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Influences of corrosion degree and corrosion morphology on the ductility of steel reinforcement

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HIGHLIGHTS

- Steel reinforcements with three typical artificial corrosion morphologies were studied.
- Corrosion morphology influenced significantly the ductility of corroded reinforcement.
- The radius of gyration *i* was found to be the key factor for the corrosion morphology.
- An empirical model was proposed to quantify the effect of corrosion morphology.

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ABSTRACT

This paper investigates the influence of corrosion degree and corrosion morphology on the mechanical properties of the steel reinforcement. Tensile tests were first conducted on the steel reinforcement corroded by long-term (26–28 years) exposures to a chloride-rich natural environment. Through the tests, besides the corrosion degree, which was the most often used parameter to assess the corrosion, the corrosion morphology (i.e. represented by the radius of gyration of the residual cross-section) was found to be a very important factor influencing the ductility of the steel reinforcement and three typical corrosion morphologies were identified. Afterwards, tensile tests on a series of steel reinforcement artificially made with the above three types of corrosion morphologies, which were simulated through mechanically induced cross-sectional losses, were conducted with the aim of quantifying the relationship between the ductility of the corroded reinforcement and the corrosion degree and morphology. It was found that, for all the corrosion morphologies, that the ultimate strain of the corroded steel reinforcement was reduced in an exponential manner with the corrosion degree up to a critical level (30% by mass loss), beyond which it then stayed stable. However, different corrosion morphologies led to significantly different degradation rates with the corrosion degree. A model was proposed to describe the above relationships and validated through comparisons with test results on both the artificially simulated and the naturally corroded steel reinforcement.

1. Introduction

Durability is considered as one of the most important characteristics of reinforced concrete (RC) structures [1]. Tremendous resources are now being spent to solve the deterioration problems of existing RC structures to ascertain their safety and reliability [2,3]. It was reported that over $20 billion are needed for the repair and rehabilitation of highway structures in the USA every year [4], and over £600 million are needed annually for repairing road bridges in the UK [5]. The durability problem not only causes economic losses, but also creates environmental and social problems during the repairing and maintenance activities [6]. Therefore, the issue about the durability of RC structures has drawn increasing attentions all over the world [7].

Corrosion of steel reinforcement is one of the major threats to the durability of RC structures [8], particularly for those exposed to chloride-rich marine environments or cold regions where deicing salts are often used in the winter [9]. As the chloride ions penetrate into concrete, arrive at the surface of steel reinforcement and reach a threshold concentration, the corrosion of steel reinforcement will be initiated and develop gradually [10,11]. During the corrosion process, steel reinforcement is transformed into rust,

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resulting in its cross-sectional loss, which will finally degrade the durability and serviceability of the RC structures [12].

Cross-sectional loss induced by corrosion of steel reinforcement would subsequently lead to the degradation of the load-carrying capacity as well as the ductility of RC structures. For instance, Zhu et al. [13] reported that every 1% cross-sectional loss of the tensile steel reinforcement led approximately to 1% loss of the flexural yield capacity and 0.84% loss of the ultimate loading capacity of corroded RC beams. Stewart [14] investigated the influence of corrosion of the flexural and shear reinforcements on the mechanical strength and ductility of corroded RC members, and revealed that the corrosion may lead to brittle failure.

Due to the importance of steel reinforcement in the corroded RC structures, the residual performance of corroded steel reinforcement has been attracting increasing research interest [15]. Ou et al. [16] proposed a reduction factor for the capacity of corroded steel reinforcement based on both natural corrosion and artificial corrosion (i.e., induced by impressed current schemes). Balestra et al. [17] found that the steel reinforcement with a gravimetric corrosion degree of over 25% would lead to a 32% reduction of the nominal and effective strength, which were deduced using virgin and residual cross-sections, respectively. Fernandez et al. [18] investigated the fatigue performance of corroded steel reinforcement and found that the fatigue life was reduced in an exponential way with the increase of the corrosion degree.

Only limited research has been conducted on the ductility of the corroded steel reinforcement [19]. Eurocode 2 [20] stipulates a minimum ductility for virgin steel reinforcement to provide an acceptable margin of safety, but no special clauses are concerned with the corrosion effect. Du et al. [21] found that a corrosion degree of 10% may result in the ductility of steel reinforcement falling below the minimum requirement. Similarly, Almusallam [6] found that the corroded steel reinforcement exhibited a fragile behavior and might fail in a brittle mode when the corrosion degree exceeded 12%. Zhang et al. [22] found that the pitting corrosion of steel reinforcement had a less significant influence on the residual strength but resulted in an obvious reduction of the residual ductility. However, how to quantify the residual ductility of corroded steel reinforcement remains unclear.

