Engineering Structures 167 (2018) 188–202

Contents lists available at ScienceDirect

Engineering Structures

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

Corrosion non-uniformity of steel bars and reliability of corroded RC beams

Xianglin Gu*, Hongyuan Guo, Binbin Zhou, Weiping Zhang, Chao Jiang

Key Laboratory of Performance Evolution and Control for Engineering Structures, Ministry of Education, PR China
Department of Structural Engineering, College of Civil Engineering, Tongji University, 1239 Siping Rd., Shanghai 200092, PR China

ARTICLE INFO

Keywords:
Corrosion non-uniformity
Mechanical property of a corroded rebar
Time-dependent reliability
Corroded reinforced concrete beam

ABSTRACT

To study the non-uniform distribution of cross-sectional areas and mechanical properties of corroded steel bars under a chloride environment, 19 concrete slabs embedded with steel bars were exposed to a chloride environment to achieve accelerated corrosion. A 3D measurement technique was employed to create geometric models of corroded steel bars, and their cross-sectional areas of a corroded steel bar, a probability distribution model of the spatial variability factor *R*, was developed through signal processing and statistical analysis methods. The *R* factor is the ratio of the average cross-sectional area to the minimum one and was applied to analyze the mechanical behavior response to the non-uniform corrosion of steel bars under tensile loading. In addition, the relationship between the mechanical properties and *R* factor of a corroded steel bar was established to predict its critical state of brittle failure. Our novel approach to this analysis enabled the calculation of the time-dependent reliability of a simply supported corroded reinforced concrete beam. The results showed that non-uniform corrosion is the critical factor affecting the time-dependent reliability of a reinforced concrete beam; moreover, changes in the failure mode of a corroded steel bar may severely impair the reliability of a reinforced concrete beam.

1. Introduction

Corrosion often takes place in reinforced concrete (RC) structures due to chloride concentration in the marine environment, which can cause resistance degradation of RC members and financial loss [1–5]. Non-uniform corrosion is widely observed to randomly occur in a longitudinal direction, because of variations in environmental conditions, concrete properties, and thickness of concrete cover. On the other hand, non-uniform corrosion might influence the mass transport properties of concrete and its service performance [6,7]. Moreover, non-uniform corrosion may severely affect the mechanical behavior of a corroded rebar, induce a failure in non-critical cross-sections, and increase failure probability in a corroded RC beam by 200% considering non-uniform corrosion [8]. Hence, corrosion non-uniformity is a significant factor affecting the time-dependent resistance of an RC member.

The pitting factor R_p has been widely adopted to quantify the corrosion non-uniformity of a corroded rebar which reads

$$R_p = p_{max}/p_{av} \tag{1}$$

where p_{max} is the maximum pit depth of corrosion pits; p_{av} is the average penetration depth of corrosion [8–13]. However, to consider the geometric complexity and the distribution randomness of pits in the cross-sectional circumference of a rebar, the spatial variability factor R was put forward to assess the corrosion non-uniformity accurately which is defined as

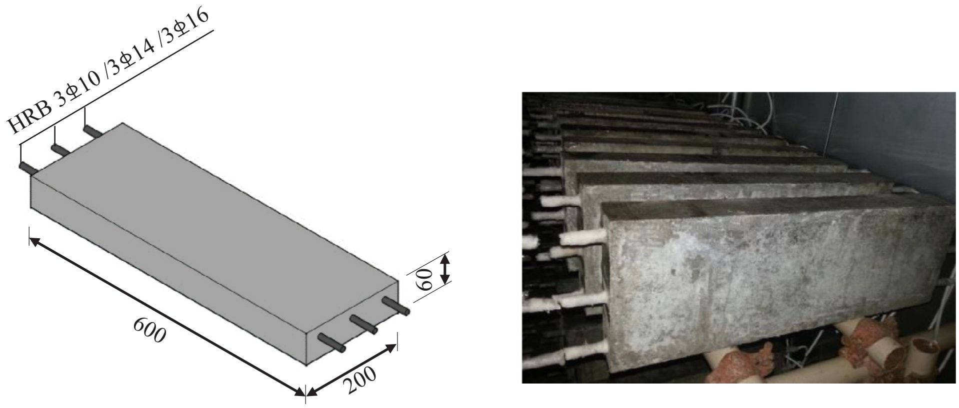
$$R = A_{av}/A_{min} \tag{2}$$

where A_{av} and A_{min} are the average and minimum cross-sectional area of a corroded rebar, respectively [14]. Being limited to the quantity of natural corroded rebars, Zhang et al. applied the galvanostatic method to obtain a vast number of corroded specimens [14]. However, the corroded rebars obtained by the galvanostatic method are different from those that have undergone corrosion in the natural environment as per electrochemistry principles, which could easily cause the differences in the characteristics of corrosion distribution on the surface of a rebar [15–17]. In addition, various corrosion environments can affect mechanical performance of corroded rebars in different ways. For example, the electrochemical corrosion process of the corroded rebars obtained by salt spray experiments and their corrosion morphology are closer to experimental results obtained in natural environments [16]. Also, galvanostatic method cannot duplicate the natural environments results, because the corrosion mechanism of the former is different with

Abbreviations: A_{av} and A_{min}, average and minimum cross-sectional area of a corroded rebar, respectively; CDF, cumulative distribution function; p_{av}, average penetration depth for corrosion; p_{max}, maximum pit depth; R_p, pitting factor; R, spatial variability factor

