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Study of the loss of bond in reinforced concrete specimens with accelerated corrosion by means of push-out tests

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HIGHLIGHTS

- Loss of bond due to reinforcement corrosion is studied by means of push-out tests.
- The specimens are slices of concrete prisms reinforced with a smooth steel tube.
- The prisms are uniformly corroded in accelerated tests up to several corrosion depths.
- Adhesion and friction are the main resisting mechanisms during push-out of the tube.
- Corrosion depth affects residual stress and a dilatant behavior is detected.

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ABSTRACT

In this work, push-out tests are presented to study loss of bond caused by corrosion of steel in reinforced concrete. The specimens are concrete prisms reinforced with a smooth steel tube, thus, interlocking of bar ribs is avoided, and adhesion and friction are analyzed. The prisms were uniformly corroded up to various corrosion depths. During push-out, widening of the main crack developed during accelerated corrosion was measured. For the corrosion levels applied in this work, the corrosion level influences the residual stress at the end of the test, and the stress and crack widening are related, showing a dilatant behavior.

1. Introduction

Bond between steel and concrete is crucial for an adequate behavior of reinforced concrete structures. However, when corrosion of the steel occurs, an oxide layer develops that modifies the properties of the steel-concrete interface and diminishes the net cross-sectional area of reinforcement, thus, reducing the ultimate strength of affected concrete members and the service life of the structure [1]. Moreover, cracking and spalling of the concrete cover can occur, due to the volumetric expansion of the oxide with respect to the sound steel [2,3], resulting in loss of confinement and, thus, loss of bond.

From previous studies found in the literature, essential aspects of the influence of corrosion on bond behavior have been disclosed. For example, Al-Sulaimani et al. [1] studied the behavior of specimens with deformed bars at four stages of corrosion, by means of concentric pull-out tests and bending tests, and found that for specimens with a low degree of corrosion, bond strength (the maximum pure shear stress transmitted between the steel and the concrete) increases, due to the generation of a firmly adhered rust layer, which increases the roughness of the surface; however, for high corrosion levels, bond strength decreases, due to development of a heavy oxide layer with a lubricating effect, degradation of bar ribs, which diminishes interlocking and bearing of bar deformations against concrete, and formation of longitudinal cracks, which diminishes confinement. Further work developed by Almusallam et al. [4] showed results in agreement with those in [1], and assessed that cracks developed in corrosion tests and rib profile degradation affect bond strength. They also explained that bond strength increases in pre-cracked specimens may be due to an increase in the reactionary confinement of the bar in the concrete, as the corrosion product develops an expansive mechanical pressure on the surrounding concrete, and reported that hoop tensile

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stresses widen the corrosion cracks. An increase in bond strength for a given small amount of corrosion and a decrease for severe corrosion were also reported for bars corroded under natural conditions before being cast in concrete by Maslehuddin et al. [5], for specimens corroded by immersion in a solution of $Ca(OH)_2$ by Fu and Chung [6], and for specimens corroded under a controlled constant current by Coccia et al. [7]. Other authors have investigated influence of stirrups for specimens reinforced with deformed bars and with smooth bars, as Fang et al. [8], and the influence of corroded stirrups, as Hanjari et al. [9] and Juarez et al. [10], finding that loss of bond due to corrosion is smaller for specimens with stirrups, since they are the main source of confinement after cracking of the cover, or have focussed their attention on the influence of the corrosion method, as Choi et al. [11]. As a summary, three main resisting mechanisms are identified that contribute to bond strength: adherence, which is the chemical bond strength between the steel and the concrete and is limited by the weakest of the strength of the steel-oxide-concrete layers, friction, which depends on the surface characteristics and on the confinement, and geometrical interlock, due to steel ribs. However, differences are found in the values reported in those works for the critical corrosion level, maximum bond stress and slip of the bars, which may be explained by the differences in the conditions of the tests and in the geometry of the specimens, which also determine the resisting mechanism contributing to bond strength. For example, most of those works utilized pull-out tests based on the ASTM-C234 standard [12], either directly [1,5–7], or with modifications [8,9], but other types of test were used as well trying to reproduce more closely the actual state of stress in the structure, such as bending tests [1,10] and cantilever bond tests [4]. As a result, parameters obtained from a given experiment may not be adequate to reproduce the behavior in other situations in which the dominating mechanisms of bond potentially differ from those in the experiment.

