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Equivalent surface defect model for fatigue life prediction of steel reinforcing bars with pitting corrosion

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A R T I C L E I N F O

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A B S T R A C T

Pitting corrosion is one of the most common corrosion damages for steel reinforcing bars. Fatigue crack usually initiates and propagates from pitting corrosion due to stress concentration and cross-section reduction. In this study, a novel equivalent surface defect model is proposed to quantitatively describe the corrosion effect for fatigue life prediction using both maximum corrosion degree and the aspect ratio. Due to the stochastic nature of the fatigue crack growth, both single crack and multiple crack cases are discussed. The proposed equivalent surface defect model is used for corrosion fatigue life prediction which includes the crack initiation life and the crack propagation life. The overall method is validated using fatigue testing data.

1. Introduction

The corrosion of steel reinforcement occurring in existing reinforced concrete (RC) bridge structures is a widespread problem with severe consequences [1–3]. The total repairing cost of corrosion damage is equal annually to 3.1% of the gross national product for the industrial sectors in USA, among which the utilities, transportation and civil infrastructures contribute the most [4]. Pitting corrosion which occurs in a localized area contributes approximately 70% of corrosion damage and is commonly recognized as more dangerous than uniform corrosion due to the difficulties associated with damage detection [5]. Corrosion pits are commonly observed on the surface of steel reinforcing bars for concrete structures in marine environments or subjected to de-icing salts. Corrosion pits cause changes in the material surface morphology such as local cross-section area reduction of reinforcing bars, which leads to stress concentration and degrades the structural performance significantly [6–10]. Particularly, RC bridges are nowadays frequently subjected to higher traffic loads due to the economic growth and thus are more susceptible to the accumulation of fatigue damage. As a result, failure of reinforcing bars in RC structures may suddenly occur without obvious signs of external distress except local concrete crack propagation [11]. When subjected to a cyclic stress higher than the fatigue limit, fatigue failure of steel reinforcing bars will control the failure of RC bridge structures [12–15]. Therefore it is of great theoretical significance and high practical value to investigate fatigue behavior of reinforcing bars with pitting corrosion under cyclic loading.

The fatigue behavior of pitted corroded bars has been studied over the past few years [16–24]. Fernandez et al. [16] carried out a research of the influence of the pitting corrosion on the fatigue life and found that fatigue life of bars with corrosion is reduced severely compared with that of un-corroded steel reinforcements. In addition, the study also indicated that the pit depth has more impact on fatigue life behavior compared with pit length. For steel bars with the ratio of pit length to bar diameter higher than 2, the pit length does not show significant influence on fatigue life. By contrast, the study showed that the impact of the depth to diameter ratio increases with deeper pit. Nakamura et al. [23] reported a series of fatigue tests conducted with corroded wire specimens on three corrosion levels. Artificial pits whose shapes and sizes were measured based on corrosion pit data were employed to represent the corrosion specimens. Ma et al. [24] expanded Nakamura et al.'s experiment and investigated the effects of pit morphologies on the fatigue performance of steel bars. Considering of the influence of pit depth and pit aspect ratios (ratio between notch depth and width; ratio between notch length and width) on the fatigue life under different stress levels, a data-driven based regression model for stress range-fatigue life-pit depth was obtained. Cerit et al. [17] assumed semi-elliptical pit geometry and studied the stress concentration caused by corrosion pits. A three-dimensional model of pitting corrosion was established using finite element method and the pit aspect ratio (ratio between notch depth and width) was identified as a main driving parameter for fatigue damage.

Although previous experimental studies on the fatigue performance

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of pitted corroded reinforcing bars have identified the influencing factors (the pit length to bar diameter ratio, the depth to diameter ratio, pit shape etc.) to the fatigue life, a physical-based model for reliable and viable fatigue life prediction of reinforcing bars with pitting corrosion still remains a practical challenge [18]. Fernandez et al. [19] studied the local effects of pitting corrosion such as non-uniform material properties distribution, stress concentration and local bending. A sectional fiber model was proposed to evaluate the fatigue performance of the corroded reinforcement. The model took both generalized and localized corrosion effects using an idealized pitted cross-section assumption. However, this model was based on linear fatigue cumulative damage theory and did not consider the behavior of fatigue crack propagation. Huang et al. [20] attempted to transfer the corrosion pit to a representative initial crack for the purpose of fatigue life prediction using linear elastic fracture mechanics. Equivalent crack size models were proposed according to two crack initiation patterns, namely, the single-crack initiation and the multi-crack initiation. But the fatigue life model in this study only focused on the crack propagation life, and the crack initiation period was not considered. Therefore, the treatment may not be suitable for cases where the crack initiation life dominates the whole fatigue life, particularly for metallic materials when the stress level is just above fatigue limit [21,22]. It is known that fatigue life consists of two parts namely, fatigue crack initiation life and propagation life. To predict the fatigue life of pitted corroded steel reinforcement, these two parts of fatigue life should be considered.

