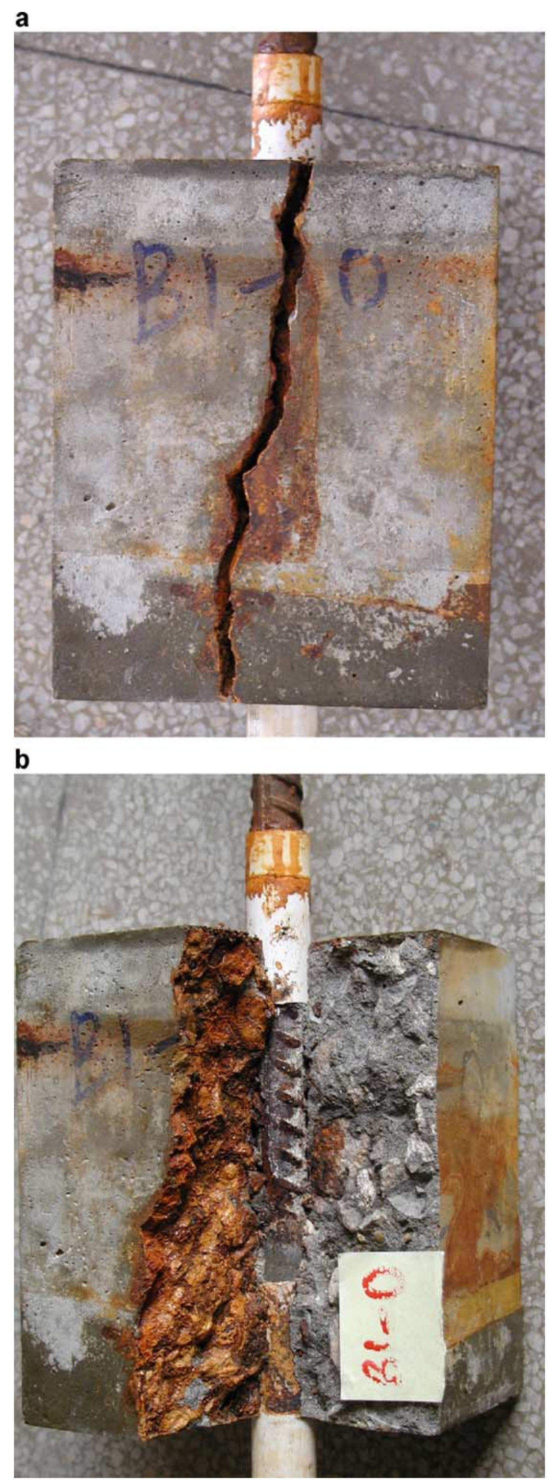

Fig. 16. Splitting of the specimen along the corrosion cracks, for deformed bar without confinement (corrosion 9%). (a) Wide crack after pullout test; (b) after decovering.

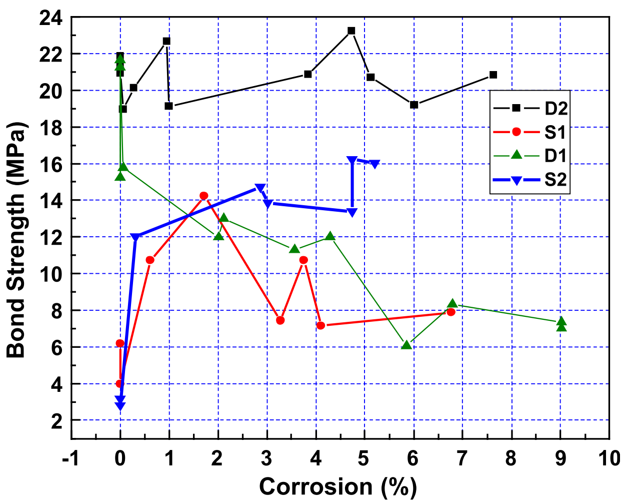

Fig. 17. Effects of reinforcement corrosion on bond strength, for different profiles of reinforcement, with and without stirrups.

specimen. The maximum bond strength of specimens with deformed bars is 3.5–6.9 times as high as for the bond strength of the specimen with smooth bars. For the deformed bar without stirrups, the sudden drop in load–slip curve at ultimate load is caused by the sudden splitting of the concrete cover over the bar. Specimens with deformed reinforcing bars with stirrups exhibited high ductility and still exhibited a high bond strength despite splitting at ultimate loading. The stirrups contribute to a very small crack width when splitting, about 0.2 mm. As a comparison, specimens without stirrups generally split at a very small slip, often with crack width up to 1.5 mm or even larger, as shown in Fig. 16, which result in a sudden drop of the bond strength, even to very small value. For smooth noncorroded reinforcing bar specimens, stirrups had no substantial influence on bond strength, as shown in Fig. 14. It should be noted that for smooth reinforcing bar specimens, in some cases, the bond strength with stirrups was less than that without stirrup. This is due to the scatter of the specimens and not a normal result.

It can be seen from Fig. 15, that the effects of corrosion at a level of 3% (fine cracks along the reinforcing bar due to corrosion were seen for all these specimens) on different specimens is as follows:

(1) No substantial influence on the bond strength for deformed bars with stirrups;
(2) Substantial reduction of the bond strength for deformed bars without stirrups;
(3) Considerable increase in bond strength for smooth bars with stirrups;
(4) Small increase in bond strength for smooth bars without stirrups.

Based on the test results, for different reinforcing profiles, the effects of reinforcement corrosion on bond strength are shown in Fig. 17.

5. Conclusions

From these tests, where splitting curves were observed for all corroded specimens, the following conclusions can be drawn:

(1) For deformed bars without confinement, bond strength was very sensitive to corrosion levels and generally decreased with the corrosion level. Bond strength decreased rapidly as the corrosion level increased; bond strength at 9% corrosion was only one third of that of noncorroded specimens. The exception is that when the corrosion level was very low, when bond strength increased as the corrosion level increased;
(2) For deformed bars with confinement, corrosion had no substantial influence on the bond strength;
(3) For smooth bar without confinement, there is a change in effect of the corrosion on the bond strength at a certain level; that is, when corrosion level was low, bond strength increased as corrosion level increased, with the ultimate bond strength as much as 2.5 times that of noncorroded, while bond strength decreased rapidly at higher corrosion levels. The break point was for corrosion levels of around 2–4%;
(4) For smooth bar with confinement, bond strength increased as corrosion level increased, up to a relatively high degree of corrosion. The increase in bond strength could be observed even at a corrosion level of more than 5%.

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