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Effect of simulated pitting corrosion on the tensile properties of steel

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HIGHLIGHTS

- Steel with narrow-deep type corrosion pits was investigated for the first time.
- Effect of multiple corrosion factors on mechanical properties of steel was fully studied.
- Prediction model and method were also presented in present work.

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ABSTRACT

The buildings including steel-structured bridges, plants and ocean platforms which take steel as the main material are prone to fall into pitting corrosion. Mechanical properties are greatly affected by pitting corrosion and hence the security of buildings can hardly be guaranteed. The mechanical drilling and milling method is employed to form conical blind holes and then to simulate corrosion pits in present work, after which the effects of the shape, depth and distribution of corrosion pits on the tensile properties of steel have been systematically investigated. The results indicate that the fracture location of steels with corrosion pits occurred at the cross section with larger pitting corrosion factor. The load-displacement curves of the steels were changed due to the existence of corrosion pits, the yield platform got shorter and even disappeared, accompanied with poorer ductility and brittle fracture. Pit shape, depth and distribution impacted little on the ultimate load of tensile samples, the ultimate strength almost correlated only with the maximum cross-sectional area. However, the yield load of steels was affected by both pit shape and distribution. The elongation was mainly affected by pit denseness and depth, denser and deeper pits per unit area would give rise to smaller elongation. Finally, multivariate regression analysis was performed to acquire the prediction model of elongation.

1. Introduction

Steel corrosion is unavoidable in both reinforced concrete and steel-structured buildings and even exists anywhere as long as steels are involved. Particularly, the corrosion rate will get remarkable increase in poor environments such as marine and industrial environments, by which the thickness of steel will get thinner and mechanical properties get deteriorated, thus contributing to diminished carrying capacity of steel-structured buildings and even producing disastrous damage. Two bridges named "Silver Bridge" and "Mianus River Bridge" experienced such disastrous collapse and damage in 1967 and 1983, respectively [1]. It was also previously proved that corrosion would lead to the decrease of strength and carrying capacity of steels and components [2–4]. Herein, new technologies are earnestly needed to estimate the residual carrying capacity of corroded steel-structured buildings, prior to which the properties of corroded steels should be acknowledged.

Pitting corrosion is a kind of localized corrosion and harmful to structures such as steel-structured buildings, ship structures and underground pipes, etc [5–9]. The investigation on the properties of steels with corrosion pits is therefore of practical significance [10–12]. Nakai et al. managed to fabricate corrosion pits by the mechanical drilling and milling method and then to study the effect of pitting corrosion on the residual strength of steel, conical pits with the ratio of diameter to depth in the range between 8:1 and 10:1 were adopted, which belong to the wide-narrow type corrosion pits (the ratio of diameter to depth is bigger than 1). They believed that the artificial mechanical method used for the fabrication of corrosion pits can well simulate the effect of natural pitting

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corrosion on the properties of corroded steels [5]. Suzumura et al. demonstrated that the artificial indentation method can be employed to simulate the corrosion pits and then to study the tensile strength of notched steel wires, the relevant results were similar with the mechanical properties of corroded steel wires, and the brittle failure was believed to be mainly affected by the stress concentration of corrosion pit location [13,14]. The corrosion degree of steel was evaluated in terms of volumetric change rate by Garbatov et al. followed by the acquisition of elasticity modulus, ultimate tensile strength and the relationship between elongation and volumetric change rate of corroded steel through regression analysis [7]. Ou et al. proposed that the corrosion degree of steel bars can be characterized by mass loss rate, based on which the prediction models of elasticity modulus, ultimate strength and yield strength of corroded steel bars were established [15]. The surface roughness of corroded steel was defined by Ahmmad et al the empirical formula with the elongation acting as dependent variable and surface roughness as independent variable was obtained through data analysis [6]. The cross section loss was then utilized to evaluate the corrosion degree of corroded steel plate by Paik, through which the relationship between residual strength and loss rate of cross-sectional area was obtained [16]. Matsumoto et.al believed that the minimum average thickness of cross section can be regarded as a representative value to evaluate the strength of corroded steel [17]. Muranaka et al. and Kariya et al. suggested that the formulas $t_R = t_{avg} - \sigma_{st}$ and $t_R = t_{avg} - 1.3\sigma_{st}$ can be regarded as the representative values for strength evaluation of corroded steel, respectively, where t_{avg} is the average thickness of corroded steel and σ_{st} is the standard deviation of thickness [18,19].

