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Effect of corrosion-induced crack on the bond between strand and concrete

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HIGHLIGHTS

- Combined effects between corrosive crack and stirrups on strand bond are studied.
- Corrosion-induced concrete cracking deteriorates bond between strand and concrete.
- Stirrups contribute in delaying the corrosion-induced bond deterioration.
- Concrete cracking makes the bond stress distribute more uniformly along the strand.

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ABSTRACT

The effects of corrosion-induced crack on the bond between strand and concrete are investigated experimentally in the present paper. The confinement role of stirrups on the deterioration of bond behavior affected by concrete cracking is addressed. Twenty pull-out specimens with and without stirrups were designed and accelerated to induce concrete cracking by strand corrosion. Data on force-slip response, bond strength, and bond stress distribution of the specimens with different crack widths are presented. Results show that corrosion-induced concrete cracking reduced bond behavior between strand and concrete. However, stirrups contribute to delaying the deterioration of bond behavior induced by concrete cracking. Bond stiffness and strength decreased immediately after concrete cracking. Under the confinement of stirrups, cracks less than 0.35 mm have no effect on bond stiffness and strength. The non-uniform degree of bond stress distribution along the specimen decreases as the cracks widen. Stirrups show a positive role in preventing this degradation. The position of maximum bond stress will shift toward the free end after the cracks exceed a critical width. Stirrups increase this critical width. In the present test, the critical crack widths of the specimens with and without stirrups are 1.29 and 0.41 mm, respectively.

1. Introduction

Bond behavior between prestressing strands and concrete plays a critical role in maintaining the property of prestressed concrete (PC) structures, especially for the pre-tensioned ones [1,2]. The bond behavior of the strand depends on factors such as material strength, steel type, external constraints, and surface condition. In addition, corrosion also influences strand bond. Corrosion induces cracking of concrete surrounding the strand because of the volume expansion of the corrosion products. This damage could decrease the confinements of the concrete to the strand, degrading bond strength. Moreover, corrosion products can change the interaction between the strand and the concrete, impacting the transmission of bond stresses. All of these factors can reduce the serviceability and durability of PC structures [3–5].

Numerous studies on the bond behavior between corroded steel and concrete have been conducted over the past decades. Among these works, more attention has focused on the bond of corroded reinforcement rather than on the prestressing strand [6]. It was found that slight corrosion can increase the bond strength before concrete cover cracking. With further corrosion, bond strength decreases, and the relative slips increase rapidly. Additionally, the stirrups were proved to have a positive effect on bond strength [7]. For the prestressing strand, however, its bond is distinct from that of the ordinary bars because of its twisting constitution and mechanical interlock. The strands have been reported to be more sensitive to corrosion [8]. Very limited attention has been paid on the corrosion effect on bond between strand and concrete.

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For pre-tensioned PC structures, strand has been widely applied for its advantages in elongation and tensile strength. Many studies on strand bond have been conducted on the basis of pull-out testing [9–12]. The pull-out test results were proved to be reliable in showing strand bond properties [13]. Several bond prediction models were also developed for pre-tensioned PC members [14,15]. In addition, some bond stress and slip distribution models were established along the transmission and anchorage lengths of prestressing strands [16,17]. In past studies, however, little attention has focused on corroded strands. Li and Yuan [18] investigated the effects of strand corrosion on bond-slip curves and bond strength. This research conducted by Li and Yuan was aimed toward short specimens rather than the transfer of tensile stress along the specimens. In addition, the bond stresses were assumed to distribute uniformly along the strand, which is difficult to detect in the non-uniform bond stresses and varying slips along the transfer and anchorage length of the pre-tensioned PC structures. Beyond that, little related research has been reported. The extent of knowledge on corroded strand bond needs to be developed further.

This study aims to investigate the effect of corrosion-induced crack on the bond property between strand and concrete on the basis of experimental approach. The paper is arranged as follows. First, the experimental design, including material property, steel arrangement, accelerated corrosion, and pull-out testing, is presented. Next, the characteristics of corrosion-induced crack and concrete strain are introduced from experimental observations. The effects of corrosive crack on pull-out force-slip curves, bond strength degradation, and bond stress distribution are then discussed. The influences of stirrups on the bond behavior of corroded strand are also studied. At last, conclusions obtained on the basis of experimental results are presented.

2. Experimental program

The experimental program in the present study was divided into two sections. First, the accelerated corrosion test was conducted to obtain different degrees of specimen corrosion. The second section contained a pull-out test on the specimens, which was designed to clarify the effect of corrosive crack on the bond behavior between strand and concrete. Throughout the whole program, the role of stirrups was also studied.

2.1. Materials and specimen description

Pre-tensioned PC structures usually use seven-wire strand as the main tensile reinforcement. Three nominal diameters of 9.5, 12.7, and 15.2 mm are generally used, with an ultimate tensile strength of 1860 MPa. The 15.2-mm strand was used in the current experiment because it has been the most frequently used in the actual project.

