Construction and Building Materials 156 (2017) 684–691

Contents lists available at ScienceDirect

Construction and Building Materials

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

Rust distribution and corrosion-induced cracking patterns of corner-located rebar in concrete cover

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HIGHLIGHTS

- Rust distribution and cracking of corner-located rebar in concrete are studied.
- Gaussian functions are used to describe rust profiles in concrete cover.
- Conceptual models are proposed to describe the rust growth in concrete.

ARTICLE INFO

Article history:
Received 2 June 2017
Received in revised form 4 September 2017
Accepted 8 September 2017

Keywords:
Corner-located rebar
Steel corrosion
Reinforced concrete
Concrete cover cracking
Concrete materials

ABSTRACT

In this work, the rust distribution patterns and concrete cover cracking behavior of corner-located rebar was studied by means of digital microscopy. The corner-located rebar with various cover thicknesses embedded in concrete specimens was exposed to artificial corrosive environments. The time-dependent evolution of rust distribution profiles around corroded rebar was measured and described by Gaussian models. The results show that for corner-located rebar, when the two side concrete cover thicknesses have the similar value, the onset of rust formation starts simultaneously and its rust pattern can be well described by two or three independent Gaussian functions. At the same level of corrosion, the cracking behavior of corner-located concrete can be considerably different, depending on the rust profiles and dimensional ratio of the two side concrete cover thicknesses.

1. Introduction

Chloride-induced steel corrosion has been one of the most common causes of deterioration in in-service reinforced concrete (RC) structures, partially in coastal or deicing salts environments [1,2]. The chloride penetration into concrete can initiate the steel corrosion, resulting in cracking and peeling-off of concrete covers due to expansive stresses associated with rust formation [3–6]. Moreover, steel corrosion reduces cross-sectional area of load-bearing reinforcement, which undermines the bearing capability and structural ductility of RC members [7]. In order to accurately estimate the service life of RC structures and plan for the structural maintenance, a considerable amount of work has been done to understand the process of corrosion-induced cracking in concrete cover. However, most of the existing studies focused on the rebar located on the side of the cross section of RC members, in which circumstance the chloride penetration can be considered as one-dimensional [8–11]. By contrast, the rebar located in the corner of the cross section, the chloride ions can penetrate into concrete covers simultaneously from two sides. As such, in comparison to the side-located rebar, the corner-located rebar may be more vulnerable to chloride-induced corrosion. In addition, the thicknesses of concrete cover for corner-located rebar may not be identical at two sides, which increases the complexity of corrosion initiation and prorogation processes. Unfortunately, the study on the corrosion characteristics of corner-located rebar is not as extensive as that for side-located rebar.

According to the previous studies, the rust distribution patterns of corroded rebar plays a critical role on the concrete cover cracking and failure behaviors of RC structures [12–15]. Many researchers simulated the corrosion-induced concrete cover cracking behavior by pre-assuming the rust distribution profiles (e.g., using a semi-elliptical model [16], a linear model [17], or a Gaussian model [13]). Understanding and characterizing the rust distribution patterns of the corner-located rebar would be crucial since

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http://dx.doi.org/10.1016/j.conbuildmat.2017.09.033

its characteristics would be different from that of side-located rebar. However, systematic studies on the rust distribution patterns and associated concrete cover cracking analysis of corner-located rebar are rarely reported.

To fill the aforementioned research gaps, this study is to investigate the rust distribution profiles of corner-located rebar with various cover thicknesses, as well as to relate the corrosion characteristics to the cover cracks development. The outcomes of this study provide an implication for the numerical simulation of corner-located steel corrosion-induced concrete cover cracking in RC structures.

2. Experimental Program

2.1. Materials and specimens preparation

The concrete was prepared by mixing ordinary Portland cement, river sand, crushed gravel, polycarboxylate superplasticizer, and tap water in a ratio of 372:698:1116:2.22:175 (kg/m^3). The 28 days compressive strength of the concrete on cubic specimens with a side length of 150 mm was measured to be 42.5 MPa. The rebars were ribbed steel bars with a nominal diameter of 10 mm and the characteristic value of yield strength of 300 MPa.

The configuration of the concrete specimens and the layouts of the rebars are shown in Fig. 1. For each specimen, four bars were embedded at the four corners of the cross section but with different values of concrete cover thickness. The concrete cover thicknesses of the two sides in each of those four rebars are different, with one being 10 mm on both sides while the other three have one side being 10 mm and another side being 15 mm, 20 mm, or 25 mm. The identification of rebar was named as C*x*, in which the *x* represents the thickness of the thicker concrete cover. After casting, the specimens were demolded at 24 h and then moved to a standard moist curing room (i.e., 100% relative humidity and 20 ± 0.5 °C).

