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Variation and degradation of steel and concrete bond performance with corroded stirrups

H.J. Zhou, X.B. Liang, X.L. Zhang, J.L. Lu, F. Xing, L. Mei *

Guangdong Provincial Key Laboratory of Durability for Marine Civil Engineering, Shenzhen University, Shenzhen 518060, China

HIGHLIGHTS

- Test of 60 specimens with stirrup corrosion levels from 0 to 20% was presented.
- Mean value and coefficient of variation of bond performance parameters were derived.
- Coefficient of variation increased for some bond parameters of corroded members.
- The degradation of bond strength was also compared to other test results.

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ABSTRACT

Stirrups are more vulnerable than rebar to environmental corrosion in real reinforced concrete structures. Corrosion of stirrups would degrade the confinement and may damage bond between rebar and concrete. This paper studied effects of stirrups corrosion on bond behaviors. 60 specimens were manufactured and divided into 5 groups with stirrup corrosion levels in the targeted range of 0–20%. Monotonic pull-out and cyclic loading scenarios were carried out to get the parameters of bond behaviors. The test results showed the degradation of bond parameters are less severe compared to that of rebar corrosion. It was also found that coefficient of variation of bond strength and corresponding slip value increased significantly for corroded members compared to that of intact members.

1. Introduction

Corrosion of steel reinforcement occurs for those reinforced concrete structures located in an aggressive environment, such as a marine environment [1]. The formation of corrosion products (rust) would change the surface of reinforcements between concrete. The rust also involves a significant increase of volume; therefore expansive stresses are induced in concrete around corroded reinforcements, which may lead to concrete cover cracking [2–5]. Bonding behaviors between the steel-concrete interfaces are essential for the composite action of reinforced concrete structures [6,7], which strongly affects both the flexural and shearing behaviors [3,8,9]. Bonding force is mainly composed by three different parts: chemical adhesion, mechanical interaction between rib and concrete and frictional resistance. The corrosion products occupy a larger volume than the steel they were formed of, which leads to splitting stresses acting on the concrete and may induce corrosion cracking of concrete cover, and thus reduces the confinement of concrete cover. The corrosion products form a weak layer, and thus may reduce the frictional resistance between steel and concrete interface. And the corrosion of steel rebar would also wear down ribs and significantly reduce the mechanical interaction force.

Many literatures are available on this topic, and it was confirmed that rebar corrosion had significant effects on ultimate bond capacity (bond strength) by experimental studies [10–15]; there are also some studies by numerical simulation or empirical regression techniques to analysis the relation between bond degradation and corrosion level [16–20]. However, there are still many unsolved issues related to the corrosion effects on bond performance; one topic was the scattering of bond parameters for the corroded members. Although many test results showed wider dispersion of bond strength after rebar corrosion [21], there were only two references [22,23] available on the statistical indicators of bond parameters

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* Corresponding author at: College of Civil Engineering, Shenzhen University, Nanhai Road 3688, Nanshan District, Shenzhen, Guangdong Province 518060, China.

E-mail addresses: haijun@szu.edu.cn (H.J. Zhou), 1308437613@qq.com (X.B. Liang), 1432301813@qq.com (X.L. Zhang), idljl01@163.com (J.L. Lu), xingf@szu.edu.cn (F. Xing), mayleeu@126.com (L. Mei).

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after rebar corrosion to the best of authors' recollection. Another blurry point was the effects of stirrup corrosion on bond performance [21,24]. Both rebar and transverse stirrups are applied in reinforced concrete structures to form reinforcing cages, and stirrups would be more vulnerable than rebar to environment corrosion due to the thinner concrete cover, which has been made manifest by site investigation and laboratory testing [4,21]. It should be noted that confinement (stirrups or concrete cover) was one of the main factors that bonding behaviors strongly depended on. Recent studies have also confirmed that stirrup corrosion would have a significant influence on the loading capacity of RC beams [25,26]. A preliminary test by the co-authors has shown a significant reduction of bond performance for specimens with more than 10% stirrups mass loss [24]. However, the preliminary study only tested 20 specimens for low strength concrete mixes (18.4 MPa) in order to simulate old concrete structures, so more detailed investigation for concrete mixes with strength about 30–40 MPa, as are used commonly in engineering, should be further addressed.

In this paper, the mean value and coefficient of variation of bond performance parameters were derived based on the tested 60 specimens of reinforcing steel in concrete with a mean strength of 36.0 MPa. The above two indexes were essential for the development of probabilistic bond-slip model [7,19,27,28] and further stochastic numerical evaluation of corroded reinforced concrete structures [29]. The bond strength degradation were further compared to other results in the available literature [15,27] to investigate the differences between rebar corrosion effects and stirrup corrosion effects on bond performance. The test results were also compared to previous data [24] to show the effects of different concrete mixes.

