Construction and Building Materials 54 (2014) 180–189

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of corrosion method of the reinforcing bar on bond characteristics in reinforced concrete specimens

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HIGHLIGHTS

- The bond capacity is affected by the corrosion method of rebar in RC specimens.
- The slip at failure was increased when the corrosion level was higher than 5%.
- The bond strength was increased when corrosion level was lower than 1%.
- The expansion pressure of corroded rebar ranged from 9.3 to 13.4 MPa.
- The brittle failure pattern was observed when the area of corrosion exceeded 50%.

ARTICLE INFO

Article history:
Received 13 May 2013
Received in revised form 18 December 2013
Accepted 19 December 2013
Available online 14 January 2014

Keywords:
Bond characteristics
Corrosion method
Artificial corrosion
Natural corrosion
Reinforced concrete

ABSTRACT

Reinforcing bars embedded in concrete structures are corroded, for example, by the ingression of chlorides from sea sand and deicing materials. Such corrosion induces interior pressure which is increased in the surrounding concrete due to expansion of rebar. As a result, the bond strength and stiffness of reinforcing bar are reduced and the structure eventually undergoes deterioration of concrete which lead to drastic shortening of service life of concrete structures. Accordingly, many researchers have investigated on relationship of bond characteristics of reinforced concrete (RC) members and corrosion of the reinforcing bar. One technique to define the relationship is to artificially induce rapid corrosion of the reinforcing bar. However, this artificial corrosion method failed to provide an accurate representation of real conditions and led to overestimation of the performance of RC members in real situations. The objective of this paper is to investigate the differences of bond characteristics in RC members corroded by artificial rapid and natural corrosion methods. The evaluation on technique suitability was also performed.

The results of this investigation indicated that the failure pattern and the critical corrosion level at which the bond capacity failed, varied depending on the RC corrosion method. The RC specimens were deteriorated at a low corrosion stage under natural corrosion conditions. More attention is needed to be given to the rapid artificial RC member corrosion method. Non-destructive test (NDT) methods were also applied to RC specimens for investigation of the naturally corroded members. A formula of corrosion area prediction from NDT was proposed.

1. Introduction

When reinforcing bar is corroded, the durability of reinforced concrete (RC) members will be severely fell and the service life will be accordingly shortened. The big and long infrastructures become more vulnerable to safety hazards as their size increase. Accurate prediction of the service life of these members has become a considerable challenge [1,2]. Corrosion of reinforcing bars in concrete can be caused by sea water, sea sand, deicing salt, or carbonation of concrete [3,4]. Among these causes, corrosion by chloride ions is a particular concern since it causes the most serious damage to reinforcing bar.

Research on bond property and other behaviors of RC member according to the corrosion of the reinforcing bar has been actively conducted. The investigation on the quantification of corrosion behaviors is being pursued [5,6]. Nonetheless, corrosion of the reinforcing bar takes a considerable amount of time and is strongly influenced by environmental factors. Consequently, investigations are difficult to perform.

The most common cause of corrosion initiation of reinforcing bar in concrete is the ingress of chloride ions to the steel surface.

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http://dx.doi.org/10.1016/j.conbuildmat.2013.12.065

Corrosion of rebar damages the reinforced concrete structures in two ways. First, it reduces the cross-sectional area of reinforcing bar. Second, it produces corrosion products with a larger volume than the rebar itself. This volume augmentation induces the tensile stress in concrete which lead to cracking and structural failure.

In response to this problem, various evaluations have been carried out by using analysis techniques such as corrosion property analysis of corroded rebar, accelerated corrosion, and simulation of extreme environmental conditions [7–9]. However, these experiments do not represent the actual behavior of a structure. The possibility of false representation of corrosion behavior cannot be excluded. Presently, there are limited studies on the comparison of corrosion behavior of reinforcing bar in concrete according to different corrosion methods [10–13]. Moreover, corrosion behavior studies are also limited for natural and artificial environmental conditions.

Therefore, the purpose of this study is to investigate the relationship between the level of reinforcement corrosion and the bond properties in accordance with the corrosion methods.

In this study, the examination of the variation of bond behavior of RC members with different corrosion methods is conducted. At the end of this paper, an appropriate method for predicting service life of the structure will be suggested. More specifically, the differences between members corroded naturally during a long period and members subjected to an artificially accelerated process in the bond property are investigated. Based on these research outcomes, data guideline for the evaluation of the corrosion property of such structures is proposed. For naturally corroded case, the possibility of corrosion prediction by a non-destructive test (NDT) is also examined in parallel with electrochemical methods.