2.2. Corrosion acceleration

After 28 days moist curing, the specimens were exposed to an artificial environment to accelerate the steel corrosion embedded in the concrete specimens. The artificial environment was comprised of two stages, namely, corrosion initiation and corrosion propagation. The corrosion initiation was triggered by exposing the specimens to a cyclic drying-wetting environment for 32 days. Each drying-wetting cycle included 1 day wetting in a 6% (by mass) NaCl solution and 3 days oven-drying at 50 °C (totally 4 days for one cycle). In order to ensure that the chloride concentrations around the surfaces of each cross section were similar, the specimens were vertically placed in the container. Based on the preliminary tests, it was found that exposing the specimens in this condition for eight cycles could ensure the rebars depassive. On the other hand, the corrosion propagation stage of rebar was accelerated by exposing the specimens in an environmental chamber with 80% relative humidity and 33 °C.

2.3. Rust distribution patterns

In order to study the time-dependent evolution of rust distribution patterns around the circumference of corner rebars during the corrosion propagation stage, the specimens were taken out of the environmental chamber at an interval of 28 days. At the desired duration (i.e., 28, 56, 84, 112, and 140 days), the specimens were sliced into eight pieces, as shown in Fig. 2. Only the middle six segments were kept and analyzed while the top and bottom parts were discarded. For each segment, it has two surfaces; therefore, each specimen has a total of 12 observation surfaces. After the segmentation, the sliced pieces were stored in isopropyl solutions to minimize secondary corrosion and oxidation. In prior to the microscopy observation, the specimens were polished using sand papers and cleaned using isopropyl alcohol.

The CMS-200 digital microscope connected to an analyzing program was used to quantitatively measure the rust thickness at the rebar-concrete interface. For each corner-located rebar at each observation surface, 12 observation regions could be assigned, as illustrated in Fig. 3. Three measurements were taken at each region; so totally 36 measurements were taken along the circumference of each corner-located rebar. Furthermore, the measured variation of rust thickness as a function of the location along the circumference of each corner rebar was fitted using a Gaussian function [13]:

$$T_r = \frac{a_1}{a_2\sqrt{2\pi}} e^{-\left(\frac{\theta-\pi}{\sqrt{2}a_2}\right)^2} + a_3 \qquad (1)$$

In which, T_r is the rust thickness at coordinate θ; a_1, a_2, and a_3 are fitting parameters, in which a_1 is the non-uniform coefficient of the rust layer, a_2 is the spread coefficient of rust layer, and a_3 is the uniform coefficient of the rust layer.

2.4. Estimation of loss of cross-sectional area

The level of corrosion of corner rebar could be estimated based on the measured rust thickness distribution. As mentioned before, the original diameter of the rebar was 10 mm, and the 36 rust thickness measurements were taken along the circumference of corroded rebar. As such, for each measuring point, it could approximately represent the average rust thickness in the surrounding range of $\pi/18$. In other words, it approximated that the rush thickness in a range of $(\theta - \pi/36,\ \theta + \pi/36)$ was considered to be the same as that of the measuring point at the angle of θ. Therefore,

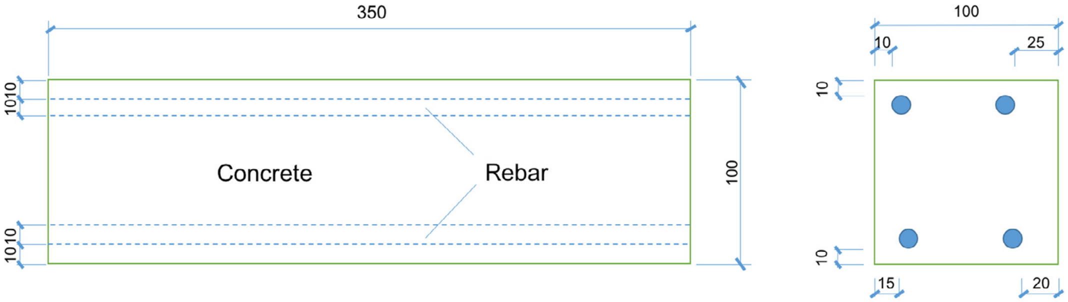

Fig. 1. Configuration of specimens and the layouts of the rebars (unit: mm).