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The bond behavior between concrete and corroded steel bar under repeated loading

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ABSTRACT

Repeated loading can affect the serviceability of RC structures by causing the bond deterioration. In the present study a series of pull-out tests have been carried out to investigate the bond deterioration due to the repeated loading of corroded reinforcement. The specimens were corroded to different corrosion level and subjected to repeated loading for various stress levels and loading cycles. The test results showed that the bond behavior under repeated loading was characterized by progressive increase of residual slip. The slip increase became more pronounced when the stress level was increased. The comparison with monotonic test results indicated that the repeated loading exhibited no significant influence on the bond strength and on the slip at peak bond stress for both corroded and non-corroded specimens. It was also found that the corrosion could lead to an increase of applied stress levels, which resulted in the substantial decrease of the fatigue life of bond. Through systematic evaluation of the test data a model for bond stress-slip relationship under repeated loading was proposed. Moreover, empirical equation for the fatigue life of bond of corroded reinforcement was also derived.

1. Introduction

The bond resistance in RC structures represents the complex interaction between concrete and reinforcing steel bar. It consists of three components: chemical adhesion, friction and mechanical interaction. For deformed steel bars bond depends primarily on the mechanical interaction [1]. It directly affects the crack width, crack spacing and stress distribution in RC flexural members. Adequate bond between concrete and steel bar is essential for the performance and durability of RC structures.

During the long term service life of RC structures the deterioration of bond often takes place. Due to the chloride contamination or carbonation the steel bar embedded in the concrete can corrode. The corrosion products have higher volume than the steel and can cause damage of concrete cover and influence bond properties. When the steel bar is only slightly corroded the bond property is improved, however, once the concrete cover is cracked due to the expansive corrosion products, the bond properties become seriously deteriorated. Numerous studies have been carried out to investigate the influence of corrosion on the bond behavior including Auyeung et al. [2], Fang et al. [3], Bhargava et al. [4], Coronelli [5], Fischer [6], Lin and Zhao [7], Coccia et al. [8], who proposed empirical or analytical models for the degradation of bond strength. The bond stress-slip behavior of corroded steel bars was also experimentally and numerically investigated by Ožbolt et al. [9], Lundgren et al. [10], Hanjari et al. [11] and Berra et al. [12].

Although the bond behavior of corroded steel reinforcement has been intensively investigated, most studies have been concentrated on monotonic loading, only a few researchers have examined the influence of repeated loading on the bond behavior. In fact, a large number of reinforced concrete structures, e.g. industrial constructions, offshore structures or bridges, also face the problem of fatigue caused by repeated loading. Repeated loading can lead to a progressive deterioration of bond and may cause premature failure [13]. Due to the slip growth, repeated loading leads to the increase of crack width and deflection, which under aggressive environment conditions strongly affect durability of RC structures. Verna and Stelson [14] investigated various failure models of reinforced concrete beams under repeated loading. They concluded that the bond failure was the most susceptible to fatigue in flexural members. Later, a series of pullout tests with various repeated loading scenario were conducted by Edwards and Yannopoulos [15], Rehm and Eligehausen [16], Koch and Balazs [17,18]. The test results indicated that the bond behavior under repeated loading was characterized by progressive slip increase. Furthermore, Rehm

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Nomenclature

A_{st}	the cross-sectional area of one leg of the stirrup
c	concrete cover
d	diameter of tensile steel bar
i_{corr}	corrosion current density
l	bond length
m_0	initial weight of the tensile steel bar
m	final weight of the tensile steel bar after removal of corrosion products
n	number of loading cycles
n_d	number of the tensile steel bars
n_f	number of loading cycles at bond fatigue failure
n_{st}	number of legs of stirrups at a section
P	pullout force
P_{max}	maximum repeated load
P_{min}	minimum repeated load
R_τ	relative bond strength
s	slip between concrete and tensile steel bar
s_f	slip corresponding to frictional bond stress
s_n	slip at maximum repeated load after n loading cycles
s_{rn}	residual slip at minimum repeated load after n loading cycles
s_{st}	longitudinal spacing of the stirrups
s_u	slip at peak bond stress
α_n	exponent after n loading cycles
η	corrosion level of tensile steel bar
δ	degradation coefficient
ξ_{st}	stirrup index of confinement
τ	bond stress
τ_{max}	bond stress at maximum repeated load
τ_{min}	bond stress at minimum repeated load
τ_n	bond stress after n loading cycles
τ_u	ultimate bond stress (bond strength)
$\tau_u(0)$	bond strength of non-corroded specimens
$\tau_u(\eta)$	bond strength of corroded specimens

