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A study on time-variant corrosion model for immersed steel plate elements considering the effect of mechanical stress

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ABSTRACT

In this study, the effect of low levels of elastic stress on corrosion behavior of Q235B steel in an aerated 3.5% NaCl solution was investigated through measurements of linear polarization resistance (LPR), potentiodynamic polarization characteristics and electrochemical impedance spectra (EIS). Through theoretical analysis and experimental results, new corrosion models which can distinguish the effect of mechanical stress on the corrosion process of actual marine structures have been respectively proposed on the basis of three representative existing corrosion models. The effect of corrosion models on lifetime assessment was studied by employing a steel plate element subjected to the combined effects of corrosion and mechanical stress. Analytical expressions have been obtained for the structure's lifetime, which is identified with the time when the stress reaches the yield level. An example was presented to demonstrate the combined effects of corrosion and elastic stress on the lifetime assessment of marine structures.

1. Introduction

Corrosion is generally considered to be the most major factor which can lead to age-related structural failures of ships and marine structures (Yamamoto and Ikegami, 1998; Qin and Cui, 2003; Guedes Soares et al., 2005; Dong and Frangopol, 2015). From the viewpoint of structural safety, corrosion could cause serious damage and wall-thickness reduction, and might facilitate fatigue cracks, brittle fracture and unstable failure, resulting in tremendous loss of economic expenses and human lives (Guedes Soares et al., 2008, 2009; Huang et al., 2010; Li et al., 2014; Saleem et al., 2014; Wang et al., 2014c; Chapman et al., 2015). So far, there have been numbers of sinkings and environmental disasters for oil tankers and bulk carriers due to poorly maintained and highly corroded hulls (Qin and Cui, 2003).

Protective coatings combined with cathodic protection are generally employed to protect steel structures against corrosion. However, field observation reveals that such corrosion protection system is not always sufficient and some areas of ships and marine structures are not or cannot be protected thoroughly, and thereby corrosion still remains one of the most important degrading mechanisms for structural integrity (Qin and Cui, 2003; Guedes Soares et al., 2005). As a result, structural hull members are usually designed to have supplementary thickness as a corrosion allowance to compensate for the expected thickness reduction during the assumed structure's lifetime (Yamamoto and Ikegami, 1998; Guedes Soares et al., 2009; Pronina, 2013). Since an inaccurate assessment for corrosion allowance can lead to a large number of redundant cost, it is therefore of great significance to accurately assess the material loss and structure's lifetime. In this case, a number of time-variant corrosion models for ship and marine structures have been developed. Existing corrosion models can be classified into two broad categories: empirical models and physical models. The former are mainly based on the measured data for different parts of marine structures, and the latter are derived by considering some physical corrosion process involved (Paik and Thayamballi, 2007; Paik and Kim, 2012).

Up to now, a series of typical time-variant empirical corrosion models based on different assumptions have been developed and applied in some structural reliability assessments (Southwell et al., 1979; Guedes Soares, 1988; Yamamoto and Ikegami, 1998; Guedes Soares and Garbatov, 1999; Melchers, 1999; Paik et al., 1998, 2003; Qin and Cui, 2003; Sun and Bai, 2003). Paik and Kim (2012) also proposed a method for developing a time-variant empirical corrosion model and this method has been applied to predict time-variant corrosion wastage for ships, subsea oil well tube and gas pipeline structures (Paik and Kim, 2012; Mohd and Paik, 2013; Mohd et al., 2014). The empirical corrosion models as mentioned above, overall, assumed time as the only variable and defined various corrosion phases (Guedes Soares et al., 2005). Such empirical models are usually limited by the data used, and for marine structures operating under very different conditions, they may

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give little actual insights into what really happens and, furthermore, what might happen when conditions change (Paik and Thayamballi, 2007).

Early physical corrosion models based on ion transport limitations were presented by Evans (1960) and Tomashov (1965). Chernov (1990) and Chernov and Ponomarenko (1991) used a similar concept and developed a physical corrosion model that takes into account the effects of some environmental factors on corrosion. Melchers reviewed the fundamental research on physical corrosion modeling in marine environments (Melchers, 2003a, 2003b, 2008). And recently, considering that corrosion is actually related to the interactive effects of metal material and its surrounding environment, the effects of some environmental and other factors that should be included in model development, such as temperature, dissolved oxygen, salinity, calcium carbonate and pH, water velocity, marine growth and some other factors contained in representative locations, have been taken into account by Melchers (2003b, 2003c, 2008), Garbatov and Guedes Soares (2008) and Guedes Soares et al. (2005, 2008, 2009).

