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Crack patterns of concrete with a single rebar subjected to non-uniform and localized corrosion

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HIGHLIGHTS

- Corrosion distribution should be considered for predicting internal crack situation.
- Crack pattern for small cover depends on how corrosion distributes around a rebar.
- Localized corrosion causes lateral cracks to incline to the concrete surface.
- Crack pattern can be well predicted using RBSM considering corrosion distribution.

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ABSTRACT

This study aims to investigate the effects of corrosion distribution, specifically non-uniform and localized corrosion, on cracks propagation in concrete. Different corrosion distributions along rebar length were simulated using a sodium chloride pond with various sizes set on the concrete cover, and a direct current was applied to accelerate the corrosion process. The test results showed that the crack pattern is more influenced by corrosion distribution than by concrete cover thickness. The cracking mechanism was analyzed using the Rigid Body Spring Method with a corrosion-expansion model, which utilized a set of experimental data relating to corrosion distribution. The crack patterns are simulated reasonably well. The analysis also indicated that the internal crack pattern is closely related to concrete surface deformation.

1. Introduction

Corrosion of reinforcing steel bars (rebars) in concrete is a principal cause of deterioration of reinforced concrete (RC) structures. As forming corrosion products occupy a greater volume than that of pure steel, the resulting internal pressure can cause cracking of concrete cover. Corrosion may also lead to a loss of rebar tensile performance as a result of loss of cross section area [1], and decreased bond strength between corroded rebars and the concrete [2], which affect the structural safety of an RC structure. Field and laboratory findings [3–5] suggest that the influence of rebar corrosion is more manifested by concrete cracking than the loss of structural strength. When internal cracks join together forming a spalling of concrete cover, falling concrete could be a risk to human safety. Several relevant incidents have been reported (e.g. [6]), and in some cases the cracking situation of concrete surface observed during the inspection was insignificant, which makes the prediction of internal crack propagation and potential cover spalling difficult. Therefore it is of great importance to understand how internal cracks develop due to rebar corrosion.

A number of studies have shown that corrosion-induced cracking behavior is dependent on the geometric conditions and configurations of concrete sections. Based on the bridge deck survey findings and laboratory research data, Callahan et al. [7] indicated that corrosion-caused cracks could be either inclined or horizontal in the plane of rebar, depending on cover thickness. The inclined crack may appear when concrete cover is smaller than 25.4 mm, while the horizontal crack can occur when the cover thickness is greater than 31.8 mm. In further analytical work, Bažant [8] suggested that the cracking resulting from rebar corrosion occurs basically in two different modes, provided that concrete with embedded rebars is a thick-walled cylinder and corrosion products distribute uniformly around the rebars. The cracking modes are related to cover thickness (C) and rebar spacing (S), as shown in Fig. 1. If the spacing S is greater than six times the rebar diameter (D) or the cover thickness (C) is relatively small, two cracks

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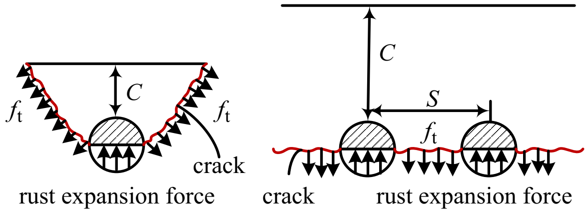
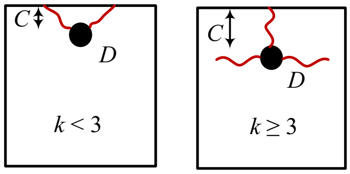


Fig. 1. Bažant's cracking mode. Adapted from [8].

propagate diagonally from the rebar to the concrete surface at an angle of 45°, leading to cover spalling. If the cover thickness (*C*) is larger than (*S*-*D*)/2, the two cracks propagate to adjacent rebars separately, forming parallel cracks to the concrete surface resulting in delamination. In a similar way, Tsutsumi et al. [9] proposed a criterion for the internal crack patterns of single-rebar specimens based on the elastic theory that takes into consideration stress concentration, as shown in Fig. 2. If the value of *k*, which is determined by the ratio of cover-to-bar diameter (*C*/*D*), is less than three, cracks propagate diagonally to the concrete surface. If the value of *k* is greater than three, a vertical crack occurs in the concrete cover along with two horizontal cracks. In addition, Caré et al. [10] studied the cracking behavior of mortar beams using an electric corrosion method, and found that the crack pattern depends upon the thickness of concrete side cover.

Although the aforementioned studies provide a good understanding of corrosion-induced cracking behavior, their assumption is based on uniform corrosion around a rebar, which is different from the corrosion pattern caused by chloride attack. Yuan et al. [11,12] observed the distribution of corrosion products around the corroded rebars that were obtained by exposing the RC specimens to an artificial climate environment. Their results showed that the corrosion products only distributed on the half rebar circumference facing the concrete cover. Such corrosion generates non-uniform expansion pressure, which may cause faster development of concrete cracks than uniform corrosion [11,13,14]. The knowledge concerning the crack patterns resulting from non-uniform corrosion, however, is still limited. On the other hand, chloride penetration usually leads to localized breakdown of the passive film of a rebar, especially in the presence of initial cracks due to creep and shrinkage [15]. As a consequence, corrosion may concentrate within a small region along the length of the rebar. Previous investigations into corrosion-induced cracking behavior as referenced earlier are mostly two-dimensional studies without consideration of the localized corrosion along rebar length. Torres-Acosta and Sagüés [16] studied this problem using a dual-material rebar that was made with a carbon steel segment connected with stainless steel at both ends. The crack patterns they observed, however, were irregular, which is possibly due to a relatively thin concrete side cover.

