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Experimental investigation of corrosion effect on bond behavior between reinforcing bar and concrete

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HIGHLIGHTS

- The bond behavior between corroded steel bars and concrete is investigated.
- The ultimate bond strength, bond-slip relationships are discussed.
- An empirical bond degradation model is proposed considering a wide range of experimental data.
- The effect of corrosion-induced crack on bond stress distribution is analyzed.

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ABSTRACT

An experimental study is conducted in this paper to investigate the effect of corrosion and corrosion-induced cracks on the bond behavior between steel bars and concrete. An accelerated corrosion test was used to corrode the steel bars embedded in concrete specimens under laboratory condition. Two series of pull-out tests were designed. Pull-out tests on the specimens with plain and deformed reinforcing bars are performed. The bond behavior of the two types of steel bar specimens including the ultimate bond strength, bond-slip relationships for different corrosion levels are discussed. An empirical bond degradation model is proposed combining a wide range of experimental data available in the literatures. The other pull-out tests on the bonding specimens with interior strain gauges are conducted and the bond stress at various positions are derived based on the observed reinforcement strains. The experimental results show that the corrosion influence on bond strength can be ignored when the corrosion loss is less than 2.4%. The bond behavior between smooth bar and concrete is more sensitive to the corrosion than that of specimen with deformed bar. The selection of steel bars is also an alternative way to improve the bond behavior especially for the deformed bar specimens. The distribution of bond stress is more uniform for the specimen with a large corrosion-induced crack width.

1. Introduction

Concrete has low tensile strength, which is often used in combination with reinforcing bars. Therefore, good bond property between steel bars and surrounding concrete is critical to ensure that the two materials work together [1,2]. Corrosion of reinforcement is one of the most important causes of significant damage of reinforced concrete (RC) structures. Corrosion decreases the cross-sectional area and the strength of reinforcement. With the increase of corrosion time under aggressive environments, the increased volume of corrosion products may cause concrete cover cracking, resulting in a bond strength degradation [3–5]. The bond strength loss for an unconfined corroded reinforcing bar is much more critical than the cross-sectional area loss [6]. For the different types of reinforcing bars, corrosion has different effects on bond strength degradation due to different bond mechanisms, which is very important for the accurate prediction of bearing capacity and serviceability performance of RC members.

Over the past few decades, some experimental works on the bond behavior of RC member considering the reinforcement corrosion have been actively conducted. The bond behavior of RC elements, including the ultimate bond strength, the load-slip curves and the effect of different corrosion rates were studied [7–9]. Pull-out and beam tests were applied by Zhao et al. [10] to study the bond behavior between normal aggregate concrete or recycled aggregate concrete and corroded steel bars, but only deformed steel bars were considered. Huang [11] indicated that partly corroded steel bars exhibit a somewhat different bond behavior from

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that of whole-surface corroded bars. Most of these tests were conducted using accelerated corrosion method. Choi et al. [12] investigated the difference of bond characteristics in RC members corroded by artificial and natural corrosion methods. Based on the experimental results, some analytical and empirical bond strength models were also proposed [13]. Li et al. [6] and Lee et al. [14] simulated the mechanical behavior of RC members subjected to corrosion using finite element method, and the corrosion-affected stiffness and maximum strength of bond were expressed as a function of corrosion loss. Berto et al. [15] developed a frictional model and a damage model for bond, which assumed a scalar damage parameter to account for the bond strength loss in the full development of slip. But this assumption neglected that a minor corrosion may enhance the mechanical performance of bond, and that the stiffness reduction of the bond at different corrosion stages may be different.

Sajedi and Huang [16] proposed a simple probabilistic bond strength model considering corrosion using a multivariable regression based on a comprehensive database. Yalciner et al. [17] developed an empirical model for the ultimate bond strength by evaluating bond strength in different concrete mixes, different covers and different corrosion levels. Previous studies focused on the bond behavior normally refers to the deformed steel bars and concrete because the deformed bars are generally used as longitudinal reinforcement along the beams. However, the smooth bars were also widely used as reinforcement in historical concrete structures, and the assessment and rehabilitation of these old structures become more highlighted [18]. Meanwhile, the smooth bars are generally used as stirrups, and stirrup corrosion will change the confinement of the rebar/concrete interface, and thus may damage the bond strength [19]. Therefore, further studies are required to quantify the effect of corrosion on bond considering different types of steel bars. Additionally, corrosion-induced cracking or spalling of the cover decreases the confinement provided by the concrete to the reinforcement, leading to a reduction in bond strength. The corrosion-induced crack can be easily observed, which is a direct inspection information used for structural performance assessment. However, the more fundamental effect of corrosion-induced cracking on the bond properties is still not fully understood. Desnerck et al. [20] used a new test to assess the bond property of steel bars in cylindrical cracked RC specimens, in which the effect of the number of cracks, confinement and concrete cover were investigated. The bond stress mentioned above is represented by the average bond stress between steel bar and concrete, but the bond-slip relationships are different in various positions.

