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Approach for fatigue damage assessment of welded structure considering coupling effect between stress and corrosion

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ABSTRACT

This paper presents a new approach to assess time-dependent corrosion fatigue damage of welded joint considering the coupling effect between mechanical factor and corrosion factor. The high stress region around weld will accelerate corrosion and be more likely to induce nonuniform corrosion of welded joint. And the effect of loading on corrosion behavior of the steel in NaCl solution was investigated. The synergistic effect between applied elastic stress and chemical attack on Q235 steel was evaluated by electrochemical experiments. A side longitudinal of ship structure is selected as a case study. Time-dependent stress concentration factor of welded joint as a function of corrosion deterioration was analyzed, and the iterative process of stress and corrosion degeneration of plate thickness was used to simulate coupling effect basing on the results of experiment. The hot spot stress approach was adopted to calculate the fatigue damage. It is revealed that the nonuniform corrosion could influence fatigue damage of welded joint, and that impact will be more and more significant with the growth of corrosion year.

1. Introduction

Fatigue cracking may be the most important type of damage in welded structure [1,2], which is also a major requirement in design of marine structures. These requirements have been reflected in some design rules published by Classification Societies [3,4]. Compared with land structures, marine structures have a long term electrochemical reaction with seawater, and the surface of the structure may be subjected to more severe corrosion. Many experiments manifested [5,6] that fatigue life in corrosive environment is significantly lower than it in air. Therefore, the effects of mechanical and environmental factors on fatigue life are not a simple line relation but a complex one. The combined action of cyclic loading and aggressive environment often result in a significant reduction in fatigue performance compared with that obtained under cyclic loading in air. For a more accurate assessment of fatigue damage in corrosive environment, it is necessary to consider the coupling effects of corrosion and stress in some cases.

Recently engineering methods accounting for corrosion had been introduced in some design rules [3,4]. The guidelines of several Classification Societies defined the values of corrosion addition in different local structures, and then reduced corrosion addition of ship structures in order to calculate the hot spot stress adjacent to critical joint such as weld toe, and finally evaluated fatigue damage according to *S*–*N* curve in air and Palmgren–Miner's rule. And for those structures without corrosion protection, the guidelines used the *S*–*N* curve in corrosive environment which is more conservative. Engineering methods are simple and practical without considering the time effect on corrosion.

In order to take into account the corrosion over time, time-dependent corrosion wastage model has been used to calculate the fatigue damage in much research. Chakarov and Garbatov [7,8] studied the effect of general corrosion in decreasing the thickness of deck plate and found that the stress concentration factor is a function of hot spot stress and nominal stress is a nonlinear increasing with time function. Tran Nguyen et al. [9] applied the spectral fatigue damage approach to evaluate a main deck longitudinal stiffener which is considering the time-dependent corrosion effect, and found that the cumulative corrosion fatigue damage increases in all calculated cases after the failure of the corrosion protection system.

However, the above calculating methods regard the corrosion reduction and fatigue as two separating processes without considering inherent coupling process between corrosion and stress, which is a limitation of these methods. Many authors studied the effect of stress on corrosion which is well known as mechanochemical interaction [10]. Gao et al. [11] reported the

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mass loss of metal under different stress, concluded that applied stress can accelerate the corrosion, and determined the degradation of mechanical properties of steel induced by corrosion. Zhang et al. [12] investigated the effect of loading conditions on the corrosion behavior of a low carbon and low alloy steel with different microstructures in NaCl solution and results indicate that the elastic stress accelerated corrosion process of the steel significantly. The coupling effect of structures in seawater is that the thickness of structure decreased due to corrosion which increased the stress level under external load, and the higher stress in turn accelerated the corrosion so that the failure of structure happens sooner.

In this study, we improve the traditional approaches of fatigue damage assessment by considering the coupling effect between corrosion and stress. The nonuniform distributed general corrosion of welded joint and the interaction between corrosion and stress are studied here. Electrochemical experiments are performed here to investigate the interaction between loading and corrosion rate. A finite element analysis (FEA) simulation procedure considering the coupling process between corrosion and stress is proposed in this paper, using a structural detail of ship structure as a case study. Time-dependent cumulative fatigue damage analysis is also performed. The aim of this work is to study the effect between stress and corrosion rate according to electrochemical experiment, and understand how nonuniform corrosion influences fatigue damage with respect to single uniform corrosion based on FEA.

