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Three-dimensional corrosion pit measurement and statistical mechanical degradation analysis of deformed steel bars subjected to accelerated corrosion

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HIGHLIGHTS

- The cross-sectional area of corroded steel bars follows a mixed normal distribution.
- Both yield and ultimate loads decrease linearly with an increase of corrosion loss.
- Corrosion does not change the mechanical properties of steel bars significantly.
- Elongation and ductility decrease exponentially with an increase of corrosion loss.
- Corrosion changes the fracture mode from mixed ductile/brittle to brittle.

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ABSTRACT

This study experimentally investigated the effect of corrosion non-uniformity on the mechanical property degradation of deformed steel bars. Both the average and critical cross-sectional areas were determined using a 3D laser scanner. Tensile test results and statistical analysis showed that both the yield and ultimate loads linearly decreased with an increase of corrosion loss while the elongation and ductility decreased exponentially. Corrosion did not affect the yield and ultimate strength based on the critical cross-sectional area. Mixed brittle and ductile fracture occurred in uncorroded steel bars while brittle fracture initiated at corrosion pits and propagated outwards in corroded steel bars.

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1. Introduction

Reinforcement steel in concrete structures is generally protected by a passive film formed in the alkaline environment due to the hydration products of cement [1,2]. However, the passive film can be destroyed by ingress of aggressive ions such as chloride and carbon dioxide [3,4]. Due to varying external environments, nonhomogeneous properties of both concrete cover and passive film, and metallurgical and compositional non-uniformity of steel, corrosion in applications is often observed to be non-uniformly distributed along the length of a steel bar. In general, pitting corrosion is usually observed for steel reinforcement in concrete structures subjected to de-icing salts or in marine environments. Corrosion pits reduce the cross section of steel bars locally, resulting in stress concentration and significantly degrading the structural performance [5–7]. With further penetration of aggressive ions, more corrosion pits would form and propagate along the surface over time. Therefore, corrosion of steel in reinforced concrete (RC) structures is generally a random/stochastic field problem with probabilistic temporal and spatial distributions. This randomness increases the failure probability of corroded RC members as the corroded bar may fail at cross sections that are not subjected to the maximum load [8–10].

Irregular shape of corrosion pits formed on the steel bar surface makes it difficult to accurately measure the loss of cross section. One conventional method is to compare the difference of steel

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bar weight before and after corrosion, referred to as mass loss, and the mass loss was used as the only parameter to quantify the corrosion level [11–13]. In order to increase the measurement accuracy and determine the non-uniform distribution of corroded cross section, the corroded steel bar was cut into many small pieces, each weighed for mass loss [14–16]. This method can give accurate information about the cross section loss distribution along the length of steel bar when the pieces of steel bars are very small, but can be time consuming in applications. Corrosion pits can also be measured with a caliper [17] unless they are curved down from the rebar surface. Du et al. [18] designed a test apparatus for the residual cross sectional areas of a corroded steel bar by down steering the steel bar inside a glass tube filled with water and recording the balanced weight of the displaced water in a glass beaker, thus determining the residual cross sectional area at various lengths of the bar. This method assumed that the volume of water displaced from a glass tube was equal to the volume of bar immersed in the water in the tube. The accuracy of this method depends on the size of water drops or the flowability and surface tension of water around corrosion pits. Recently, Apostolopoulos et al. [19] used the image analysis technique to determine the size of corrosion pits with high accuracy. Moreover, a 3D scanner was used to determine the depth of corrosion pits; it proved to be a relatively more precise tool than other conventional methods [20,21]. With the aid of a 3D scanner, complex physical dimensions, such as varying pit size and depth and thus cross-sectional area loss can be measured more precisely and efficiently.

The non-uniform distribution of corrosion pits along the length of a steel bar affected the mechanical properties of the corroded bar. Many tensile tests have been conducted to characterize the reduction of the mechanical properties of corroded steel bars [11,12,18]. However, these studies used the average corrosion loss (average mass loss or average cross-sectional area loss) without considering the non-uniform distribution of corrosion pits. In this study, non-uniform degradation of the corrosion-induced mechanical properties of steel bars was evaluated with the aid of a 3D laser scanner. Firstly, the distribution of residual cross-sectional areas was determined using the 3D laser scanner along the length of each corroded steel bar, and the critical section with minimum cross-sectional area was identified. Secondly, degradation of the mechanical properties of corroded steel bars was evaluated in terms of elastic tensile stiffness, yield load, ultimate load, yield strength, ultimate strength, elongation, and ductility. Both the average and critical cross sectional area losses were determined, reflecting the overall distribution corrosion and the severest pitting corrosion, respectively. Finally, the microstructure of fracture surface was examined to investigate the effect of corrosion on the fracture mechanism.

2. Materials and methods

2.1. Specimen design and preparation

Grade 420 and No. 19 (metric unit) steel bars with a diameter of 19.1 mm were used in this study. The steel bars were produced using the conventional hot-rolling method, and their chemical composition was determined and listed in Table 1. The nominal cross sectional area is 284 mm^2, and the minimum requirements for yield strength, ultimate strength, and elongation are 420 MPa, 620 MPa, and 9.0% as specified by ASTM A615, respectively [22].

