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Experimental and numerical study on collapse of aged jacket platforms caused by corrosion or fatigue cracking

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ABSTRACT

This paper presents experimental and numerical study on the collapse of aged steel jackets, caused by corrosion or fatigue crack. The test models were manufactured in accordance with a scale ratio of a prototype jacket. Corrosion and crack damages calculated by some empirical equations were subjected to the model. The collapse experiments were performed for the intact, corroded and cracked jacket model. Damaged versus intact model comparison indicates that the crack and corrosion damage will degenerate the ultimate loads of structure significantly, and they will induce the different failure modes of the damaged jackets with intact one. The two damaged jackets are both failed by the crack tearing of the leg. Nonlinear finite element method was applied for experimental results validation. Numerical and experimental results are proven to be in a good agreement.

1. Introduction

Steel jackets have been widely used in offshore oil industry in recent 20 years [1]. A number of over 15-years old jackets are still operational in Bohai bay of China, Mexican Gulf and Brazilian waters. As structures reach their design service lives, the fatigue life should be reassessed. The crack and corrosion play major role in structural aging, when jacket is subjected to environmental conditions like wave, wind and current loads. The ultimate strength will degrade with the crack and corrosion growth, causing risk of in the collapse and failure of the whole jacket, which will result in the loss of people, property and environment pollution. Some aspects of aged jacket fatigue life reassessment are presented in [2], in which the collapse assessment was performed by pushover method. One of the main motivations for this reassessment may be the safety or the need to extend their life.

The attention has been paid on the residual ultimate strength of the aged structure such as ship or elements for other marine structures and the intact jacket and other ones with crack and corrosion damages. Some works about global nonlinear collapse analyses of three-dimensional steel jacket were done using numerical method in [3]. The strength of tubular structure as ring-stiffened DT-joints in offshore jacket was predicted using finite element method [4]. Fatigue reliability analysis was done for the jacket support considering the corrosion and inspection [5]. The influence of crack and corrosion on the ultimate strength of aged ship was analyzed by Paik [6]. Reliability analysis of the ship subjected to the damages was also performed by Akpan [7] and Guedes Soares [8], but the resistance of the aged ship was simplified to the initial yielding that will underestimate or overestimate the ultimate strength. Besides, the collapse behavior of the ship plate under crack, corrosion and dent was assessed by the numerical and experimental methods [9], and also for the plate with pit corrosion using nonlinear finite element by Paik [10]. A general expression of the ultimate strength of the plate with any crack was derived based on the experimental and numerical results [11]. The experimental investigation for the scantling box girder under slight, average and severe corrosions was done recently [12,13].

The collapse behavior of the complex structure need to be studied by performing global nonlinear analyses of the overall structure [14,15]. The ultimate strength theory of ship structure has been developed during the last decades since Caldwell [16], including the progressive collapse method, idealized structural unit method and nonlinear finite element method [16–22]. And the experimental studies were carried out for the ultimate strength of the scantling ship hulls, as the box girder by Recking [23] and Nishihara [24], the model with residual stress and initial imperfections by Akhras [25], and the model under bend, shear and torsion by Ostapenko [26].

Nonlinear pushover approach is commonly used to determine the ultimate strength of framed structures [14,15,27]. Pushover analysis types can be categorized either static or dynamic [28]. In static analysis dynamic effects are either neglected or included as

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a multiplier of the static forces, and the forces are applied as incremental static loads until the platform collapses.

In this paper static analysis is employed. Static pushover is a common methodology in jacket structural design. For the ultimate strength study of the steel jackets see e.g. [3]. The ultimate strength analysis is rather related to extreme loading; while crack and corrosion is another important cause of collapse, which needs to be studied in detail. Crack and corrosion prediction requires experimental as well as nonlinear numerical analysis.

To assess the collapse behavior of the aged jackets, three scantling models designed by the similar rules were tested respectively under quasi-static progressive loading including the intact, crack and corrosion model. In order to investigate the corrosion or crack effect on collapse of the jacket platform, two different experimental jacket models were compared, the intact one and the one damaged by corrosion and crack. The response in terms of load–displacement and load–strain relationship was given; showing the failure mode of the jacket platform, damaged by crack and corrosion. Numerical nonlinear finite element analysis of the damaged jacket was performed. Finally, numerical and experimental results were compared in this paper.

2. Fundamental theory

2.1. Crack model

To predict the crack propagation during the jacket lifetime, Paris–Erdogan equations are adopted [29]

$$\frac{da}{dN} = C(\Delta K)^m \tag{1}$$

$$\Delta K = Y\Delta\sigma\sqrt{\pi a} \tag{2}$$

where ΔK is the stress intensity factor, Y is the geometric factor, $\Delta\sigma$ is the stress range, a is the crack size, N is the number of loading cycles, C and m are material parameters, determined by the experiment.