* Corresponding author at: Department of Structural Engineering, College of Civil Engineering, Tongji University, 1239 Siping Rd., Shanghai 200092, PR China.
E-mail address: gxl@tongji.edu.cn (X. Gu).

https://doi.org/10.1016/j.engstruct.2018.04.020
Received 10 December 2017; Received in revised form 6 April 2018; Accepted 7 April 2018
0141-0296/



(a) Schematic of specimen (mm) (b) Specimen in the marine environmental chamber

Fig. 1. Preparation of RC slabs in a marine environmental chamber.

that of the latter [16]. Thus, the existing probability model of *R* factor may not completely reveal the corrosion non-uniformity profile in a practical chloride induced environment. In other words, it is necessary to apply salt-spray experiments to simulate the real corrosion environment and then establish the distribution model of *R* factor. On the other hand, the existing *R* model was based on plain round rebars [14], but ribbed rebars have been widely applied in practical engineering. Hence, ribbed rebar experiments are needed to develop corresponding strategies to set up a ribbed rebar-based *R* model.

The problem in developing a ribbed rebar-based model is the different values on the analysis length of a non-uniformly corroded rebar. Stewart et al. utilized a 100 mm length in modeling R_p, according to St. Venant's principle that element length should not be less than two times the rebar diameter [8]. On the other hand, Zhang et al. suggested 150 mm in modeling *R* because those results would be more conservative than others [14]. It is apparent that different analysis length values may affect the joint probability density function of the adjacent elements. For instance, small analysis length may reveal a strong relevance between adjacent elements. Hence, ignoring the effect of relevance and assuming that R/R_p is an independent stationary random field can cause engineers to overestimate both corrosion non-uniformity and failure probability of a corroded RC beam. On the other hand, due to the limited rebar length, long analysis length will reduce the data quantity and then decrease the precision in determining distribution parameters of *R*, which leads to more deviations in the reliability calculation of a corroded RC beam. Thus, selecting an appropriate analysis length plays an important role both in modeling of factor R and reliability calculation.

According to the statistical model on mechanical properties of corroded rebars varying with their average corrosion ratios, it is well known that an increasing average corrosion ratio of a corroded rebar accompanies a decline in rebar nominal yield stress, ultimate tensile stress, and ratio of nominal yield tensile stress to ultimate tensile stress [18–23]. However, previous tensile experiments have shown failure related to location as subject to the most severe corrosion of a rebar, namely the minimum cross-section. Conversely, Almusallam [22] found that adopting the minimum cross section to calculate strength did not decrease the strength of corroded rebars and Palsson et al. [24] found the ratio of actual yield strength to ultimate tensile strength can rise with an increasing cross-sectional area loss. In addition, relevant studies have also shown that the yield strain and the ultimate strain of a corroded rebar drops with a growing average corrosion ratio. Cairns et al. [2] found that the ultimate strain of a corroded rebar degrades to the yielding strain when the average corrosion degree reaches about 20%, which, according to Stewart [25], is the critical corrosion ratio that marked the transformation from ductile failure to brittle failure. Through a series of tensile tests on corroded rebars, Zhang et al. also found the phenomena of yield platform's disappearance, which indicated that the critical corrosion ratio was about 20–30% rather than a determined value [26]. Because average corrosion ratio cannot express the non-uniform distribution of corrosion characteristics in rebars, it was hard to employ an average corrosion ratio to predict the critical point of yield platform disappearance accurately. Thus, it is of great importance to establish a corrosion non-uniformity-based mechanical model for rebars and to predict the critical point of failure mode transformation in this paper.

The authors used the salt spray test to predict the time-dependent reliability of a corroded RC beam. The salt spray test required a 3D optical measurement, a signal processing method, and a tensile test, which helped established a probabilistic model for non-uniformity of cross-sectional areas and the mechanical properties of a corroded rebar under a chloride environment. In addition, as an example, the time-dependent reliability of a simply supported RC beam was calculated through Monte Carlo simulation considering non-uniform corrosion and mechanical behaviors of corroded rebars. Finally, concluding remarks and further research plans are provided.

2. Experimental program

Nineteen RC slabs sized 600 × 200 × 60 mm, were cast, with an identical cover thickness of 15 mm. Embedded in the covers were three hot rolled ribbed bars (HRB 335) [27]. Three types of rebar diameters were applied: 10 mm, 14 mm and 16 mm. Each RC slab contained three rebars of the same diameter, as presented in Fig. 1a. Fifty-mm-long extensions of these rebars were covered by epoxy resin to avoid corrosion at their two ends (Fig. 1b). Before casting the slabs, surfaces of all rebars were polished by a grinding wheel then dipped in acetone solution. Meanwhile, three 700-mm-long un-corroded rebars were prepared to represent the initial geometric models of the corroded rebars.

Table 1 showed the mix constituents of the slabs. After their 28-day curing, their top surfaces were exposed and other surfaces were sealed with epoxy resin. Meanwhile, the compressive strength of the concrete prism after 28-day curing was 40.4 MPa. Further, the slabs were transferred to an environmental chamber to dry saturated concrete under 10% relative humidity (RH) at 55 °C for 30 days to accelerate the transport of chlorine salt in the following step. Due to no microcracks observed from the surfaces of slabs in the present study, the effect of microcracks [28,29] was not taken into consideration in the present study. Then, the slabs were moved to the marine atmosphere