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Estimating the effects of corrosion pits on the fatigue life of steel plate based on the 3D profile

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ABSTRACT

The effects of corrosion pits on the fatigue life of pre-corroded Q235 steel plates were investigated. 3D profile measurements were conducted to obtain the distribution and morphology characterization of corrosion pits. Three types of pits were observed and categorized for thoroughly understanding their effects on fatigue behavior. Results indicate that corrosion pits reduce the fatigue life significantly, particularly the sharp pits and the interacting pits. A nondestructive methodology based on 3D profile data for fatigue life prediction has been presented. This method (a) provides a finite element method (FEM) to determine the dimensions of critical pits, (b) considers pit-to-crack transition and (c) considers the effect of multiple critical pits. The predictions are shown to compare well against experimental results.

1. Introduction

Steel structures exposed to corrosion environment for a long time often show signs of apparently severe and alarming surface corrosion although they are usually supported with one or more protective measures [1,2]. Corrosion and corrosion-related problems are considered to be the predominate factors that lead to age-related structural degradation [3]. Structural integrity can be dramatically decreased by corrosion, particularly the pitting, because fatigue cracks would be much easier to nucleate at corrosion pits and would propagate rapidly under dynamic load. Although safety factor in initial design may delay the occurrence of fatigue problems, the priori negligence of corrosion pits in structural integrity analysis may lead to significant overestimation of the damage tolerance ability of existing steel structures [4]. Corrosion is also an economic burden because some artificial allowance for future corrosion in initial design and repair operations undertaken to mitigate the effects of corrosion are usually conservative owing to the lack of a reliable methodology to predict future corrosion effects [5].

Over the past few years, fatigue performance of corroded aluminum alloy material has been studied extensively. But for structural steel, it is less than satisfactory with the existing information. Only a few literatures can be found on the aspects of this problem [6–14]. Most studies concluded that corrosion could dramatically reduce the fatigue failure resistance of steel material. Zahrai [6] and Turnbull [9] concluded that fatigue failure of corroded steel plate can be explained by irregularities that may act as concentrators of stress and strain and provide the local aggressive environment conducive to crack initiation. Rahgozar and Sharifi [7] revealed that the reduction in the fatigue life of corroded steel was due to the "notch factor" effect, and a considerable reduction of fatigue performance would occur with pit depth increased. Nakamura and Suzumura [8] found that deeper and sharper corrosion pits decreased the fatigue strength of corroded wires more severely; thus, corrosion must be immediately detected while pits are not yet deep.

One of the great relevance in estimating the pernicious effects of pits is the quantification of pitting itself. A sectioning method [15–20] in a laboratory setting has been successfully used for pit examination, shape classification, and fatigue life prediction. This method provides a definitive high-resolution "glimpse" inside a material with the principal crack growth plane [19]; however, this method is destructive in nature. A number of non-destructive evaluation techniques (X-ray tomography [9,21–23], confocal scanning laser microscope [24,25], white light interferometry [26], white light axial chromatism [27–29], etc.) have also been applied to pitting measurement with varying degrees of success. White light axial chromatism as a non-contact method can give fast (up to 1 m/s), accurate (up to 0.05 μm) and large-area (up to 150 mm × 150 mm) surface topography in three dimensions, thus constitutes a simple and useful way to quantify profile height distributions. This technique has already been used for investigating 2D corrosion profile in previous studies [27–29]. In order to conduct a detailed analysis about the influence of corrosion pits on fatigue life, it is necessary to have quantitative, 3D experimental

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data of corrosion pits. This can also be provided by white light axial chromatism.

In order to include the pitting corrosion effect into the fatigue analysis for predicting the remaining fatigue life, two different approaches can generally be used in the theoretical modeling of corrosion effect, i.e., surface features can be modeled as either notches or cracks [30]. Most of the researchers considered the corrosion pits as an initial crack on the surface. Considering the complex corrosion morphology, the fatigue crack nucleating pit was usually represented by an equivalent initial flaw size (EIFS) [5,15,16,18,19,31–34], which was generally obtained by measuring the size of crack initiation sites (depth, width or area) based on fracture microscopic analysis. Gruenberg et al. [15,16] modeled fatigue life of aluminum alloy specimen degraded by surface corrosion by converting nucleating pit area to a crack of equivalent semi-circular area with the radius of r_i. This area-based conversation was based on the observation [31] that fatigue cracks can be simply assumed to have a semi-circular shape and this assumption provided good results. Sankaran et al. [5] and DuQuesnay et al. [34] successfully predicted the fatigue lives of pre-corroded specimens with pitting dimensions serving as the semi-elliptical crack sizes for the analysis. Medved et al. [32] modeled a crack-nucleating pit as a semi-elliptical crack with the same aspect ratio as the original pit and allowed either center-wide surface or corner crack growth. In the above literatures, a single-propagating fatigue crack was invariably assumed. However, in some applications, a single dominant or critical crack may develop but there were examples where crack colonies may form, or where several cracks developed at the adjacent defect sites or corrosion pits, and crack coalescence was a key factor in their subsequent evolution [9–11,13,17–19,24,27,34]. In the work of van der Walde et al. [18,19], crack growth was similarly simulated as the method in [32], with the addition of the capability to simultaneously grow multiple adjacent flaws. This multiple cracks model successfully solved the issue that EIFS did not consider the effect of multiple interacting cracks on fatigue crack propagation [35]. Another important factor that EIFS cannot capture is the pit-to-crack transition process. At the point of transition from a pit to a crack, the crack was customarily considered to have the same dimensions or area as the source pit. However, with the improvement of visualization and measurement techniques, different conclusions about how a crack actually emerges from a corrosion pitting were derived [23,24,36]. This issue will also be considered in the life predicting model.