The experimental study consisted of testing 20 concentric pull-out specimens. The 20 specimens were divided into two groups: Group S and Group R. Each group consisted of 10 specimens. In this testing design, the stirrup effects on strand bond were considered. Group R was reinforced with smooth bars as stirrups, which had a diameter of 8 mm and spacing of 150 mm. Four deformed bars with a diameter of 10 mm were used as linked bars. No stirrups and linked bars were reinforced in Group S.

Both groups contained one uncorroded (control) and nine corroded ones. All specimens were equipped with a single 15.2-mm strand embedded in the center and a concrete cover of 67.4 mm. These specimens were the same size with a rectangular cross section (150 × 150 mm) and a length of 1200 mm. The geometric details and reinforcement arrangement of the specimens are shown in Fig. 1.

To reduce the compressive stress concentration at the loaded end, a 100-mm-long PVC pipe was placed over the strand surface to create an un-bonded area, and the bond stress is ignored in this area (see Fig. 1). Hence, the effective bond length is 1100 mm.

The specimens were constructed by using salted concrete with an average compressive strength of 35 MPa. The average strength was obtained by testing three 150 × 150 × 150 mm cubes. NaCl, 5% by weight of cement, was put into the mixture for a better simulation of the actual corrosion environment. The mix proportions, by weight of cement, water, and coarse and fine aggregate were 1: 0.43: 2.46: 1.27. The stirrups and hanger bars in the specimens of Group B were epoxy coated to keep them free from corrosion.

The specimens denominated R-x and S-x were characterized by the specimens with and without stirrups, respectively. The uncorroded specimens in the two groups were named R-0 and S-0 and taken as the control one. The remaining corroded specimens were denominated R-1–R-9 and S-1–S-9.

2.2. Accelerated corrosion

The electrochemical method has been widely used to accelerate strand corrosion due to its superiority in corrosion time. Wang et al. used this method to accelerate strand corrosion in post-tensioned concrete beams [3,19]. Darmawan et al. conducted the accelerated corrosion tests for prestressing wires to study spatial time-dependent reliability of prestressed concrete bridge girders [20]. In the present study, the specimens were also subjected to electrochemically accelerated corrosion to obtain various strand corrosion degrees.

As for the corrosion process, in the preparation stage, a water tank assembled by PVC materials was hung beneath the bonded region of the specimen. The gaps between the concrete surface and the tank were blocked by structural adhesion to avoid outflow of corrosion solution. After the structural adhesion achieved the expected strength, the 5% NaCl solution was poured into the water tank. After that, the specimens were soaked for 1–2 days to ensure that a sufficient amount of chloride ions invaded the concrete.

Fig. 2 shows the schematic of the accelerated corrosion device. The corrosion system consisted of a DC power, a strand anode, and a stainless steel cathode immersed in the 5% NaCl solution. After the power was turned on, a direct current moved from the positive pole of the power to strand, and then through soaked concrete and NaCl solution to stainless steel, and eventually to the negative pole of the power. During this process, the strand was oxidized with loss of electrons, which resulting in corrosion [3]. The direct constant current density is 270 μA/cm^2 in this test. The specimens were subjected to different durations of corrosion to obtain various degrees of strand corrosion. The durations of corrosion for specimens S-1–S-9 are 3, 5, 7, 8, 10, 12, 15, 17, 18 days, respectively. The corrosion times for R-1–R-9 are the same with S-1–S-9, respectively.

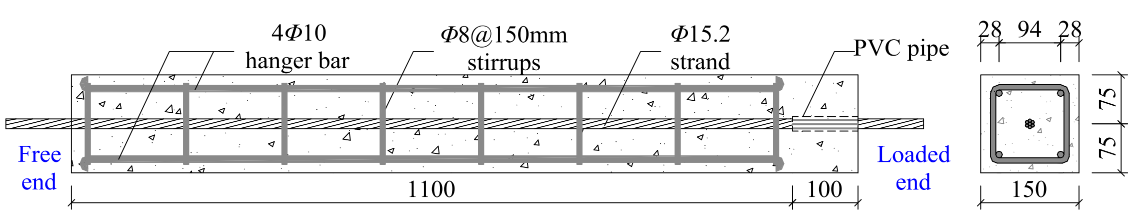

Fig. 1. Geometry of test specimens (unit: mm).

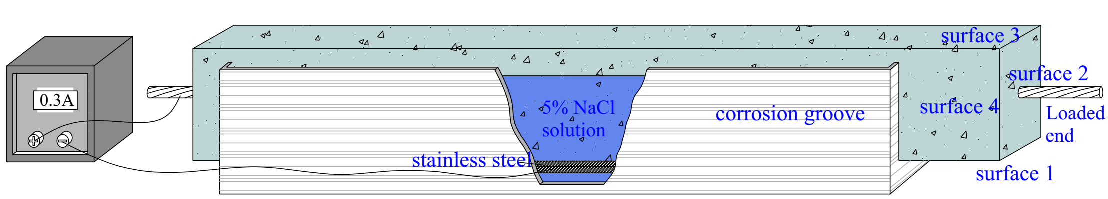

Fig. 2. Accelerated corrosion system.