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An extended engineering critical assessment for corrosion fatigue of subsea pipeline steels

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ABSTRACT

Engineering critical assessment (ECA) is widely used to assess the structural integrity in offshore industry. But industry standards provide limited guidance on ECAs of structures subjected to corrosion fatigue (CF). In this paper, a critical stress intensity factor (SIF) derived from a corrosion-crack correlation model is proposed to improve the traditional ECA for steel structures in seawater. The proposed critical SIF extends the traditional ECA for CF in that it accounts for the influence of load frequency and initial crack size on the model selection within current ECA guidelines for the ECA of marine structures under CF. The extended ECA is applied for ×65 carbon pipeline steels subjected to CF. The crack growth curves are built using a three-stage CF crack growth model and the experimental data. Fatigue lives are calculated based on those curves as well as traditional ECA models. Results show that the critical SIF can effectively improve the ECA for ×65 carbon pipeline steels under CF. The extended ECA provides a reasonable assessment with reduced conservatism in contrast to the traditional ECA for CF.

1. Introduction

The structured programme for assessing the integrity condition of a structure is commonly referred as the structural integrity management (SIM) (ISO 19902, 2000). SIM as a maintenance strategy has been widely adopted for marine structures for a long time [1,7]. Various approaches are available for structural integrity assessment and the most popular nowadays is the fracture mechanics based approach, which is also known as engineering critical assessment (ECA) or fitness-for-service (FFS) assessment. The established philosophy behind the approach is to ensure that the material of which the component is made, is able to withstand the maximum applied load when a crack-like flaw exists.

ECA has been regularly performed in today's offshore oil and gas industry to ensure the safe operation of critical structures as well as to maximize their earning capabilities [15]. There are several industry standards that can provide guidance on conducting ECAs, such as BS 7910 [6], API 579-1/ASME FFS-1 (2007)[2], SINTAP (1999) [24], FITNET [13], etc. Although these guidelines have specified corrosion fatigue (CF) as an important damage mechanism, they are not able to provide as detailed, in depth and generality, and accurate assessments to CF as to failure modes such as fracture/collapse, fatigue, creep fatigue, etc. [6]. And this insufficiency often leads to overestimation or underestimation of the damage by CF to structural integrity. Offshore structures, for instance subsea pipelines, are vulnerable to CF. The excessive conservatism can ensure safe operation, but also leads to unnecessary and costly underwater inspections; while the lack of conservatism will put the structure at a high risk of failure, which may result in enormous

Abbreviations: AD, Anodic Dissolution; CF, Corrosion Fatigue; CP, Cathodic Protection; EAC, Environment Assisted Cracking; EAZ, Environment Affected Zone; ECA, Engineering Critical Assessment; FFS, Fitness For Service; HE, Hydrogen Embrittlement; HEDE, Hydrogen Enhanced De-cohesion; LEFM, Linear Elastic Fracture Mechanics; SCC, Stress Corrosion Cracking; SD, Standard Deviation; SIF, Stress Intensity Factor; SIM, Structural Integrity Management

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economic loss as well as catastrophic environmental disasters. There is thus a practical and pressing need to improve the traditional ECA for the marine structures suffering CF.

Based upon previous research work [8,9], a critical stress intensity factor (SIF) is proposed from the perspective of CF severity. It accounts for the influence of load frequency and initial crack size on the model selection for the ECA of marine structures under CF. The critical SIF is decided according to the specific CF cracking behaviour pattern, and it is calculated invoking a corrosion-crack correlation model [8]. While the subcritical crack growth is estimated using a three-stage CF crack growth model [9], with each stage involving both the cracking processes assisted by anodic dissolution (AD) and by hydrogen embrittlement (HE). Finally, the proposed ECA is applied to × 65 grade pipeline carbon steels to demonstrate the capability of the extended ECA.

