Thin-Walled Structures 119 (2017) 727–736

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Computation of plastic collapse capacity of 2D ring with random pitting corrosion defect

Jianxing Yu[a,b], Huakun Wang[a,b,*], Zhiyuan Fan[a,b], Yang Yu[a,b]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University,Tianjin 300072, China
[b] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai Jiaotong University, Shanghai 200240, China

ARTICLE INFO

Keywords:
Random pitting
2D ring
Snap-through
Collapse

ABSTRACT

This paper is aimed at assessing the effects of local random pitting corrosions on the collapse pressure of a 2D ring under external pressure. A Python program was used in combination with the FE code ABAQUS to solve the FE model. Firstly, a series of non-linear FE analysis of rings were carried out to study the influence of such random pitting factors, as diameter-to-depth ratio, distribution form, and pitting number. This indicated that the mass loss and maximum pitting depth were the main factors that govern the collapse pressure of 2D ring. A high-order buckling mode was found with higher collapsed pressure under specific combination of random pitting corrosion factors, which turned out to be the snap-through of archer beam. Finally, a closed form formula able to predict the collapse pressure of a 2D ring with 2-wave form out-of-roundness and random pitting defects was established by nonlinear regression analysis of FE results with consideration of mass loss, maximum pitting depth, diameter-to- thickness ratio (D/t) as well as out-of-roundness ($\triangle$).

1. Introduction

Both internal and external corrosion defects are the major causes of accidents in liquid and natural gas pipelines. While internal pressure is the predominant load for onshore and shallow water pipelines, ultra-deep pipelines must be designed to resist collapse due to the external pressure [1]. The failure of subsea tubes are often caused by local buckling rather than blast failure especially for deep-sea application [2].

The collapse of a pipe is affected by such parameters as D/t, material properties, initial geometric imperfections and thickness variations [3], dents caused by the impact objects [4], material yield anisotropy and the residual stress induced by the manufacturing process [5]. However, local ovality and wall thickness thinning caused by corrosion were verified to be the most significant geometric imperfections that cause buckling for a subsea pipeline [1,6–10]. Both experimental and numerical results have confirmed that the corrosion depth was the major factor that governs the collapse pressure of a pipe both with internal and external corrosion. The effect of the corrosion length could be neglected when $l/D > 10$, while the effect of the corrosion width was marginal [1,8–10].

The 2D ring model is widely used as a simplified model to investigate the corrosion defects on the collapse pressure of pipe [1,2,11–13]. Based on Timoshenko's theory, Yan and Xue [2,12] derived analytical formulas of instability failure for corroded rings, and the coupling effects of double corrosion were also studied [2,13]. However, all the models mentioned above have assumed that the corrosion defect was uniform, some even assumed that corrosion defect symmetry about the neutral axis of the ring [2,11–13], which is far from the actual situation.

Subsea pipelines are vulnerable to suffer pitting corrosion [14], whose generation and growth process are inherently random. Some studies have found the generation of pitting corrosion can be described as a nonhomogeneous Poisson process, and its growth process to be a nonhomogeneous Markov process [15–17]. Previous studies that focus on the collapse behavior of a corroded ring have taken the corrosion defect as a uniform wall thickness reduction model and focus on the effect of a single corrosion defects without consideration of the coupling effects of multiple corrosion. Besides, most studies ignored the randomness characteristics in the generation and growth process of the corrosion defects.

This paper is aimed at investigating the buckling behavior of a 2D ring with random pitting corrosion and also to develop a simple design formula for predicting the collapse pressure. For this purpose, a Python program was developed and combined with the FE code ABAQUS. The correlation between the collapse pressure and the corrosion damage as well as geometric parameters of a ring was deduced theoretically, and an empirical formula was obtained from nonlinear regressing analyses,

* Corresponding author at: State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University,Tianjin 300072, China.
E-mail address: tjuwhk@tju.edu.cn (H. Wang).

http://dx.doi.org/10.1016/j.tws.2017.07.025
Received 21 March 2017; Received in revised form 24 July 2017; Accepted 28 July 2017
0263-8231/

Table 1
Model parameters and material parameters.

Material	Yield stress σ_y (MPa)	E (GPa)	υ	n	D/mm	t/mm	D/t	2D Ring depth/mm
API 5L X52	359	206.1	0.3		51	1.46	35	10
				10.7		1.7	30	10
						2.04	25	10

which can be used in reliability analysis.

2. Numerical model

2.1. Material and geometric properties of a 2D ring

The API 5L X52 was used in the analysis as mentioned in API SPEC 5L-2007 [18], the relationship between stress σ and strain ε was described by Ramberg-Osgood (R-O) model [19], which can be written as follow:

$$\varepsilon = \frac{\sigma}{E}\left[1 + \frac{3}{7}\left(\frac{\sigma}{\sigma_y}\right)^{n-1}\right] \tag{1}$$

where n is the hardening parameter, σ_y is the nominal yield stress, and E is the elastic modulus. The corresponding model parameters and material parameters are listed in Table 1.

