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Predicting the residual strength and deformability of corroded steel plate based on the corrosion morphology

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HIGHLIGHTS

- Conducted 3D profile measurement and tensile test to evaluate the corrosion effects.
- Quantitatively characterized the corrosion profile and developed a dedicated program.
- Summarized the empirical formulas used to predict residual performance.
- Established a morphology based numerical method to predict residual performance and fracture.
- Surface strain of corroded specimen was measured by using DIC technology.

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ABSTRACT

The effects of corrosion on the mechanical performance of steel were investigated by conducting surface measurements and tensile tests on naturally corroded steel plates. With increasing corrosion damage, significant degradations in strength and deformation can be observed. We summarized the existing empirical formulas and elaborated a morphology based numerical method to predict the residual performance of corroded steel. With the aid of specially developed programs, it is easy to extract the pertinent evaluation indicators from the corrosion morphology and generate the finite element model of corroded surfaces. By conducting error analysis of predicted results, we found that most empirical formulas could achieve satisfying predictions in tensile strength but were unworkable in predicting the deformability. The profile based numerical method could not only achieve more reliable predictions in strength but also provide the degraded load-displacement curve of corroded steel plates.

1. Introduction

Steel structures including transmission towers, steel bridges, workshops, and offshore platforms exposed to harsh environment such as urban, industrial and offshore atmosphere for a long time often show signs of apparently severe surface corrosion, when the protective coatings and cathodic protection systems either are non-existent or have become ineffective [1,2]. Corrosion has been considered to be the predominate factor leading to age-related structural degradation of steel structures due to the harmful consequences including strength degradation, thickness penetration, fatigue cracks, brittle fracture and unstable failure [3]. These forms of damage can give rise to significant issues in terms of safety, health and environment.

The plate thickness and mechanical properties of structural steel such as yield strength (f_{yi}), ultimate strength (f_u), elongation at failure (δ), as well as yield ratio (f_{yi}/f_u) are important in structural design according to the present standards. However, during the actual service, these properties are considered to be constant, neglecting the corrosion-induced deteriorations that the steel structures may suffer. Although the design of steel structures are required to contain a certain allowance for corrosion wastage and the safety factor in initial design may delay the occurrence of structural failure, the priori negligence of corrosion in structural integrity analysis may lead to significant overestimation of the damage tolerance ability of existing steel structures [4,5].

Conventionally, the residual bearing capacity of corroded component is assessed using the required effective thickness, aiming to meet the minimum strength requirement. This method is convenient and simple to apply. However, up to now, this method has not been developed systematically and the associated evaluation indicators are still less than satisfactory, for instance, the determination of effective thickness. Moreover, how to determine

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the influence of localized corrosion using the required effective thickness approach is still full of controversy [5], because corrosion discontinuities (pits) can lead to stress/strain concentration [1,6–9] and even premature fracture.

The method of introducing degradation mechanism into material constitutive relation may be a near-perfect approach to consider the corrosion effects, which can achieve a good balance in predicting precision and computational efficiency. The standard tensile test provides an intuitive and convenient way to evaluate the influence of corrosion on the mechanical properties of steel plate and have been successfully conducted in a laboratory setting [10–15]. However, for existing structures, this approach is destructive in nature. For this reason, many empirical formulas used to predict the residual performance of corroded steel were proposed based on the experimental results.

A good prediction of the corrosion effects by using the empirical formula is largely dependent on the quantification of corrosion itself. Recent years, several physical probe techniques (SEM [16], AFM [6], X-ray tomography [17–19], white light interferometry (WLI) [20], white light axial chromatism [21,22], etc.) have been proposed and applied to characterize the corrosion features and quantify the corrosion level. All these investigations promote the innovation of corrosion measurements and also provide a new way for non-destructive evaluation (NDE). Extensive literatures and standards [21,23–28] have presented numerous parameters to characterize the corrosion morphology and quantify its severity. Many empirical formulas based on the morphological parameters were also proposed by researchers to estimate the degradation of mechanical properties. However, these formulas were established by making some simplifications, and their application conditions were not described in detail by researchers. Therefore, the practicality have not been widely verified and recognized.

More recently, due to improved computational capabilities, the numerical method based on corrosion morphology has gained greater emphasis. Initially, researchers typically focused on the simplification of corrosion morphology [29–32] and forming the surface degradation by utilizing the empirical corrosion models [3,13,33–35]. A disadvantage of this simplification is that the predicted mechanical properties are dependent on how the actual corrosion is interpreted or the corrosion model behavior [5]. After that, the direct scanning [1,6,9,10,22,28] from a corroded surface was also applied in modeling. Pidaparti [1,6] and Kainuma [9] developed a numerical method based on the scanned corrosion morphology to evaluate the stress concentration level around pits. A similar method was also employed in our previous work [22] to predict the possible nucleation site of pitting induced crack and then predict the fatigue life of corroded steel plate. Appuhamy [10] discussed the feasibility of establishing a numerical methodology to preliminary predict the residual strength of corroded steel plates using fewer number of scanning points. In the work of Ahmad [13], the quasi-static tensile tests and numerical simulations were both conducted on replica specimens.