2. Experiments and measurement

2.1. Experimental program

2.1.1. Test variables

This test was carried out to evaluate the bond characteristics between concrete and reinforcing bars corroded in RC members. Moreover, corrosion methods of rebar were divided into three patterns. To evaluate the effect of rebar cross-section reduction (High level corrosion), the first case, rebar corroded before concrete placement (method A), was conducted. The corroded rebar was actually prepared before concrete placement. To evaluate the effect of the tensile stress due to the volume increasing, the second case, rebar corroded artificially after concrete placement (method B) in which the rebar was corroded by an electrical accelerating method. To evaluate the effect of low level corrosion, the final case (method C), rebar corroded naturally by mixing chlorides into specimens, was applied. Water–cement ratio ($W/C = 0.4, 0.6$), corrosion level of the reinforcing bar, and the amount of chlorides inside the specimens were considered as test variables. Additionally, with the aim of developing NDT method for predicting corrosion level, the test results from specimens corroded naturally were compared and evaluated by using half-cell potential and polarization resistance methods. Experimental variables are summarized in Table 1. In this study, test data for corrosion were obtained and evaluated over a period of two years since a long duration is required to induce natural corrosion.

2.1.2. Specimen preparation

Fig. 1 showed dimension of molds for the pullout test specimens. Various types of specimens were used for bond tests such as the popular ones from American Society for Testing and Materials (ASTM) C 234 [14] and modified beam tests. In ASTM, it was specified that the concentric pullout test can be used only for comparison purposes. The details of other test setups can be found in a research report by Chapman and Shah [15]. After evaluating various setups, a modified version of the setup proposed in Danish Standard (DS) 2082 [16] was chosen to be used in this study (Fig. 1).

The test specimens were fabricated in cubic with 150 × 150 × 150 mm cubes dimension by considering the appropriate size and shape for the pullout test and current corrosion measurement. The bond length was set to four times the diameter ($d_b \approx 25$ mm) of rebar (i.e., $4d_b \approx 100$ mm). Moreover, the rebar exposed to air was treated with a rust inhibitor to prevent its corrosion. After removal from the mold, the specimen was water-cured in a water chamber for four weeks at a temperature of 20 ± 3 °C. For the case of artificially induced corrosion of the rebar (method A), the bond test was conducted at 28 days. On the other hand, the specimens with artificially corroded rebar after placement (method B) were subjected to accelerated corrosion for 14 days and a bond test was performed at 28 days. In contrast, the naturally corroded specimens (method C) were air-cured in an outdoor environment until the occurrence of corrosion. The usual cylinder molds with diameter of 100 mm and height of 200 mm were used to prepare specimens for the compression test.

2.2. Materials and concrete mixture proportion

In this test, D25 deformed bars and ordinary Portland cement were used for the bond test. Natural sand and crushed stones of 25 mm maximum size were used as fine and coarse aggregates, respectively. The physical properties of the aggregates used in the concrete mixture are listed in Table 2.

Table 3 showed the mixture proportion which satisfied the target slump and void content of 10 ± 2 cm and 5 ± 1%, respectively. Chemical admixtures were used in order to get the same slump and void content for each W/C.

2.3. Artificial corrosion method of the reinforcing bar

2.3.1. Corrosion of the rebar before concrete placement (method A)

The anode of direct current power supply was connected to the rebar and the cathode was connected to a mesh wire placed inside a 5% NaCl solution as a method to corrode the rebar prior to the concrete placement (Fig. 2(a)).

The corrosion level of reinforcing bar was represented by the weight reduction ratio of corroded rebar. The level was determined by measuring the weight of the rebar before and after the corrosion procedure. Fig. 3 illustrated the corrosion status of the rebar.

$$\text{Level of weight reduction } (\%) = \frac{\text{weight before test} - \text{weight after test}}{\text{weight before test}} \times 100 \qquad (1)$$

2.3.2. Corrosion of the rebar after concrete placement (method B)

Accelerated corrosion test on rebar was carried out by building a direct current circuit on it with anode and cathode of the direct current power supply connected to reinforcement and NaCl solution, respectively [7]. The concrete specimen with embedded rebar was then immersed in a 3% NaCl solution (Fig. 2(b)). The amount of corrosion was indicated by the quantity of corrosion including the cumulative current value and the weight reduction ratio. The expected corrosion value with the current value is estimated by the following equation based on Faraday's law.

$$\text{Amount of corrosion (mole)} = \frac{1}{2 \times 96,500} \int q\,dt \qquad (2)$$

In this equation, the amount of corrosion (mole) is the number of moles of corroded iron ion (Fe), and q (Ampere) is the amount of current passed through each stage.

The artificial corrosion accelerated test was carried out up to a 10% corrosion level. However, the expansion pressure of the rebar caused corrosion cracks at only above 2% of corrosion. When cracks occur, the durability and strength of the specimen were suddenly decreased [8,9]. Accordingly, the bond test was conducted on the specimens with corrosion up to approximate 2%. Fig. 4 showed the cracks of specimen due to excessive corrosion.

Table 1
Experimental variables.

W/C (%)	Corrosion method		Measurement
40	Artificial corrosion	Rebar corroded before placement (method A) (corrosion level: 0%, 2%, 5%, 7%, 10%) Rebar corroded after placement (method B) (expected corrosion level: 0%, 2%, 5%, 7%, 10%)	Bond capacities by pullout of rebar
60	Natural corrosion	Corrosion by chloride ion intrusion (method C) (0.6, 0.9, 1.2, 1.5, 1.8, 2.4, 3.0, 3.6 kg/m^3)	Bond capacities by pullout of rebar Half-potential Polarization resistance