Another important aspect in the tests is the condition during accelerated corrosion. As pointed out by Prieto et al. [13], current densities much higher than those observed in natural conditions may yield unrealistic values of bond strength, since density of current affect the type of oxide generated, as indicated in reference studies of corrosion-induced cracking [14]. In this regard, in [15] limitations of accelerated corrosion tests in reproducing the actual behavior of the reinforcement were pointed out and it was recommended that such tests should be avoided, except for fundamental research on the corrosion process, as in the case of the current paper. Besides, other variables such as the humidity and the temperature also influence the corrosion process. In summary, corrosion introduces additional uncertainties in the determination of bond-slip relationship, as explained in [16]. Therefore, it is essential to perform tests with repeatable conditions.

To decouple the various resisting mechanisms and to study the effect of corrosion on them, Cairns et al. [17] designed a test to control the amount of confinement, using specimens with lateral steel plates, to which controlled normal and shear forces were applied, and calculated the friction coefficient between the steel and the concrete, finding that the prime factor for changes in bond due to corrosion may be the confinement pressure of the bar, rather than changes in friction characteristics. As another example, Ouglova et al. [18] designed specimens to avoid lateral confinement, with a polished bar as reinforcement and with a window to measure the displacement of the bar by digital image correlation, detecting interface opening normal to the interface for high corrosion levels. However, further work is required to characterize individually the effect of corrosion on the mechanisms contributing to bond, which motivated this work.

In the current paper an experimental study is offered with the main purpose of providing fundamental research on loss of bond between the steel and the concrete due to reinforcement corrosion, focusing on adhesion and friction. In particular, bond behavior is studied by means of push-out tests of smooth reinforcement, using the experimental device developed in [19]. The specimens are concrete slices cut from prisms reinforced with a calibrated steel tube, which were corroded under a constant current in such a manner that uniform corrosion was expected to occur along the tube length, as explained in [20,21]. Since in the cut slices the steel tube does not protrude from the concrete, push-out instead of pull-out was selected [19], which has the advantage of allowing using a simple loading device, as explained later in the paper. Moreover, since the reinforcement in the tests is a smooth tube, instead of a bar, interlocking between bar ribs and concrete is avoided, and adhesion and friction can be studied. During the tests, the applied load, the displacement of the tube and the additional opening of the main crack which was developed through the cover during accelerated corrosion were recorded. This allowed analyzing the maximum shear stress, residual stress and loss of confinement of the specimens. Results are presented for specimens corroded up to three different corrosion depths, as well as for virgin specimens.

It should be noted that the reinforcement of this work differs from that of concrete structures; thus, different values of the shear stress may be obtained. The geometry of this reinforcement, though, was essential in this study to disclose essential aspects of the bond behavior of the steel-oxide-concrete system. Furthermore, the presented method could be applied to study the behavior of specimens for other test conditions.

This paper is organized as explained next: following to this introduction, Section 2 presents the main aspects of push-out tests and the design of the experimental devices, Section 3 describes the procedure of preparation of the slices for bond tests, including the technique used for accelerated corrosion of the specimens, Section 4 discusses the results, and Section 5 summarizes the conclusions of this work. Finally, details on the processing of results are given in Appendix A.

2. Basis of push-out test

2.1. Context

Push-out tests presented in this work have been carried out within the framework of a general study of cracking of concrete due to reinforcement corrosion [19–21]. In that study, concrete prisms reinforced with a calibrated steel tube, as those sketched in Fig. 1(a) and (b), were artificially corroded under a constant current, using the experimental setup presented in [21], with such conditions that uniform corrosion was expected to occur along the length of the tube, as further explained in Section 3. After the tests, each specimen was cut into five slices, as sketched in Fig. 1 (c); the two external slices were discarded, and the central slice, labeled as 3 in the figure, was subjected to the push-out test. The two remaining slices were impregnated with fluorescent resin, following the method presented in [20], to study the crack pattern of the specimens, which is out of the scope of this paper. During accelerated corrosion, a main crack developed through the cover, together with several thin secondary cracks, as sketched in Fig. 1 (d), which was assessed from the inspection of the impregnated slices under ultraviolet light. In parallel to the experiments, numerical simulations of the accelerated corrosion tests were conducted, using a model that reproduces the cohesive fracture of concrete by means of elements with an embedded adaptable crack [22] and the mechanical behavior of oxide by means of expansive joint elements [20]. The comparison of the numerical and experimental curves of crack width, variation of inner diameter and variation of inner volume of the tube permitted disclosing the best