In conclusion, the corrosion pits developed by the mechanical drilling and milling method can well simulate the effect of real pitting corrosion on the properties of steel. Nevertheless, the effect of corrosion pits on mechanical properties of corroded steel is less concerned, especially for the narrow-deep type corrosion pits (the ratio of diameter to depth is smaller than 1), which do appear in some of the buildings. The prediction of properties of corroded steel is mainly performed by proposing a representative variable which can describe the corrosion degree, the relationship between residual mechanical properties of corroded steel and the variable is thereafter obtained through regression analysis, and eventually, the empirical model for the prediction of residual mechanical properties of corroded steel can be established. But there arises a problem that mechanical properties are affected by various corrosion factors rather than a single one, which needs to be comprehensively studied. Herein, the mechanical drilling and milling method was firstly employed to fabricate tensile samples with narrow-deep type corrosion pits in present work, the effects of pit shape, depth and distribution on the mechanical properties of pits were then systematically investigated by tensile experiment. Finally, the prediction model of steel elongation which was affected by corrosion pits was established through multivariate regression analysis, the prediction method of ultimate load of corroded steel was also proposed. The combined results were believed to present both scientific and practical significance for the investigation of steels with narrow-deep type corrosion pits.

2. Experimental scheme

2.1. Sample fabrication

The Q235 steel ($0.12\% \leqslant C \leqslant 0.20\%$, $0.3 \leqslant Mn \leqslant 0.67$, $Si \leqslant 0.30$, $S \leqslant 0.045$, $P \leqslant 0.045$) was utilized in this experiment, the tensile samples were fabricated according to ASTM E8/E8 M-11, the shape and size of tensile samples are presented in Fig. 1. The wire-electrode cutting method was adopted for all studied samples and they were derived from the same steel plate. The thickness and gauge length were 8 mm and 90 mm, respectively. The artificial drilling and milling method was then utilized to fabricate blind holes (impenetrable holes) on the surface of tensile samples to simulate corrosion pits.

A total of 22 tensile samples were fabricated in present work, three of which acted as control samples and were utilized to measure the mechanical properties of steel plate, which are statistically exhibited in Table 1. The average values were regarded as representative values of mechanical properties of the steels used in this experiment. Other 19 tensile samples contained corrosion pits, which were processed by the drilling and milling method. In present work, narrow-deep type corrosion pits were selected, the ratio of diameter to depth was lower than 1, which do exists in real steel corrosion, the characteristics of which were as follows: 1) pit shape was similar with cone; 2) the ratio of diameter to depth was not a fixed value, which presented big discreteness (but diameter-depth ratio was always lower than 1); 3) there is also no fixed rule for real pit distribution. Herein, the effects of diameter and depth on mechanical properties of steel was studied by artificially controlling pit diameter. Based on previous study, the pit shape was simplified as conical, the ratios of diameter to depth were set to be 1:1.2, 1:2, 1:3 and the thickness were 2 mm, 4 mm, 6 mm, respectively. The pits were distributed on one side of the surface of the tensile samples to simulate the asymmetry of corrosion. To reduce the effect of machine chuck, all pits were distributed within the central 50 mm of the tensile samples, which was called the distribution region of corrosion pits, as presented in Fig. 2. The distribution region of pits was divided into 5 small regions with a width of 10 mm, which were then called the localized regions of pits distribution and convenient for further use. A mixture of two kind of pits was employed for samples ranged from N17A6C6 to N19B4C6 and one kind for other samples.

2.2. Naming method of samples

A total of 3 tensile samples with no corrosion pits (i.e., 3 control samples) were named as N01, N02, N03, respectively. The naming method in more details was determined as follows: according to the difference in the ratio of diameter to depth, A, B and C represented three different kinds of pits, in which A represented the pit with a diameter-depth ratio of 1:1.2, B and C represented a ratio of 1:2 and 1:3, respectively. Conical pits were utilized in present work, which can be determined by the undersurface diameter and the height of the cone. Herein, the corrosion pits can be determined via diameter-depth ratio and pit height (height of cone). Therefore, different pits can be represented by diameter-depth ratio and pit depth. For example, A2 represented the pit with a diameter-depth ratio of 1:1.2 and a depth of 2 mm, while B4 represented the pit with a diameter-depth ratio of 1:2 and a depth of 4 mm. Furthermore, sample number + diameter-depth ratio + pit depth was utilized as the naming method, for example, N16B6 represented the No.16 pit with a diameter-depth ratio of 1:2 and a depth of 6 mm; N17A6C6 represented the No.17 pit with two kinds of pit, that is, A6 and C6. A6 represented the pit with a diameter-depth ratio of 1:1.2 and a depth of 6 mm, C6 represented the pit with a diameter-depth ratio of 1:3 and a depth of 6 mm.

2.3. Tensile experiment

The 300kN universal testing machine (Docer testing machine technology Co., Ltd, Jinan, China) was adopted in this experiment. Displacement loading with a loading velocity of 1.8 mm/min (strain rate: $0.00025\ s^{-1}$) was then adopted based on ASTM E8/E8 M-11. The load-displacement values were automatically recorded by the testing machine. The digital speckle analysis