A total of 50 pieces of steel bars including 2 uncorroded and 48 corroded steel bars were prepared and tested, each approximately 457 mm long. Each steel bar was first sandblasted to remove the mill scale and rust layers on its surface. After sandblasting, the weight of the cleaned steel bar was measured with an electronic balance with an accuracy of 0.1 g. To limit fracturing of the steel bar within the middle portion during tensile tests, two gripped ends were encased in a 152.4 mm long, 25.4 mm in diameter PVC pipe each. The gap between the pipe and the bar was filled with epoxy. The middle portion of approximately 203 mm long was subjected to corrosion as shown in Fig. 1. A copper wire was welded at one end of the bar and connected with the external power supply in accelerated corrosion tests.

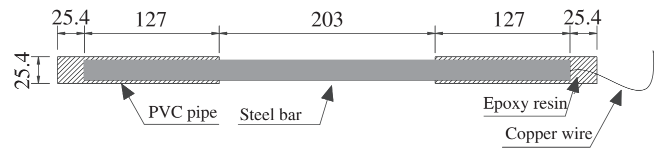

Fig. 1. Details of a steel bar specimen (unit: mm).

Six 229 mm × 279 mm × 508 mm concrete blocks with 25.4 mm cover were prepared as schematically shown in Fig. 2, and each concrete block contained 8 pieces of steel bars. To completely embed the steel bars into the concrete, the concrete block was designed such that each PVC pipe was extended into the concrete by 38.1 mm. The concrete used in this study was a mixture of Portland cement, coarse aggregates, fine aggregates, and tap water with a ratio of 1:1.47:3.29:0.45 by weight. Type I Portland cement was used and its chemical composition was determined and listed in Table 2. Limestone with a maximum diameter of 19 mm was used as coarse aggregates, and sands with a fineness modulus of 2.78 were used as fine aggregates. The water cement ratio is 0.45 with no admixtures. The 28-day average compressive strength of 100 × 200 mm concrete cylinders was 38.58 MPa in accordance with ASTM C39 concrete cylinder tests [23].

For the casting of concrete, plywood molds were built as shown in Fig. 3. Sixteen holes with a diameter of 28.6 mm were drilled on two side plywoods at the location of steel bars. Silicon resins were applied to seal the void between the plywood hole and the encasement PVC pipe. Prior to casting, a layer of oil was applied to avoid water penetration to the plywood during and after casting of concrete.

2.2. Accelerated corrosion test

After air curing in room temperature for 28 days, all the concrete blocks were placed in a corrosion bath established with wet sands, as shown in Fig. 4a. The target corrosion level in this study ranged from 0% to 30% mass loss. To accelerate reinforcement corrosion, direct electric current was impressed on each steel bar embedded in concrete using an external power supply that provides a constant electrical potential (10 V). As illustrated in Fig. 4b, the steel bar was connected to the positive end and a graphite rod with a diameter of 6.4 mm was connected to the negative end of the power supply. The specimens were placed side by side and the space between them was filled with sands. To create a corrosive environment, 3.5 wt.% NaCl solution was sprayed approximately every week on the sands to provide moisture and chloride ions. In order to monitor the electrical current through the steel bar, one 10 ohm resistor was connected in the circuit. The voltage of the resistor was recorded at an interval of 1 min with a DataLogger 880 system for the determination of the electrical current. The measured current was used to calculate the mass loss and terminate the test once the specified corrosion level has been reached. The corrosion mass loss can be evaluated by:

$$\Delta m = MIt/(zF) \quad (1)$$

where Δm is the mass of steel consumed (g), M is the atomic weight of the metal (56 g/mol for iron), I is the corrosion current in A/s, t is the time in s, z is the ionic charge (2 for iron), and F is a constant (96,500 A s/mol). The 48 steel bars subjected to accelerated corrosion tests were evenly divided into 4 groups in different corrosion levels: (a) 0–5%, (b) 5–10%, (c) 10–15%, and (d) >15%. The time to reach the specified corrosion mass loss was calculated based on Eq. (1) and the recorded corrosion current from DataLogger 880.

Fig. 5 shows the corrosion current density evolution over time for three representative steel bars. Two stages can be observed: before and after concrete cover cracking. Their average corrosion current densities were 80 μA/cm^2 and 220 μA/cm^2, respectively. After each spray of salt water, the corrosion current density increased rapidly due to the increased conductivity of concrete and then decreased slowly due to the evaporation of salt water. After reaching a specified corrosion mass loss, corroded bars were taken out from the concrete specimens and sandblasted to remove the attached concrete debris and corrosion products. After cleaning, the weight was measured again with the same electronic balance as used to weigh the pre-corrosion samples, and the overall mass loss of each steel bar was

Table 1
Chemical composition of steel rebar.

Element	C	Si	Mn	P	S	Cr	Mo	Ni	Co	Cu	V	Sn	Fe
wt.%	0.38	0.18	1.00	0.12	0.06	0.10	0.07	0.20	0.01	0.37	0.02	0.03	97.40