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Bond-slip behavior between pre-corroded rebar and steel fiber reinforced concrete

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HIGHLIGHTS

- The bond between pre-corroded rebar and SFRC simulated the retrofit condition.
- A slip plateau was observed near the peak stress for specimens with c/d of 5.75.
- The effect of corrosion ratio on bond behavior was related to c/d and failing mode.
- A bond strength model was proposed considering coupling effect of corrosion and c/d.

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ABSTRACT

For the corroded reinforced concrete (RC) members repaired using steel fiber reinforced concrete (SFRC), bonding between corroded rebar and SFRC greatly affected the mechanical performance of repaired members. In the present paper, the central pull-out tests were carried out to investigate the bond behavior of SFRC and pre-corroded steel bar obtained in concrete specimens. The varied parameters included corrosion ratio and cover thickness to rebar diameter ratio (c/d). The experimental results revealed that the confinement and bridging action of fiber can improve the bond strength and transform the failure mode from splitting to pull-out or combined splitting and pull-out. Bond strength decreased with increasing corrosion ratio and decreasing c/d, whereas the residual bond strength remained no less than that of non-corroded rebar especially for specimens with a small c/d. Bond strength degradation, bond toughness variation and bond-slip descending behaviors with corrosion ratio were correlated to c/d and failing mode. A modified bond strength model considering the coupling effect of corrosion and c/d was proposed, and the calculated strength agreed well with the tested.

1. Introduction

Bonding between rebar and concrete is a foundation in reinforced concrete (RC) structures. For RC structures subjected to long-term carbonation and chloride corrosion, bond of steel bar and the surrounding concrete is first improved due to the filling effect of corrosion product, and then reduces due to corrosion-induced cover cracking [1,2]. For unconfined rebar, a rebar mass loss of about 0.5% resulted in about 50–60% enhancement in bond strength, whereas a mass loss of 3.9% led to a sharp reduction up to 54% [3]. In contrast, for confined rebar with around 4–6% corrosion ratio, the bond strength was almost 30–65% larger than that of unconfined rebar at a similar corrosion level, and the confinement of transverse reinforcement can counteract the bond loss induced by corrosion effectively [4]. Moreover, the reverse loading greatly aggravated the corrosion-induced bond degradation, especially within the first five cycles and for the unconfined rebar [5]. In addition, the corrosion-induced bond degradation decreased with increasing strain rate, but strain rate effect was gradually weakened with increasing corrosion level [6].

More severely, the structural performance of corroded RC members at the service and ultimate limit states degraded apparently due to the deteriorated bond as well as reduced rebar area, ductility and strength of rebar, etc. And thus, the patch repair for corroded RC members is usually applied to improve the load-carrying capacity, stiffness and durability for extending the service age. Steel fiber reinforced concrete (SFRC), showing good mechanical properties in tension, flexure, shear, impact and fatigue, etc. [7–11] and durability in freezing and thawing, permeability and carbonation, etc. [11–13], has been used in retrofit and strengthening of old and damaged structures as well as the construction of new

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structures [14]. Note that the property of SFRC subjected to chloride corrosion is of great significance for the engineering application in marine environment. The review on SFRC [15] confirms that the steel fiber in uncracked SFRC had a superior chloride corrosion resistance compared with rebar in concrete mainly due to the discontinuity and the uniform steel surface of fibers along with the dense and uniform fiber-matrix interface. For cracked SFRC with crack width below the critical width (i.e., 0.2 mm), the crack and damaged fiber-matrix interface can heal eventually [16,17]. In the meantime, fiber-matrix interface bond was improved due to the increasing fiber roughness, healing fiber-matrix interface and accumulated chemical binding products [18]. The study conducted by Granju and Balouch [19] indicated that the flexural strength of pre-cracking SFRC specimens was enhanced under chloride corrosion for one year. The fibers across the crack within a 2–3 mm rim from the specimen surface suffered severe corrosion, whereas the fibers located out of this rim exhibited a light corrosion without section loss. Balouch et al. [20] further revealed that the minimum cover of 0.1 mm or 0.2 mm can prevent the surface corrosion of SFRC with w/c no larger than 0.5. Therefore, SFRC may be used in the repair of marine engineering structures if a certain thickness of cover can be provided for fiber.