2. Corrosion characteristic of welded joint

The welded joints are commonly used in marine structures, and the failure around weld toe has been an area of particular concern in engineering. Kang and Kim [13,14] performed experiments for high performance steel to validate that corrosion fatigue life of the heat affected zone (HAZ) is shorter than base metal and weld metal, and HAZ exhibits a much higher stress sensitive characteristic than the others. The stress concentration around HAZ may have any influence on the corrosion and then affect the fatigue life of welded joints. To know the corrosion damage of welded joints in engineering, Nakai et al. [15] investigated the corrosion state around welded joints of eight ships include seven bulk carriers and one single hull oil tank, the service time of these ships ranges from 6 to 22 years, and the cross sections of fillet weld of ships are shown in Fig. 1. Fig. 1(a) and (b) shows the corrosion of welded joints in frame of No. 6 (BC6) and No. 2 (BC2) bulk carrier, it can be observed that the corrosion around fillet weld is more severe than any other place. Fig. 1(c) reveals that both the weld and the stiffeners of ship deck of No. 1 (SHT1) suffer serious corrosion in long term service for 22 years, and most of weld toe have been corroded. It can be seen from Fig. 1 that corrosion around welded joints are always more serious than any other place in ship structure sand should be paid more attention to these details.

Moan [16] considered corrosion rates for steel in seawater may fluctuate between 0.04 and 1.2 mm/year, which exhibit a very large scatter depending upon the location in structure, and the investigations of Nakai et al. [15] also indicate that corrosion rates around welded joints scatter largely in different locations of ship structure, which are ranging from 0.04 to 0.77 mm/year as shown in Fig. 2.

The corrosion of welded joints is not only affected by potential difference between weld and base metal, but the high stress also accelerates corrosion behavior of welded joint. The interactions between mechanical and chemical effects enhance surface reactions on materials, resulting in accelerated failure of welded joints. So the corrosion resistance of welded joints is affected by the stress distribution around welded joints. The region of high stress which is also called hot spot region will become more sensitive to corrosion, this region is vulnerable to suffer corrosion, and lead to nonuniform corrosion of welded joints over time. The combined effects of corrosion and stress may accelerate damage when welded joint is under the effect of external load.

3. Laboratory testing

3.1. Experimental procedures

Many researchers [17–20] studied coupling effect between mechanical factor and corrosion factor by the mechanochemical tests which are made up of the mechanical tensile or bending test and electrochemical test. The present paper adopts similar method to study the coupling effect between stress and corrosion.

The specimen used in this study is Q235 steel plate, which are widely used for marine structures. Mechanical properties are as follows: yield strength 235 ± 3 MPa, tensile strength 476 ± 1 MPa,

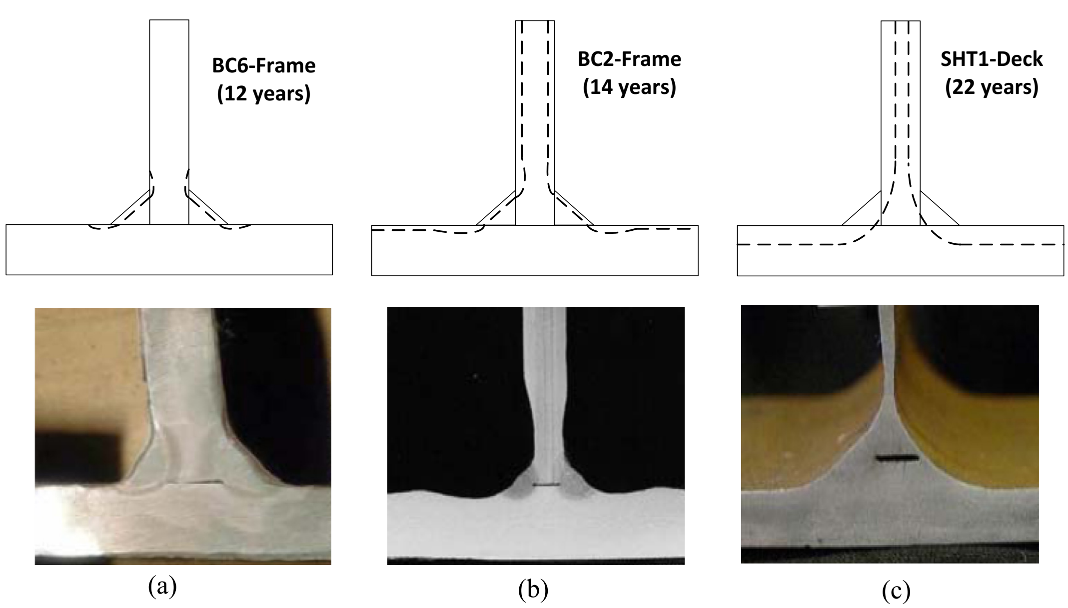

Fig. 1. Corrosion of welded joint. (a) BC6-Frame; (b) BC2-Frame; (c) SHT1-Deck.