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Mechanical properties of corroded steel bars in pre-cracked concrete suffering from chloride attack

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HIGHLIGHTS

- A 4-year chloride-induced corrosion of steel bar in cracked concrete is achieved.
- Obvious pitting corrosion occurs on embedded bars due to the transverse crack.
- Both nominal strengths and ductility decrease with increasing the corrosion degree.
- The non-uniform coefficient can effectively assess the mechanical properties.

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ABSTRACT

A 4-year natural corrosion experiment coupled with a cyclic wetting-drying process with 5% NaCl solution and an indoor natural corrosion process was carried out for pre-cracked reinforced concrete elements in this study. The diameter loss along the bar length which was greatly influenced by crack effect was measured, and the degree of corrosion evaluated by average mass loss was calculated for all cleaned bar specimens. The tensile test results showed that both the nominal yield and ultimate strengths and the percentage elongation decreased with the increase of mass loss, and that the effect of corrosion on degradation of ductility was much greater than that of tensile strengths. Taking the impact of pitting corrosion into account, a non-uniform coefficient, *S*, directly related to pit depths of corroded bars was proposed and the degradation models of yield strength, ultimate strength and percentage elongation were derived based on *S*. It seems that this method might be a more effective way to assess the mechanical properties of corroded bars with obvious pits. Finally, the reduced area at necking and fracture surface morphology were compared between sound and corroded bars.

1. Introduction

Corrosion of reinforcing steel bars has been recognized as one of the major causes of performance deterioration of reinforced concrete (RC) structures worldwide [1,2]. It is estimated that the annual investments on corrosion related maintenance and repairs for concrete infrastructure cost approximately $100 billion around the world [3]. Corrosion of reinforcement in concrete can be usually induced by two major mechanisms: concrete carbonation and chloride attack, and the latter, which is typically caused by chloride ions from seawater or de-icing salt, is more predominant than the former [4,5]. Steel corrosion in concrete usually brings the following coupled consequences [6]: i) longitudinal cracking, spalling and delamination of concrete cover; ii) reduction of cross section and mechanical property of corroded steel and, iii) loss of bond between steel and concrete and eventually degradation of bearing capacity of RC element. This study will focus on the second issue of steel corrosion in chloride contaminated environment.

Much research work has been conducted on the mechanical properties of corroded rebars in recent years, as summarized in Table 1. The tested specimens of corroded steel bars were mainly obtained from following ways: i) bare bars directly subjected to chloride salt spay [7–10] or accelerated corrosion with impressed current [11,12]; ii) bars embedded in concrete subjected to accelerated corrosion with impressed current [5,11,13–17]; iii) bars got from service concrete suffering from chloride attack [9,18] or carbonation [15] and; iv) bars in experimental concrete element exposed to cyclic wetting and drying condition [14] or artificial chloride environment [10,19]. Some commonly recognized conclusions can be made from above studies that the yield loads, ultimate

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Table 1
Summary of recent research work on mechanical properties of corroded rebars.

No.	Authors	Specimens	Corrosion condition	Yield strength		Ultimate strength		Elongation/ Ductility	Elastic modulus
				Nominal area	Residual area	Nominal area	Residual area		
1	Almusallam et al. [5]	Bars in concrete	Electrical	N/S	N/S	Decreased	Marginally increased	Decreased	N/S
2	Palsson and Mirza [18]	Bars in old concrete	Service/chloride	Not affected	N/S	Not affected	N/S	Decreased	N/S
3	Cairns et al. [13]	Bars in concrete	Artificial pitting; Electrical	N/S	Not affected	N/S	Slightly increased	Decreased	N/S
4	Du et al. [11]	Bare bars; Bars in concrete	Electrical	Decreased	Decreased	Decreased	Decreased	Decreased	N/S
5	Apostolopoulos et al. [7]	Bare bars	Chloride salt spay	Decreased	Decreased	Decreased	Decreased	Decreased	N/S
6	Apostolopoulos and Papadakis [8]	Bare bars	Chloride salt spay	Decreased	Not affected	Decreased	Decreased	Decreased	N/S
7	Lee and Cho [14]	Bars in concrete	Electrical; Salt + wetting and drying	Decreased	N/S	Decreased	N/S	Decreased	Decreased
8	Papadopoulos et al. [9]	Bare bars; Bars in old concrete	Chloride salt spay; Service	Decreased	N/S	Decreased	N/S	Decreased	N/S
9	Zhang et al. [15]	Bars in old concrete; Bars in concrete	Carbonation; Electrical	N/S	Decreased	N/S	Decreased	Decreased	N/S
10	Francois et al. [19]	Bars in concrete	Chloride	Decreased	Not affected	Decreased	Increased	Decreased	Not affected
11	Xia et al. [12]	Bare bars; Bars in concrete	Electrical	Decreased	N/S	Decreased	N/S	Decreased	N/S
12	Apostolopoulos et al. [10]	Bare bars; Bars in concrete	Chloride salt spay	Decreased	Decreased	–	–	Decreased	–
12	Tang et al. [16]	Bars in concrete	Electrical	N/S	Marginally increased	N/S	Marginally increased	Decreased	Tensile stiffness decreased
13	Zhang et al. [17]	Bars in concrete	Electrical	N/S	Not affected	N/S	Not affected	Decreased	Not affected