The present study is concerned with a physical corrosion model allowing for the mechanical stress effect. Ships and marine structures are usually subjected to the combined effects of mechanical and electrochemical actions when they are in service, and the stress caused by welding, machining, cold working and operating force etc. is also inevitable (Hua and Cheng, 2013; Yang et al., 2016). A number of studies have shown that the both mechanical effect and chemical effect interacting with each other can accelerate the failure of structural components (Gutman, 1994; Lu et al., 2009; Gao et al., 2010; Melchers and Paik, 2010; Ren et al., 2012; Yang et al., 2013; Zhang et al., 2013; Wang et al., 2014a, 2014b; Liu et al., 2015; Lin et al., 2016; Yang et al., 2016). This synergistic effect has been defined as the mechano-chemical effect (MCE) (Gutman, 1994; Ren et al., 2012). It is noteworthy that most of the stress level on structural surface should not be too high, but should be in the elastic range of steel to meet the safety design of marine structures. However, the stress levels considered in previous studies were generally relatively high and only small amounts of mechanical stress were in elastic region, resulting in an incomplete understanding about the influence mechanism of pure elastic stress on corrosion behavior. In addition, previous studies related to MCE were mostly focused on very short-term electrochemical experiments and could not evaluate the evolution of MCE with corrosion time, and thus the measured data cannot characterize the time-variant corrosion progress. Therefore, to quantify the effect of elastic stress on the time-variant corrosion behavior of metals, an experimental program was undertaken to study a system consisting of Q235B steel in an aerated 3.5% NaCl solution. The detailed results of this study will be reported in a follow-up publication on the effects of elastic stress on corrosion behavior of Q235B steel, and some measured experimental data were integrated into corrosion models to assess the time-variant corrosion process (Butler et al., 2010).

The major objective of present study is to develop a new time-variant physical corrosion model that allows for the effect of elastic stress on actual marine structures. The approach adopted was to develop a functional relationship between corrosion rate and mechanical stress on the basis of mechano-chemistry theory and experimental investigations as mentioned above, and apply this relationship to modify the referenced corrosion model by increasing or decreasing the corrosion rate depending on the stress level in a similar way as done by Guedes Soares et al. (2005, 2008, 2009). The effect of corrosion models on lifetime assessment was studied by employing a steel plate element subjected to the combined effects of corrosion and mechanical stress, which is widely used in marine structures. Analytical expressions were obtained for the structure's lifetime, which is identified with the time when the stress reaches the yield level. Next, the measured experimental data were integrated into the corrosion model to determine model parameters. The new stress corrosion models were also compared with the referenced existing corrosion models. Finally, an example demonstrated how to apply these models to assess the lifetime of the steel plate element, and meanwhile the influence of mechano-chemical effect on lifetime assessment was also evaluated. It is anticipated that some concluding remarks achieved in this study will provide some insights into the accurate assessment of corrosion wastage in actual ships and marine structures.

2. Corrosion mechanism and corrosion modeling

Since ships and marine structures are the typical examples of marine immersion corrosion, and thereby only the immersion corrosion of mild and low alloy steels was considered in this study (Qin and Cui, 2003). The electrochemical anodic and cathodic reactions of mild and low alloy steels in the oxygenated 3.5% NaCl solution usually contain the oxidation of iron and the reduction of dissolved oxygen, respectively:

$$\text{Anodic reaction:}\ \ \mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}^{-} \tag{1}$$

$$\text{Cathodic reaction:}\ O_2 + \ 2\mathrm{H_2O}{+}4\mathrm{e}^{-} \rightarrow 4\mathrm{OH}^{-} \tag{2}$$

According to active polarization electrochemistry (Bard and Faulkner, 2001), the corrosion kinetic equation can be expressed as follows:

$$i_{corr} = i_c^0 \cdot S_c \cdot \exp\left(\frac{\varphi_{e,c} - \varphi_{corr}}{b_c}\right) = i_a^0 \cdot S_a \cdot \exp\left(\frac{\varphi_{corr} - \varphi_{e,a}}{b_a}\right) \tag{3}$$

where i_{corr} is corrosion current density; φ_{corr} is corrosion potential; i_a^0 and i_c^0 are anodic and cathodic exchange current densities, respectively; S_a and S_c are anodic and cathodic areas, respectively; $\varphi_{e,a}$ and $\varphi_{e,c}$ are anodic and cathodic equilibrium potentials, respectively; b_a and b_c are anodic and cathodic Tafel slopes, respectively.

Solving Eq. (3) for the corrosion potential

$$\varphi_{corr} = \frac{b_a b_c}{b_a + b_c}\ln\frac{i_c^0 S_c}{i_a^0 S_a} + \frac{b_a}{b_a + b_c}\varphi_{e,c} + \frac{b_c}{b_a + b_c}\varphi_{e,a} \tag{4}$$

According to the theory of Gutman (1998), the change of electrode equilibrium potential caused by external pressure can be characterized by the following equation:

$$\Delta\varphi_e = -\frac{\Delta P V_m}{zF} \tag{5}$$

where ΔP is hydrostatic pressure, V_m is the molar volume of electrode material, z is the valence of metal ions and F is Faraday's constant.

Generally, two main corrosion mechanisms can occur on steel plates: uniform corrosion and localized corrosion (Qin and Cui, 2003). For a uniform corrosion system, the micro areas of anode and cathode are randomly distributed over the entire surface of steel plate, and the probabilities of both reactions are the same, indicating that the anodic area S_a should be equal to the cathodic area S_c. Replacing the $\varphi_{e,a}$ in Eq. (4) with $(\varphi_{e,a} + \Delta\varphi_{e,a})$, and then the variation of corrosion potential can be expressed as

$$\Delta\varphi_{corr} = \frac{b_c}{b_a + b_c}\Delta\varphi_{e,a} \tag{6}$$

Substitution of Eq. (6) in Eq. (3), and then the variation of corrosion current density (i_{corr}^{σ}) under the applied stress σ is