In this paper, two series of tests were conducted to investigate the effect of corrosion on the bond behavior between steel bars and concrete. The paper is organized as follows. First, pull-out tests on the bonding specimens with plain and deformed reinforcing bars were conducted to compare the influence of corrosion, reinforcement types on the bond properties. Next, a bond degradation model was proposed based on a wide range of experimental results. Following this, the results from pull-out test on the specimens with interior strain gauges were introduced, and the reinforcement strains at various positions in bonding specimens with different corrosion-induced crack widths were obtained. The effect of the corrosion-induced crack width on the bond stress distribution was analysed. Finally, some conclusions and future work were drawn based on the proposed study.

2. Experimental program

In this section, material properties, specimen design, accelerated corrosion test and pull-out test will be introduced. Two series of tests were conducted: pull-out tests for two types of steel bars and three different steel diameters were considered to investigate the effect of corrosion on the bond performance; pull-out tests for deformed reinforcing bars were installed with interior strain gauge to study the effect of corrosion-induced cracks on the bond stress distribution at different positions. Details are shown subsequently.

2.1. Test specimens

The pull-out tests were conducted on the cubic bonding specimens of 150 mm length per side. A common Portland cement was used, and the content was 425 kg/m^3. A concrete mix of proportions, by weight of cement, sand and gravel were 1:1.73:3.5. Medium sized sand and the largest gravel with a size of 40 mm were chosen. Three percent NaCl based on admixture by weight of cement was added into concrete mixture to accelerate corrosion process. The 28-day cured cubic specimens had an average measured compressive strength of 24.81 MPa. The specimen cover on one side was 30 mm. A PVC casing with 50 mm length was embedded into the loading end to avoid local failure and resulted in bond stress uniform. The bond length of reinforcement was set to 100 mm to prevent the yielding of reinforcement before bond failure.

For the first group pull-out tests, all embedded reinforcing bars were hot rolled steel bars: smooth HPB235 bar or deformed HRB335 bar. The measured yield strength of HPB235 and HRB335 reinforcement were 258.68 MPa and 373.64 MPa. The Young's modulus of HPB235 and HRB335 reinforcement were 210 GPa and 200 GPa, respectively. Three diameters of steel bars were included, i.e. 18 mm, 20 mm and 22 mm. Fig. 1 shows the geometry and the dimension of the pull-out test specimens.

Deformed reinforcing bar of 20 mm diameter installed with interior strain gauges was used in the other group pull-out test. The deformed reinforcing bar was cut into two parts along the axial line and a 2 mm × 4 mm groove in each part was made to install the interior strain gauge. Six 2 mm × 1 mm strain gauges with 20 mm spacing interval were arranged into the groove. Following that, the two parts of steel bar were bound in together to ensure them work together. The groove was filled with the epoxy resin. Fig. 2 shows the arrangements of the strain gauge for specimens.

2.2. Accelerated corrosion and pull-out test procedure

Direct electric current was impressed on the steel bars embedded in the specimen. The current can be controlled and monitored. The free end of reinforcement was coated with a layer of epoxy resin to prevent the bare reinforcement corrosion. The specimens were fully immersed in a 5% NaCl solution in a tank for 5 days before the direct current was applied. The reinforcing bar served

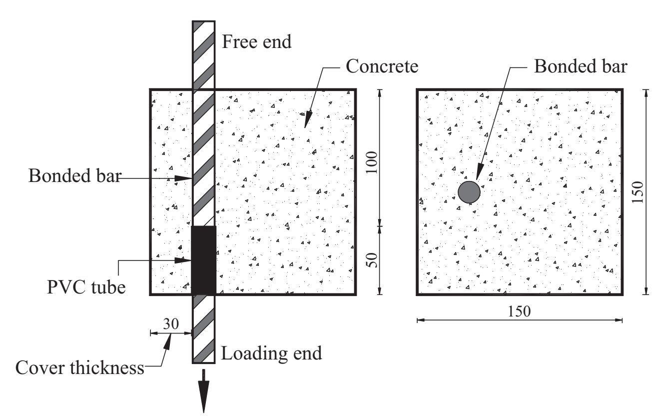

Fig. 1. Geometry and dimension of pull-out test specimens (unit: mm).