This paper aims to investigate the influence of pitting corrosion on the residual ductility of corroded steel reinforcement. The corrosion morphology (shape of the corroded cross-section) and corrosion degree (mass loss) at the critical section (i.e., with the maximum cross-sectional loss) are considered as the two most important factors. Tensile tests were then conducted to find out the relationships between these two parameters and the residual ductility of corroded steel reinforcement. Two series of tensile tests were involved: (1) tests on corroded steel reinforcement extracted from two RC beams that had been exposed to a chloride-rich environment for 26 years (labeled as B2Cl2) and 28 years (labeled as B2Cl3), respectively; Hereafter, this series of tests is termed as “natural corrosion series” (NC series); (2) tests on a series of steel reinforcement with mechanically-induced cross-sectional losses that simulate different scenarios of pitting corrosion. Hereafter, this series is termed as “artificial corrosion series” (AC series).

2. Natural corrosion series

2.1. General information

The RC beams used to obtain the naturally corroded steel reinforcement were cast in 1984 at Laboratoire Matériaux et Durabilité des Constructions (L.M.D.C.) in Toulouse, southwestern France. For nearly the past three decades, the beams were subjected to service loads and exposed in a confined corrosive environment with saline spraying – drying cycles continually. The saline fog with the NaCl concentration of 35 g/L was adopted in the exposure test, which corresponded to the salt concentration of common sea water. More detailed information about the exposure conditions, loading levels and corrosion propagations in the beams could be found in the previous publications [23,24].

All of the longitudinal and transversal steel reinforcement in the beams was made of high yield steel with the nominal yield strength of 500 MPa. The typical stress-strain curve of virgin (non-corroded) steel reinforcement is presented in Fig. 1 (the experiment was tested on the steel reinforcement retrieved from the unexposed control beam, which was cast at the same time together with the exposed beams but stored in a normal laboratory condition).

Having been exposed to the chloride-rich environment for a long period, the RC beams were already highly corroded and corrosion cracks could be found in parallel to both the longitudinal and the transverse reinforcement throughout the whole span of the specimens. Spalling of the concrete cover was observed in some zones varying from the compressive area to the tensile area. In 2010 and 2012, the corroded beams B2Cl2 and B2Cl3 were crushed. The concrete was crushed and then the cages of the corroded reinforcement were retrieved as shown in Fig. 2. That means the steel reinforcements in B2C12 and B2C13 had experienced 26 years and 28 years of exposure, respectively. Different corrosion patterns and corrosion levels were found throughout the span of the reinforcement. The spatial distribution of corrosion was rather irregular and the reinforcement was covered by a thick layer of rust around their perimeters in most areas.

2.2. Preparation of test specimens

The corrosion products were cleared away from the corroded steel reinforcement by Clarke’s solution [25]. Afterwards, the corroded steel reinforcement were cut by a saw and separated into several test specimens with the length ranging from 420 mm to 670 mm. The residual mass of each specimen was measured by a balance with an accuracy of 0.01 g. The detailed information about the specimens from two corroded beams is summarized in Table 1. In total, 7 and 8 specimens were obtained from beam B2C12 and beam B2C13, respectively.

It should be noted that the residual cross-section of the corroded reinforcement was calculated by the residual mass divided the density of the reinforcement and the length of the corresponding specimen. So the residual cross-section represented an average value over the specimen length. It is seen in Table 1 that the average cross-sectional area losses of the specimens were ranged from 4.37% to 25.23%, while the maximum cross-sectional loss evaluated using the special coupon could reach as high as 53.08% (see the specimen labeled TBS-VI in the beam B2Cl3).

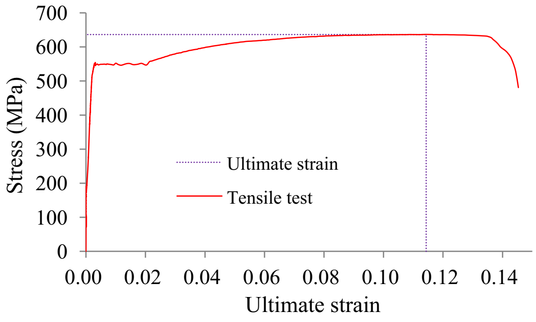

Fig. 1. Tensile stress-strain curve of non-corroded steel reinforcement.