For the small crack size Y can be assumed to be constant, then integration of Eqs. (1) and (2) leads to the following crack size estimate

$$a(T) = \begin{cases} \left[a_0^{1-m/2} + \left(1-\frac{m}{2}\right)C(\Delta\sigma Y\sqrt{\pi})^m (T-T_0)\omega\right]^{\frac{1}{1-m/2}} & m \neq 2 \\ a_0 \exp C\Delta\sigma^2 Y^2 \pi (T-T_0)\omega & m = 2 \end{cases} \tag{3}$$

where a_0 is the initial crack size, $N = (T - T_0)\omega$ is the number of load cycles, T is the age of platform in years, T_0 is the time of initial crack generated.

2.2. Corrosion model

This paper assumes most common form of corrosion for mild and low alloy steels, namely uniform corrosion, where the loss of material is relatively uniform over the structural surface. Corrosion reduces the base shear capacity of platform by thinning the thickness of primary structural members; it reduces the ability of the structure to resist external loads. Different models of general corrosion growth have been suggested. Nonlinear model proposed in [30], enables accurate prediction of the thickness loss induced by corrosion. Basic equations of this model are

$$\begin{aligned} t_r(T) &= C_1 T_e^{C_2} \\ r_r(T) &= C_1 C_2 T_e^{C_2-1} \end{aligned} \tag{4}$$

where $t_r(T)$ is the corrosion depth for loss of thickness in mm; $r_r(t)$ is the corrosion rate in mm/year, T_e is the exposure time in years, after breakdown of coating, which is taken as $T_e = T - T_c - T_t$; T_c is the life of coating in years, and T_t is the duration of transition in years which may be pessimistically taken as 0, C_1 and C_2 are coefficients to be determined by the statistical analysis of corrosion measurement data.

2.3. Ultimate strength with the damages

2.3.1. Nonlinear finite element method (NFEM)

In the Finite Element Analysis (FEA), the set of equations describing the structural behavior is

$$[k(\delta)]\{\delta\} - \{F\} = 0 \tag{5}$$

where k is the stiffness matrix of the structure, δ is the nodal displacements vector and F is the external nodal force vector.

The ultimate strength of the offshore jacket structure is studied by the NFEM, in which the geometrical and material nonlinearities are considered. The nonlinear equations as in Eq. (5) are solved by the incremental iteration method, described as

$$\begin{cases} \{\Delta\delta\}_m^i = \left[K_m^i\right]^{-1}\left(\{R_m\} - \left\{F_m^i\right\}\right) = \left[K_m^i\right]^{-1}\left(\Delta R_m - \psi_m^i\right) \\ \left\{\delta_i^{j+1}\right\} = \left\{\delta_i^j\right\} + \left\{\Delta\delta_i^j\right\} \end{cases} \tag{6}$$

where $\{R_m\}$ is the load vector at the mth step, $\left\{F_m^i\right\}$ is the nodal force at the ith iteration, $\{\Delta R_m\}$ is the load incremental, $\left\{\psi_m^i\right\}$ is the unbalance force after ith iteration.

2.3.2. Ultimate strength of offshore jacket with damages

In this section Euler beam theory is used to describe beam elements.

(1) For crack damage. The stiffness matrix K of the crack element, of which the effective area is reduced, can be described as [31]

$$[K]_{es} = \frac{a_1 EI}{L^3}\begin{bmatrix} 12a_2 & 6La_2 & -12a_2 & 6La_2 \\ 6La_2 & 4L^2a_3 & -6La_2 & 2L^2a_4 \\ -12a_2 & -6La_2 & 12a_2 & -6La_2 \\ 6La_2 & 2L^2a_4 & -6La_2 & 4L^2a_3 \end{bmatrix} \tag{7}$$

where I is the sectional inertia, $a_1 a_i < 1, i = 2, 3, 4$, are the parameters of the crack size.

(2) For corrosion damage. The stiffness matrix K of the corroded hollow circular element can be written as

$$[K]_e = \frac{EI}{L^3}\begin{bmatrix} 12 & 6L & -12 & 6L \\ 6L & 4L^2 & -6L & 2L^2 \\ -12 & -6L & 12 & -6L \\ 6L & 2L^2 & -6L & 4L^2 \end{bmatrix} \tag{8}$$

where the section inertia $I = \frac{\pi}{64}\left((D_{ou} - d(T))^4 - D_{in}^4\right)$ for corrosion jacket; D_{ou}, D_{in} are outer and inner diameters respectively; $d(T)$ is the corrosion thickness.

In this paper, the FEM software ANSYS is used to perform nonlinear analysis. The jacket platform crack is modeled as discontinuous region with thin opening, shown in Fig. 1, while the corrosion modeled as the thickness loss of the element.