N/S = not stated.

loads and elongation (or ductility) of corroded steel bars will reduce obviously with the increase of the degree of corrosion. The effect of corrosion on the tensile strengths of corroded bars, however, shows great difference and even contradiction in these researches shown in Table 1, due to the facts that various specimens with different non-uniform reduction in the cross-sectional area along the length of the bars were examined, and that different methods were used to assess the strength properties, such as nominal (or apparent) strength and residual (or true) strength.

For the nominal yield and ultimate strengths of corroded rebar calculated with nominal steel area, Apostolopoulos et al. [7], Apostolopoulos and Papadakis [8], Papadopoulos et al. [9], Apostolopoulos et al. [10], Du et al. [11], Xia et al. [12], Lee and Cho [14] and Francois et al. [19] believed that they would decrease with increasing the degree of corrosion of rebars based on their experimental results. Only the investigation completed by Palsson and Mirza [18] reported the nominal strengths of corroded bars got from abandoned concrete bridge wouldn't be affected by the level of corrosion.

However, the results of residual strength determined based on the effective cross-sectional area of corroded steel were diverse. Although some experimental data obtained by Apostolopoulos et al. [7], Du et al. [11] and Zhang et al. [15] showed that the residual yield strength would also decrease with increasing the corrosion degree, many researchers, such as Apostolopoulos and Papadakis [8], Cairns et al. [13], Zhang et al. [17] and Francois et al. [19] reported that the residual yield strength shouldn't be affected by corrosion, and the results got by Tang et al. [16] even showed a marginal increase in yield strength of corroded bar. The similar conclusions can also be found for corroded bars when the residual ultimate strength was assessed, as shown in Table 1. Except for the influence of bar type and diameter on residual capacity of corroded rebar [11,17], the main reasons of discrepancy in above studies may be ascribed to two aspects: i) corrosion types of reinforcing steel bars corroded by impressed current corrosion is very different from that under natural corrosion condition [19,20], that is, different patterns varying from uniform corrosion to localized (pitting) corrosion have different effect on performance degradation of corroded bars and, ii) the critical residual steel area is hard to determine accurately even with 3D laser scanner [16,17], so many researchers [11,15–17] adopted average cross-sectional area predicted by mass loss to analyze the effective tensile strengths of corroded bars.

It should be recognized that these above efforts have made great contributions in analyzing the mechanical properties of corroded steel bars, however, experimental data on them under condition of natural corrosion are still scarce [10,19] and a deeper understanding of tensile behaviors of corroded bars under the chloride-induced pitting corrosion in concrete is required. Moreover, from the viewpoint of life cycle cost strategies with maintenance, repair and rehabilitation of deteriorated RC structures [21,22], the initial corrosion process before or during longitudinal cracking of cover and its influence on performance degradation of the steel bar should be effectively analyzed and modelled in advance. Aiming at this problem, in this paper, a natural corrosion experiment coupled with a cyclic wetting-drying process with 5% NaCl solution and an indoor natural corrosion process was carried out for several pre-cracked RC elements. The total duration of the experiment was 4 years. The corroded bars were extracted from these elements and the non-uniform reduction in the cross-sectional area along the length of the bars were measured. A tensile test for these corroded bars was completed and the influence of corrosion degree and pitting effect on mechanical properties of corroded bars were studied and discussed.