The present work aims to investigate the crack patterns influenced by various corrosion distributions, which can contribute to efficient maintenance work on corroded RC structures. Both experimental and numerical studies were conducted for investigation into the effects of non-uniform and localized corrosion. In the test, different corrosion distributions were obtained using an improved electric corrosion method, and the crack patterns generated were examined in detail. On the other hand, the Rigid Body Spring Method (RBSM) with the corrosion-expansion model [17] was employed to evaluate the cracking behavior, in which the corrosion distributions were assumed with test data.



$$k = \frac{2C + D}{D}$$

Fig. 2. Tsutsumi's criterion for crack pattern. Adapted from [9].

2. Experimental program

The electric corrosion method with a sodium chloride (NaCl) pond built on the concrete cover was used to accelerate the corrosion process. The applicability of this method to simulate non-uniform corrosion around a rebar was firstly checked. Then different corrosion distributions along rebar length were simulated using NaCl ponds of various sizes.

2.1. Electric corrosion test

The natural corrosion process of a rebar embedded in concrete is very slow, since it may take several years for chloride ions to penetrate through concrete cover. For evaluation of structural behavior of corroded RC members, researchers thus employ several accelerating corrosion techniques to obtain the desired corrosion damage within a reasonable time frame. The techniques used include adding chlorides into the concrete mix [18,19], the electric corrosion method that is immersing the specimen in a NaCl solution and applying a direct current to the rebar [20,21], and a combination of the two methods [3,10]. The typical corrosion pattern implemented by the above techniques, however, is uniform corrosion [22]. Hence a method that can simulate non-uniform corrosion is required.

For accelerating techniques, Poursaee and Hansson [22] and Malumbel et al. [23] recommended that only selected faces of the concrete specimens should be contaminated with chlorides following the practical conditions. In this study, a 100 mm wide pond filled with 3% NaCl solution was built on the concrete cover of each specimen. A copper plate was placed in the NaCl pond as the cathode. Fig. 3 shows a diagram of the electric corrosion method. It was assumed that the corrosion current for the rebar upper part facing concrete cover would be greater than that for the lower part. This is attributable to a smaller distance from the upper part to the cathode. On the other hand, the cracks generated in concrete can cause faster chloride ingress [24], increasing the corrosion rate of the rebar upper part. Therefore, the upper part should be more corroded, showing a non-uniform corrosion pattern. A preliminary experiment was carried out to prove this point.

2.1.1. Test specimens of the preliminary experiment

The test included 12 prismatic concrete specimens with dimensions of 200 × 500 × 200 mm^3 as shown in Fig. 3. In each specimen, a 600 mm long round rebar with a diameter of 16 mm was embedded at a depth of 30 mm oriented along the 200 mm length of the specimen, with exposed parts of the rebar extending 200 mm beyond each end. The round rebars were used for an easy measurement of radius losses with a laser meter. Since the laser meter used has a limited scanning length of 200 mm, the length of the rebar part exposed to corrosion was confined to 180 mm by coating the other parts with anti-corrosion paint, waterproof tape and insulating tape in sequence to prevent from corroding. Before casting the concrete, the rebars with anti-corrosion covers were weighted for initial weights.

The concrete was made with High Early Strength Portland Cement. Table 1 presents the mixture proportion of concrete, which was used in the entire study. The maximum diameter of the coarse aggregates used was 20 mm. The volume fraction of coarse aggregates to total aggregates was 0.6. After casting, the specimens were cured in a room at 20 °C for 14 days, and then the electric corrosion test was conducted. Prior to the test, the Young's modulus, compressive strength and splitting tensile strength of the concrete were determined as 30.75 GPa, 38.45 MPa and 2.94 MPa, respectively.

2.1.2. Test procedures of the preliminary experiment

The corrosion time was varied as shown in Table 2 to obtain different concrete cracking situations. The specimens were named in the form T86, meaning a period of approximately 86hours applied with a direct current. Four specimens were used for each test series, which were connected in series to a DC power and supplied with a constant current of 0.08A, as shown in Fig. 4. The nominal current density applied was about 900 $\mu\text{A/cm}^2$, which is greater than the maximum corrosion rate recorded in real corrosion cases (100 $\mu\text{A/cm}^2$ as indicated by Andrade et al. [3]). Although the current density may affect the evolution rate of surface crack width [25,26], there are no conclusive findings regarding its effect on the crack pattern. Therefore, the larger current density was used to allow quick crack generation, as referred to in other reported electric corrosion tests [11,27].