2. Corrosion fatigue

The impact from environment on the structural integrity of marine structures is multi-aspect and complicated. Take subsea pipelines for example, in the aspect of mechanics, huge external hydrostatic pressure will be imposed in a deep-sea situation. Intervention vessels, current and other met-ocean events may also be a source of loads acting upon the structures. Additional attention is required to the possible thermal and pressure expansion and contraction. In engineering practice, the load frequencies, stress ratios and even temperatures related to subsea pipelines can vary in rather big ranges. In the aspect of materials, the presence of aggressive environment can severely degrade the material properties such as fracture resistance, while unfortunately subsea pipelines are exposed to aggressive service environments both internally and externally. In the aspect of chemicals, the contact of salts and water with the metal surfaces, either inside or outside the pipelines, gives corrosion a chance to happen. Potential carbon dioxide and hydrogen sulphide in the product flow makes the situation even worse. Under such severe service conditions, environment-assisted cracking (EAC) is very likely to occur and damage the integrity of subsea pipelines.

EAC describes the aggravated cracking process of metals by the presence of aggressive environment. Stress concentrations such as as-built pipeline defects or dents caused by interference as well as corrosion pits may act as initiating sites for EAC. Depending on the loading profile, EACs are sorted into two major categories, i.e. the stress corrosion cracking (SCC) and the corrosion fatigue (CF). CF is the environment enhanced cracking under fatigue loads and SCC represents the accelerated cracking synthetically induced by environments and static loads. In contrast to CF, researches on SCC are relatively extensive and fruitful [5,12,21,29]. SCC cracks are found to initiate from bottoms of surface blemishes, and then propagate into the material either transgranularly, intergranularly or sometimes in a mixed way, depending on the interaction of corrosion reactions and mechanical stress. For high-pH (9–13) SCC, cracks often grow along intergranular paths. This is thought to be associated with the strong environmental influence it receives, manifesting as local corrosion at crack tips. The transgranular crack path of near-neutral pH (5–7) SCC has been suggested to be associated with the ingress of hydrogen, a byproduct of corrosion, and the local corrosion at the crack tip. While hydrogen is well known for its adverse effect on the material's fracture toughness which has the name of hydrogen embrittlement (HE), local corrosion is believed to be caused by anodic dissolution (AD). That is to say AD and HE should be mainly responsible for the crack-tip material damage in near-neutral pH SCC. Interestingly, CF cracks usually follow a transgranular path similar to that of near-neutral pH SCC. The similarity in crack morphologies implies a similarity in cracking mechanisms. Further studies confirm that the mechanisms, which have generally been proposed to explain near-neutral pH SCC, are also applicable for CF. Combining with the fact that practical operations commonly generate varying working stresses in engineering structures, some researchers even consider SCC as a special case of CF where the stress ratio reaches unity [23]. BS 7910 [6] suggests using CF threshold to assess the starting of SCC, as it has recognized that structures are seldom subjected to pure static loads and the threshold of SCC can be considerably reduced if a cyclic component, even of very small magnitude, is superimposed on the static loading. Hence, it is of significant necessity to reasonably assess the damage on structural integrity due to CF.

Experimental observations [15,25,27,30] have confirmed that CF can change the crack growth behaviour and lead to remarkably higher crack growth rate than that of fatigue in air for carbon pipeline steels such as × 65 (shown in Fig. 1), and a few researchers have examined the CF damage in the view of the consequently lower overall fatigue life. For example, Baxter et al. [4], based on their experimental results, found fatigue lives of steels in seawater, with or without cathodic protection (CP), at high stress range can be a factor of three lower than those in air.

Most of the researchers have been aware that load frequency has an important influence on the crack growth in the situation of CF, which is quite different from fatigue crack growth in dry-air environments. Holtam [15] investigated the effect of crack size on CF crack growth. However, there is a lack of research performed on assessing the CF damage with respect to both initial crack size and load frequency. The main objective of the study is to fill this gap. Cheng and Chen [8] proposed a corrosion-crack correlation model for predicting the cracking behaviour of HE-influenced fatigue. Based on this model as well as the physics of CF, Cheng and Chen [9] further established a two-stage crack growth model for CF. The previous research work has provided a solid theoretical foundation for extending the traditional ECA of structures suffering CF to account for the influence from both load frequency and initial crack size.

3. Extended engineering assessment (ECA)

Since it was developed in the 1950s by Irwin [16], linear elastic fracture mechanics (LEFM) analysis has been widely applied to ECA for steel structures. It introduces the concept of stress intensity factor (SIF) K to describe the crack growth under sustained loads,

$$K = YS\sqrt{\pi a} \tag{1}$$

where a is the crack size, Y stands for the geometry function, and S is the applied stress perpendicular to the crack plane. For the case