In this study, a novel equivalent surface defect (ESD) model is proposed to predict the corrosion fatigue life for steel reinforcing bars. In most of the realistic scenarios, the fatigue cracks tend to nucleate around corrosion pits and usually both single crack and multiple cracks can be formed from the corrosion pits. Both single- and multi-crack initiation cases are considered in the proposed model. The maximum corrosion degree and the aspect ratio between pit depth and width are employed to quantitatively describe the corrosion effect on fatigue life. The fatigue testing with naturally developed crack is used for model development and validation. Total 15 pre-corroded specimens are employed to investigate the corrosion fatigue behavior. Both fatigue crack initiation life and crack propagation life are included in the current study. Results from the fatigue testing are used to validate the proposed ESD model and corrosion fatigue life prediction. The validation results agree well with the experimental data.

The rest of the study is structured as follows. First, the pre-corrosion process and fatigue testing are introduced. The pre-corrosion is induced by the impressed-current method using 5% NaCl solution. The geometry and the morphology of the corroded surface are measured with 3D scan technique. Next, a novel equivalent surface defect (ESD) model is proposed to describe the relationship between equivalent initial defect size and geometry parameters of corrosion pit. Next, fatigue life prediction is performed considering both the crack initiation life and the crack propagation life. Following that, validations are made by comparing the model prediction of fatigue life and the actual experimental data. Finally, conclusions are drawn based on the current study.

2. Experiments

The experiment conducted in this paper includes the following steps. First, the material properties of un-corroded steel bars are tested and used as reference for fatigue testing. Second, pits with different geometries are induced on the surface of specimens and the morphology of the corroded areas is measured with 3D scan technique. Next, total 15 steel reinforcement specimens with pitting corrosion are used for fatigue testing. In the following paragraphs the experimental operations are described in detail.

2.1. Material and specimens

The specimen is shown in Fig. 1. The smooth standard specimen used in this study is machined from hot-rolled ribbed steel bars (HRB400) with a diameter of 20 mm. The outside layer of the original steel bar is removed by lathe processing. The chemical composition of the material is shown in Table 1. The geometry of the specimen is designed with reference to GB/T 228.1-2010 standard entitled Metallic materials-Tensile testing [25] and GB/T 3075-2008 standard entitled Metallic materials-Fatigue testing-Axial-force-controlled method [26].

Monotonic testing of 4 un-corroded specimens is carried out to determine the main mechanical properties of specimens such as yield strength, tensile strength, etc. The resulting material properties of HRB400 bars are listed in Table 2. The average values of the mechanical properties for the 4 un-corroded specimens are used in the later fatigue testing. The measured $\sigma-\varepsilon$ behavior is presented in Fig. 2.

2.2. Pre-corrosion protocols

A total of 15 specimens shown in Fig. 1 are used in the pre-corrosion process and fatigue testing. Corrosion is induced by the impressed-current method. The specimens are immersed in 5% NaCl solution. Before the corrosion process, the specimens are wrapped tightly using insulation tapes. An elliptical shape is marked on the tape and is removed to provide an exposure window for the metallic material. A wire is connected to one end of the specimen and then both ends are sealed by hot melt adhesive (Fig. 3(a)). Pit corrosion process is conducted through a direct current power supply which can set and monitor the current intensity. The steel specimen is fixed as anode and a stainless steel bar is served as the cathode (Fig. 3(b)). Fig. 3 shows the treatment of specimen and the test setup. After the corrosion process, the specimens are carefully rinsed in running water, and then dried and stored in a desiccator for future tests. It has been reported in Refs. [16,24] that the pit length has less influence on the fatigue life and can be neglected compared with the pit depth and pit width. Therefore, the pit length is set to be a constant in current study. Different initial width and exposure time are used to study the influence of pit morphology on corrosion fatigue life. The detailed experimental information can be found in Table 3.

2.3. 3D surface profile measurements

There are two parameters commonly used to assess the severity of the pitting corrosion, namely mass loss ratio and maximum corrosion degree (MCD). The mass loss ratio is the ratio between the mass loss and the initial mass, which reflects the generalized influence of corrosion damage, and is easy to be obtained [16,27–29]. Thus, it is widely adopted as a corrosion parameter. However, extensive researches have shown that not only the mass loss but also the morphology of the pits (the pits depth, pits width and aspect ratios etc.) is a significant influence factor for corrosion fatigue behavior [24]. Thus, the maximum corrosion degree (MCD, denoted as $\eta_{\max}$) can also be seen in many literatures [6,24,30] as another corrosion index. Maximum corrosion degree is the ratio between the area loss of the minimum cross-section in the corrosion pit region and the initial cross-sectional area, defined as Eq. (1).

$$\eta_{\max} = 1 - A_{\min}/A_0, \tag{1}$$

where $A_{\min}$ is the minimum cross-sectional area in the pit region and A_0 is the initial cross-sectional area. Studies have shown that single feature is difficult to obtain an accurate corrosion fatigue life prediction. In this paper, both MCD and ratio between notch depth and width are adopted to quantify the local corrosion degree.

The area and shape of the minimum cross-section are identified with a high-resolution three-dimensional (3D) laser scanner. The 3D laser scan and measurement technique allows for capturing the varying cross-section along the length axle of the specimen [6]. After scanning, the 3D coordinates of surface points can be obtained and then the raw data are further processed with Geomagic wrap software for hole filling,