The present study is undertaken as a first step toward quantitatively investigating the effects of corrosion on the fatigue behavior of steel plate based on the 3D profile. In this work, 3D profile measurements without destruction are first conducted to obtain the distributions and characterizations of pitting corrosion, including 3D surface roughness, pitting size, and topography. The pitting characterizations are then analyzed and used to establish a quantitative relationship with fatigue test results. At the end of this paper, an AFGROW model based on three hypothesis and a multiple crack model to predicting the remaining fatigue life is proposed. This model incorporated critical pit location and dimension, micro-pit size and aspect ratio, pit-to-crack transition process, effects of multiple cracks coalescence, and fatigue crack growth rates for this steel. The pitting quantification, several key experimental observations, and numerical analysis based on the 3D profile data potentiate the effectiveness of the model to generate life prediction.

2. Experimental procedure

2.1. Material and specimens

The material investigated in this paper was a Q235 steel (named in China), which was obtained in a plate form with 8 mm thickness. This steel is a normalized 0.25% low-carbon steel, widely used in industrial and civil construction: the matrix consists of a ferrite–pearlitic microstructure with a 20–40 μm ferrite grain size, as shown in Fig. 1; its chemical composition is presented in Table 1. All samples were extracted from a single lot of material and cut out parallel to the rolling direction of sheet. Material performance testing was conducted with an electric-fluid servo universal testing machine to determine the yield strength, tensile strength, and other mechanical properties of the material used in this study. Such properties are shown in Table 2.

Fig. 2 shows the dog-bone specimen for fatigue testing, with a size based on GB/T 3075-2008 [37]. To obtain the specimen for fatigue studies, that for corrosion must be longer and wider. Thus, the rectangular specimens used for corroding were designed to be 280 mm in length and 50 mm in width. To acquire the corrosion depth, the edge of the corrosion specimen acting as reference

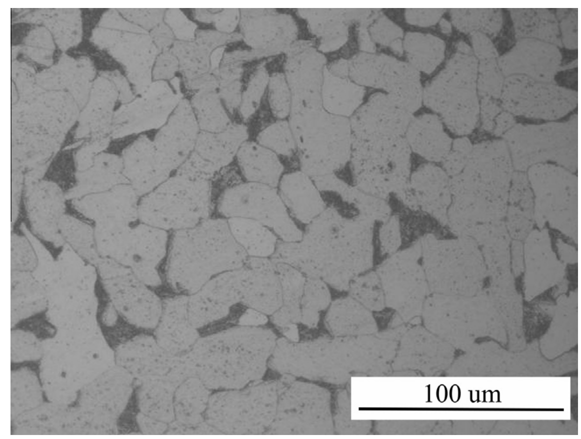

Fig. 1. Microstructure of Q235 steel material.

Table 1
Chemical composition of Q235 steel (wt.%).

C	Si	Mn	P	S	Cr	Ni	Cu	N
0.2	0.35	1.4	0.045	0.045	0.3	0.3	0.3	0.008

Table 2
Mechanical properties of Q235 steel at room temperature.

Specimens no.	f_y (MPa)	f_u (MPa)	δ (%)	E (10^5 MPa)
A001	315.3	450.6	38.1	2.02
A002	292.2	446.8	38.2	1.94
A003	326.2	470.0	38.4	1.96
A004	315.6	464.5	38.0	2.00
Mean	312.3	458.0	38.2	1.98

f_y – the yield strength, f_u – the ultimate strength, δ – the elongation ratio, E – the Young modulus.

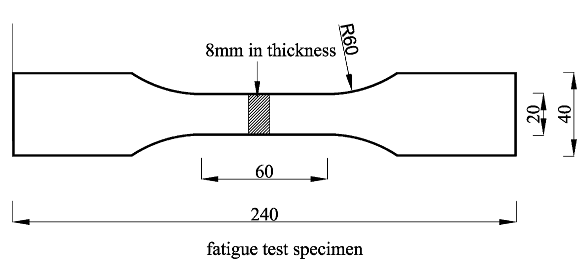

Fig. 2. Specimen for fatigue test (unit: mm).