The corrosion morphology is identified as the most intuitive data because it can comprehensively reflect the corrosion levels without any simplification or quantification. Although a few literatures have utilized the corrosion morphology to evaluate the effects of corrosion on material properties, it has not been paid enough attention in the field of NDE of existing corroded steel structures. There is almost no literature involved the prediction of loading and deformation behavior of corroded steel plates during the whole process of stretching, especially for the large deformation behavior after necking. In addition, most conclusions, methods and empirical formulas in previous studies were obtained or proposed under artificial or specific corrosion conditions, their applicability still needed to be verified. In the present study, we summarized the existing empirical formulas and elaborated a corrosion morphology based numerical method to predict the residual performance of corroded steel. Their effectiveness and applicability were also investigated by conducting a series of experiments including corrosion morphology measurement and characterization, uniaxial tension and surface strain measurement on the naturally corroded steel plates. Special programs were also developed to extract the morphological parameters and generate the finite element (FE) models based on the surface data. The research results would provide technical support for the residual performance evaluation of existing corroded steel structures.

2. Experimental procedure

2.1. Material and specimen preparation

The test specimens were all cut out from an H-beam steel truss (shown in Fig. 1a) with 8 years nature expose at Xi'an (a city in western China). The appearance after removing the rust is shown in Fig. 1d. The tested material was a normalized 0.2% low-carbon steel (named Q235 in China), which is widely used in infrastructure and civil engineering. Its chemical compositions are presented in Table 1. According to the different position and obliquity (see Fig. 1a), the truncated components were categorized into three general types: horizontal (H), vertical (V) and sloping (S) members. One specimen was cut from the severely rusted top flanges (TF), bottom flanges (BF) and webs (W) of each selected member. In addition, one corrosion-free specimen (NC) was fabricated to act as a control and determine the material properties of flanges and webs by removing the corrosion features using a milling machine.

2.2. 3D corrosion profile measurements

The dimensions of specimen for profile measurement are shown in Fig. 2a. Before conducting the surface measurements, corrosion products were removed carefully by using the electric wire brushes. Note that the two corroded surfaces of each steel plate were scanned separately, therefore the relative position of the two surfaces need to be determined before conducting the quantitative characterization and establishing the finite element (FE) model. To solve this problem, a reference zone with the width of 7.5 mm shown in Fig. 2a was prefabricated at the edge of specimen using a milling machine.

A PS50 non-contact 3D profiler produced by NANOVER was employed to obtain the 3D morphology of corroded surface. The vertical and horizontal resolutions were 280 nm and 8 μm, respectively. Each corroded surface had one measurement region of 32.5 mm × 50 mm, which covered the whole parallel part of tensile test specimen and the reference plane. The equipment and the schematic of measurement area are shown in Fig. 2. The longitudinal and transversal scanning steps (S) were both 50 μm. Thus, a regular grid with 651 × 1001 points was generated by this arrangement. After the profile tests, the thickness of reference zone (T_{sa}) was measured with an ultrasonic thickness gauge or vernier caliper.

2.3. Tensile test procedure

The geometry of dog-bone specimens (see Fig. 2c) for standard tensile test was designed based on GB/T 228.1–2010 [36]. The distance between the two black markers in Fig. 2c denotes the initial gauge length. All specimens should be machined with no residual stress, surface damage, and deformation.

All specimens were tested according to GB/T 228.1–2010 [36] at room temperature in laboratory air. The uniaxial tension was performed by an Instron Model 1341 electro hydraulic test frame with a 200 kN load cell. The temperature and humidity were 25 ± 3 °C and 65 ± 5%, respectively. In each test, the coupon was fully clamped at both ends and stretched up to fracture under strain control at a constant strain rate of 2.5×10^{-4}/s. An extensometer was utilized to track the elongation of parallel part in real time and control the crosshead speed.

2.4. Surface strain measurement

A stereo digital image correlation (SDIC) system produced by XTOP was employed here to measure the in-plane displacements at the specimen surface. In this system, two 2448 × 2048 pixels CCD cameras and a REGER-100 electromechanical materials testing machine were used. Before the measurements, a fine speckle pattern was required on the area of interest (AOI) where the full-field displacements were measured (see Fig. 3b). The initial size of AOI was 25 mm (width) × 50 mm (initial gauge length). During the tensile test, a series of digital images corresponding to AOI were firstly captured and then processed by SDIC analysis