When corroded RC members were repaired using SFRC, the cracking cover, damaged and chloride-rich concrete surrounding the corroded rebar and corrosion products bonded on rebar must be removed before repair [21,22]. Accordingly, bonding between corroded rebar and SFRC is of great importance for the mechanical property of repaired members. However, the related studies concerning the bond between rebar and SFRC mainly concentrated on the non-corroded rebar and the effect of fiber fraction and parameters. The experimental results reported by Yazici et al. [23] revealed that bond strength was enhanced with increasing fraction and fiber length to diameter ratio (l_f/d_f). In detail, for steel fiber with l_f/d_f of 40–60, the addition of 60 kg/m^3 fiber resulted in 6–9% bond strength enhancement [23]. The bond experiment conducted by Campione et al. [24] indicated that the use of steel fiber in volume fraction within 0.5–2% produced 7–38% improvement in bond strength. For pre-stressing strands, the bond strength increased by 30% when using 15 kg/m^3 steel fiber, and the optimal fiber fraction was related to the strand diameter and fiber parameters [25]. In contrast, the experimental study conducted by Gao et al. [26] indicated that the addition of steel fiber within 2% volume fraction merely resulted in a 3% increase in bond strength.

However, the bond behavior of corroded rebar embedded in SFRC remains unclear, especially for the corroded rebar on which corrosion products bonded are removed under the retrofit condition. In the present paper, the pre-corroded rebar, obtained in concrete specimens through accelerated corrosion test, was cleaned and used for pull-out specimens to simulate the actual repair condition. The effect of corrosion ratio and cover-rebar diameter ratio on bond behaviors was discussed concerning failure modes, bond-slip curves, bond strength and bond toughness, etc. The experimental results can provide a reference for the retrofit of corroded RC members using SFRC.

2. Experimental program

2.1. Pre-corrosion of rebar

For simulating the retrofitting condition of corroded RC members, a total of 27 steel bars used for bond test were pre-corroded in concrete cylinders. The pre-corrosion region was taken as 150 mm in the middle of concrete cylinder, and concrete cover thickness was 25 mm. The non-corrosion region of rebar in concrete was covered with epoxy resin and protected using PVC sleeve. Fig. 1 shows the detailed configuration of pre-corroded specimens. The variable of pre-corrosion test included rebar diameter and corrosion ratio. The deformed rebar with 12, 16 and 20 mm in diameter was used and, the corresponding center distance between crescent ribs was 8.48, 9.94 and 10.05 mm for these three types of rebar. The target corrosion ratio was designed as 5%, 10% and 15%. Thus these 27 specimens can be divided into 9 groups with 3 specimens each group.

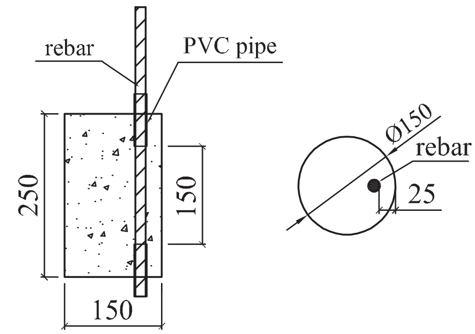

Fig. 1. Details of the pre-corroded specimen.

The accelerated corrosion test using applied direct-current was employed for pre-corrosion. Concrete cylinders were immersed into 3.5% NaCl solution covering the whole pre-corrosion region of rebar. The reinforcement was connected with the anode of power, and stainless steel bars with a diameter of 8 mm were connected with the cathode. The corrosion current density applied was 300 μA/cm^2, and corrosion age can be estimated according to Faraday's law,

$$t = \frac{zF\Delta m}{MiS} \tag{1}$$

where, F is Faraday's constant (96,500 C/mol), z is the ionic charge number ($z = 2$) of iron, Δm is the mass loss of corroded reinforcement (g), M is the molar mass of iron (56 g/mol), i is the corrosion current density (A/cm^2), and S is the superficial area of rebar within the corrosion region (cm^2). After the pre-corrosion, the corroded rebar was removed though splitting cylinders. Further, corrosion product and concrete bonded on the rebar were cleaned up using steel wire brush to obtain a similar rebar surface to that in an actual repair condition.

2.2. Pull-out specimens

The 150 mm cube with a centrally placed rebar was used as the pull-out specimen. A total of 45 pull-out specimens were cast including 9 concrete comparison specimens and 36 SFRC samples. The variable parameters included corrosion ratio (ρ) and cover thickness to rebar diameter ratio (c/d). In this test, corrosion ratio was taken as 0% and the actual pre-corrosion ratio. c/d was designed as 5.75, 4.19 and 3.25 with increasing rebar diameter from 12 to 20 mm. Note that the actual pre-corrosion ratio was measured after pull-out tests, and the details were presented in the following section.

Fig. 2 shows the details of pull-out specimen. The bond length-rebar diameter ratio (l/d) was taken as 5.0 with bond length of 60, 80 and 100 mm for 12, 16 and 20 mm rebar respectively. A pair of PVC sleeves was used at two ends to obtain a precise bond length. And the gap between PVC pipe and rebar was sealed using glue to prevent the infiltration of fresh cement matrix.