2. Test setup

2.1. Test specimen design

There were 60 specimens cast in total in this test (Table 1). The configuration of test specimens followed previous studies by the co-authors [24], and were similar to some previously reported tests [15,27,30]. The tested specimen consisted of one 18 mm-diameter deformed steel rebar set in a 200 mm × 200 mm concrete prism with two 8 mm-diameter stirrups to provide confinement (Fig. 1(a)). The stirrups were in a square shape with a length of 150 mm from outside to outside surface. The concrete cover of stirrup was 25 mm; Fig. 1(b) shows the reinforcement and the wooden mould before concrete casting. Six mortar spacers were used to fix the position of the two stirrups for one specimen. The stirrups were artificially corroded after concrete casting. The bonded length was limited to 80 mm by 2 PVC pipes. There were twelve specimens for each corrosion level, in consideration of the fact that the bond performance parameters may be dispersed widely.

It should be noted that this test configuration simulated the case when rebar was well confined, such as a rebar was situated some distance from stirrups in a beam, and it will give an upper bound to bond performance. Caution should be taken when extrapolating quantitatively the test data to real structures, as longitudinal rebar is frequently placed close to the transverse stirrups in real situations. The effects of rebar location, rebar diameter and concrete depth were not studied in this test, as the main research focus was the effects of different stirrup corrosion level on the bond behaviors between rebar and concrete in this test. Although these factors would also affect bond behaviors, qualitatively the effects of stirrup corrosion on overall bond behaviors are similar, only probably of different magnitudes. And the study of this paper could push our understanding forward about the effects of stirrups corrosion on bond performance of rebar in concrete for follow-on studies.

2.2. Concrete mix design and construction

The concrete was designed to have a value used for the common concrete applied in engineering structures in mainland China: the compressive strength of about 30 MPa with a w/c ratio of 0.46. The concrete mix per cubic meter was: 171.23 kg water, 285.39 kg ordinary Portland cement, 801.94 kg sand, 1155.82 kg stone, 77.05 kg fly ash and 8.56 kg water reducer. $100 \times 100 \times 100\ \mathrm{mm}^3$ concrete cubes were also cast for compressive strength testing. It transpired that this mix had a 28 day average compressive strength of 36.0 MPa.

The stirrups were dried thoroughly and weighed prior to pouring the specimens. Copper electrical wire was used to connect the two stirrups for the next step of artificial corrosion. The rebar was protected by cement mortar, the two ends also by epoxy resin and electrical tape as that into avoid possible rebar corrosion. The orientation of the reinforced rebar was horizontal for the casting (Fig. 1(b)).

2.3. Artificial corrosion program

The expected mass loss of the tested specimens was ranged from 0% to 20% (Table 1). The mass loss of the stirrup could be regarded roughly as the level of corrosion to establish different corrosion levels for the stirrups. Direct current was impressed through the specimens in a 5% NaCl solution to accelerate the oxidation process. Then Faraday's Law was applied to calculate amount of corrosion products in terms of the electrolytic time:

$$T = \frac{m_t \times 2 \times F}{I \times 55.847}$$

where T is the corrosion duration time, m_t is the mass loss, F is the Faraday constant and I is the average electrical current.

The accelerated corrosion of the stirrups was carried out by 3 specimens in series (Fig. 2(a)). Fig. 2(b) shows a photograph of the artificial corrosion process. The input current density was set as $150\ \mu\mathrm{A/cm}^2$ in this study. Three specimens (No. 40, 59, 60) became useless due to the damage of one DC power supply during the artificial corrosion (Table 1), so only 57 reinforced concrete specimens with stirrup corrosion levels from 0 to 20% were tested in the following studies. The maximum required artificial corrosion process took approximately 758.64 h (about one month) for specimens having a mass loss of 20%.

2.4. Loading and measuring instrumentation

The specimens were loaded in MTS300 with a specially fabricated loading frame (Fig. 3(a) and (b)). Grease was used to lubricate the concrete and the steel plate surfaces to eliminate the effects of the friction force. Fig. 3(c) and (d) shows the details of the extensometer installation. Both the loading-end and the free-end slips were measured using an extensometer with a precision of ±0.001 mm. The loading-end slip was limited to 3 mm due to the space limitation. There were two force sensors in the test (Fig. 3(a) & (b)); the lower force sensor was added to MTS 300 so that the force and slip data could be gathered simultaneously. Data from both the lower force sensor and the two extensometers were collected by a Donghua SN3816 data logger and then transferred to a computer. Three different loading schemes were used in this experiment. The first was monotonic increased slip loading until pull-out, the loading speed was set as 0.4 mm/min. The second was ±0.1 mm free-end cyclic slip loading repeated 10 times followed by pull-out. The third was a varied cyclic loading: first ±5 kN loading for 3 cycles, then ±0.1–0.3–0.6 mm free-end slip loading, each displacement loading for 3 cycles, then pull-out. The loading speed was set at 0.4 mm/min for the cyclic loading