A 2D ring random pitting model is shown in Fig. 1 and some basic assumptions are made as follows:

(1) The shape of pitting is semi-elliptical [20,21] with center located in the outside surface of the ring.
(2) The pitting number is fixed at 60 and the pitting depth obeys a Normal distribution [21].
(3) The material was homogeneous and isotropic, and the pitting distribution along the circumference obeys a uniform distribution.

FE models were established within the framework of the nonlinear finite element code ABAQUS with CPE3 (3-node linear plane strain triangle) elements. A Python program was developed to finish model preprocessing. The degree of freedom in X, Y direction of point A was constrained (Fig. 1) to avoid rigid body displacement. A modified Riks method was used to solve the collapse pressure (P_{co}) of the ring and trace the unstable post-buckling equilibrium path. A convergence study was carried out to determine a fine mesh size of finite element model as shown in Table 2, based on the balance of computational efficiency and accuracy, the case of No.5 was adopted in this paper. The corresponding load and boundary condition as well as the mesh were shown in Figs. 2 and 3, respectively. As shown in Fig. 4, the reaction force of

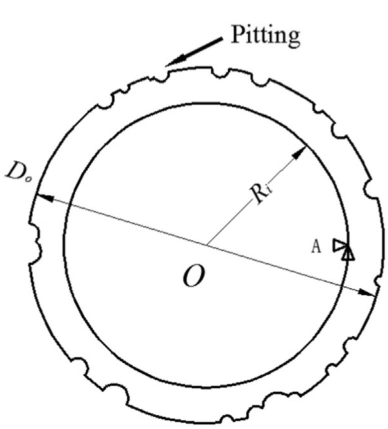

Fig. 1. 2D ring random pitting model.

point A in X and Y direction was very small comparing to the resultant force acting on the cross section of the ring (For example: once buckle initiated, four plastic hinge will form in the ring (in the case of 2-wave form collapse mechanism), and the resultant force acting on these position is approximately equal to $\sigma_y\, t\times 1$(unit-thickness), which is high enough comparing to the reaction force shown in Fig. 4), and had little impact on the solution procedure, which indicated that the applied boundary condition was reasonable.

2.2. Growth model of the pitting depth

According to Rivas et al. [21], the pitting depth obeys a normal distribution and its mean value is fitted well by the following function:

$$u_d = 1.41 + 13.7t^{0.45} \tag{2}$$

where u_d is the mean pit depth (um) and t is the time (day).

Noted that the standard deviation of the normal distribution has a rapid increase for immersion period shorter than 15 days. However, the standard deviation versus time curve saturates after 15 days of immersion. This may correspond to the period when equilibrium in the pit growth conditions has been established [21]. In this paper, since the elapse time interested was long enough (>>15 days), the standard deviation of pitting depth distribution was chosen to be 26.5 μm in this study according to the test data in [21]. According to the time evolution model of pitting depth (Eq. (2)) and the numerical model mentioned above, the time variant collapse pressure of 2D ring was available.

3. Parametric study

3.1. Diameter-to-depth ratio (DDR) of corrosion pits

It was found that the shape of the pitting corrosion on hold frames in bulk carriers is a circular cone [22], while a nearly hemispherical shape is observed for all the pits recorded in the pipe [21]. The diameter-to-depth ratio (DDR) is in the range between 8 to 1 and 10 to 1 for circular cones, while for pits on the bottom shell of the oil tanker it ranges between 4 to 1 and 6 to1 [22]. However, in the case of stress corrosion cracking, the value of DDR usually falls in the range of 0.5–2 [20,23]. To investigate the effect of DDR on the collapse pressure of corroded ring, an elliptical pitting shape was adopted, and only the ratio between 0.5 and 2 was investigated in this paper. Models with different DDRs are shown in Fig. 5, where *RL* means the lower bound of DDR and *RU* means the upper bound. For each model, the depth distribution form and pitting number were kept to be consistent, and the DDR was assumed to obey a uniform distribution.

The collapse pressures of corroded rings with three kinds of DDR were analyzed as shown in Figs. 6 and 7, where M_t is the total mass of the ring, t_{min} is the minimum remaining wall thickness, P_{co} is the collapse pressure of corroded ring and $P_y = \sigma_y t/R$. It indicated that the collapse pressure of a corroded ring was affected not only by mass loss and minimum remaining wall thickness, but also affected by the DDR (i.e. actual shape of pits). However, its influence was limited, especially for small mass loss. Fig. 8 shows the Equilibrium paths of the corroded rings, where vertical axis is load proportionality factor (LPF) and horizontal axis is Arc Length. The results confirm that the influence of DDR of pitting on post-buckling process was more significant. The collapsed configuration of the corroded ring is shown in Fig. 9. Generally, the region with severe pitting tends to more easily yield and then collapse inward or outward (Fig. 9(b)).

As mentioned above, the DDR does have some impact on the collapse pressure of corroded ring, especially for ones with severe pitting corrosions. In spite of this, the semicircle model was more consistent with experiment results [21], and it will be used in our following studies.