and Eligehausen [16] also concluded that if no fatigue bond failure occurred, the repeated loading did not negatively affect the deformational behavior of the anchorages near failure or the ultimate load, compared with monotonic test. This is further verified by the test results of Oh and Kim [19]. They proposed a model for local bond stress-slip relationship after repeated loading, however, the model did not cover the post-peak response. Recently, pullout tests were carried out by Lindorf et al. [20,21] to investigate the bond behavior of reinforced concrete under transverse tension and repeated loading. The test results showed that at high maximum repeated loads the bond fatigue limit was to be expected long before reaching the steel fatigue and the longitudinal cracks due to transverse tension showed a great influence on bond behavior under repeated loading. The influence of corrosion on the fatigue of bond was firstly investigated by Al-Hammoud et al. [22], Rteil et al. [23]and Soudki et al. [24] through reinforced concrete anchorage-beam specimens. The test results revealed that corrosion could result in the decrease of fatigue bond strength, whereas the use of CFRP sheets for beam repairs could increase the fatigue bond strength. The redistribution of the bond stress along the bond length was also observed in their tests.

So far, the existing studies have enhanced the understanding of the bond deterioration of non-corroded steel bars due to repeated loading, however, there is still a gap in knowledge concerning the fatigue of bond between corroded steel bars and concrete, and the local bond stress-slip models for non-corroded or corroded steel bars under repeated loading are still rarely available in the literature. Therefore, the primary goal of this study is to investigate the bond behavior of corroded specimens under repeated loading. Based on the test results of 43 eccentric pullout specimens, the combined effect of corrosion and repeated loading on the bond deterioration is investigated.

2. Experimental program

2.1. Test specimens

In the framework of the experimental tests 43 eccentric pullout specimens were cast with deformed steel bars in the horizontal position. Each specimen was 300 mm in length, 150 mm in width and 250 mm in height. The steel bar was cast in the specimen with an effective cover of 35 mm from the top face, and 65 mm from the two lateral side faces. The steel bar was in contact with the concrete over a 100 mm embedment length, i.e. 5 times the bar diameter. The bond length was short enough to reflect the local bond behavior and ensured that the bond failure dominates. In order to provide the required anchorage length, two plastic tubes were placed over the steel bar in the un-bonded zones on both ends of the specimen. For each specimen, two 8 mm plain stirrups were used along the bond length with spacing of 50 mm to simulate situations in real structures. Another reason for the use of stirrups is that stirrups can prevent the substantial degradation of bond strength caused by the corrosion of longitudinal steel bars, which makes it possible to carry out repeated loading [7]. The cross section and reinforcing details of the specimen are shown in Fig. 1.

2.2. Materials

The concrete, supplied by a local concrete mixing plant, was made with an ordinary Portland cement with the content of 296 kg/m^3, a water-cement ratio of 0.35 and a maximum aggregate grain size of 25 mm. The concrete mix details are given in Table 1. The slump of the concrete was 180 mm. The average cubic compressive strength (150 mm cube) at the time of experimental test was 50.0 MPa. The diameter of the deformed steel bar was 20 mm with yield stress and tensile strength 450 MPa and 632 MPa, respectively. The deformation pattern of the tensile steel bar is shown in Fig. 2. The yield strength of the stirrups was 378 MPa.

2.3. Accelerated corrosion

Accelerated corrosion technique was used to accelerate steel bar corrosion in concrete. Power supplies with adjustable voltage and current were used to impress constant current on the specimens. The tensile steel bars served as the anode and the outside stainless steel net was fixed on the surface to serve as cathode (see Fig. 3). Sponge was placed between the stainless steel net and the concrete surface to provide an adequate contact and it was every day sprayed with a 5% chloride solution. During the accelerated corrosion relatively constant current density of 400–600 μA/cm^2 was applied on the tensile steel bar. The time necessary for obtaining the target corrosion was evaluated based on the Faraday's law.