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Effect of 3D random pitting defects on the collapse pressure of pipe — Part I: Experiment

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ABSTRACT

This paper is aimed at assessing the effects of local random external pitting defects on the collapse pressure of pipe under external pressure. In this two-part paper series, the buckling performance of locally random corroded pipe was experimentally and numerically studied. The experimental program described in Part I involves seamless carbon steel tubes with $D/t = 17$ and with different size of pitting defects. The random pitting defects were introduced into the outside surface of pipe using 6% $FeCl_3$ solution and then the collapse pressure of such locally random corroded pipe was obtained experimentally. The profile of pipe was examined in details using Hexagon's new RA7320 Portable Arm Coordinate Measuring Machine (PACMM) and the measured data were analyzed meticulously. It indicated that either the out-of-roundness imperfection shape $n = 2$ or $n = 3$ fits best with the measure data. The characteristics of random pitting corrosion were statistically analyzed and the mass loss of pipe due to pitting corrosion was also determined after buckling test, the analysis results indicate that both lognormal and generalized extreme value (GEV) distribution are adequate to depict the distribution of pitting depth and pitting diameter-to-depth ratio (DDR). The corrosion morphology was observed using scanning electron microscope (SEM), which indicates that the shape of pitting defect is cylindrical or semi-ellipsoid. Finally, the relationship between collapse pressure and geometry defects was analyzed based on the experiment results.

1. Introduction

It has been widely reported that corrosion damage is the primary cause of ultimate strength reduction of engineering structure [1–17]. Many researchers indicate that the maximum cross-sectional loss is a good parameter to correlate the residual load-bearing capacity and corrosion damage of corroded beams [7–10], while for random corroded plate, the effect of corroded volume loss and plate slenderness ratio on ultimate strength dominates [11–17].

For structures exposed to a harsh oceanic environment, pitting corrosion is more likely to exist, which is the major cause of accidents in liquid and natural gas pipelines [18–22], which usually occurs when the protective coatings or cathodic protection systems become ineffective. 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 [23–25].

The collapse of pipe is affected by parameters as D/t (D: outside diameter of pipe, t: wall thickness), material properties, initial geometric imperfections (out-of-roundness and thickness variations) [26], dents caused by the impact objects [27], wall thickness thinning caused by corrosion or wear [23–25,28] and so on. Out-of-roundness and wall thickness thinning caused by corrosion were verified to be the most significant geometric imperfections that cause buckling for a subsea pipeline [23–25,29–33]. It had been confirmed that the corrosion depth was the major factor that governs the collapse pressure of a pipe both for internal and external corrosion, the effect of the corrosion length (l) could be neglected when $l/D > 10$, while the effect of the corrosion width is marginal [23–25].

The effect of single corrosion defect on the collapse pressure had been widely studied both for 2D and 3D models [23–25,34–36]. However, all the models mentioned above assumed that the corrosion defect to be uniform on the pipe surface, some even assumed that corrosion defect symmetry about the neutral axis of the ring [34–36], which is far from the actual situation. In the practical projects, subsea

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pipelines are vulnerable to pitting corrosion damage [20], whose generation and growth process are inherently stochastic [37–39].

Even though the effect of random pitting defects on the ultimate/buckling strength of engineering structure have been widely investigated [1–17], the effect of random pitting defects on the collapse pressure of pipe under external pressure has not meticulously studied. In addition, most corrosion defects applied in previous studies were machined artificially and exaggerated sometimes. Besides, the corrosion morphology is also different from the actual ones, and the applicability still needed to be verified. In the authors' previous work [40], the collapse pressure of a 2D random corroded ring was investigated using FE method, due to the limitation of 2D model, no experiment was carried out. Considering that precise prediction of the buckling capacity of random corroded pipe could lead to savings in the cost of maintenance and avoid pipeline failure caused by buckle propagation. In this two-part paper series, a 3D locally random corroded pipe was carefully studied using experimental and numerical methods, which provides further information of the effect of random pitting corrosion defects on the buckling strength of pipelines.

As a consequence, in this first paper, based on the authors' previous work of 2D random corroded ring under external pressure [40], which provides basic information for the evaluation of the buckling capacity of random corroded pipelines, a pipe with random pitting defects is used to carry out local buckling test. The geometry imperfection of pipe was described using RA 7320 PACMM and depth gauge, and then the relationship between collapse pressure and geometry imperfection of pipe was quantitatively analyzed.

2. Experiment

Seamless carbon steel tubes with 51 mm nominal diameter and 3 mm wall thickness were used to carry out pitting corrosion and buckling test. The experiments can be divided into three parts, pitting corrosion tests, tensile tests of material and buckling tests of random corroded pipe. The experimental procedure are described as follows.

2.1. Pitting corrosion test of pipe

To introduce random pitting defects into the outside surface of pipe, 6% $FeCl_3$ (dissolve 100 g of reagent grade ferric chloride, $FeCl_3{\cdot}6H_2O$, in 900 mL reagent water) was used according to ASTM G48 [41]. The outside surfaces of pipe were polished with a 120-grit abrasive paper, which provides a satisfactory standard finish [41] and then rinsed well with deionized water, cleaned with acetone and finally air-dried. A cylindrical PET (polyethylene glycol terephthalate) plastic tank was used to contain the $FeCl_3$ solution, the interface between pipe outside surface and the plastic tank was sealed with epoxy resin. The test scheme is shown in Fig. 1. The pitting defects affected zone along the axial direction of pipe was determined by the length of plastic tank (L_T) and the experiment was carried out at room temperature. Out of seven test specimens, one specimen did not have any corrosion defect (sample 3–3) and thus was referred as the control specimen. Other samples had different sizes of pitting defects. The solution was changed every day. Three exposure times were chosen: 5, 7 and 9 days. The choice of three exposure times is based on our pretest results. In these cases, the size of pitting corrosion is visible and distinguishing. For the pitting corrosion test of whole pipe, extensive $FeCl_3$ solution was required and the longest exposure time was chosen to be 9 days for economic purposes. The maximum pitting depth is 0.397 mm when the exposure time was 9 days. Considering that pitting corrosion and general corrosion are combined during corrosion test, the wall thickness of corroded region of pipe were re-measured using ultrasonic thickness gauges. Detail information of material and geometry parameters, as well as collapse pressure, are shown in Section 3.3.

After exposure, a steel brush was used to remove rust and the specimens were cleaned with water and then dried in air. The depth of

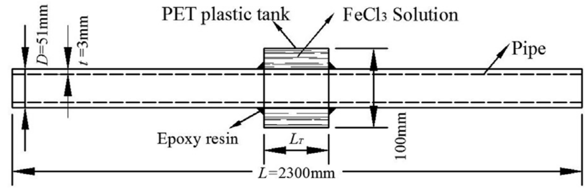

Fig. 1. Schematic of random pitting testing scheme.

corrosion pits was measured using depth gauge FLANK QFW-325A with resolution up to 0.001 mm. In addition to the pitting depth, the diameter of the pits were also measured and recorded using vernier caliper, which was used to calculate the diameter-to-depth ratio (DDR) of pits and give a quantitative description of pitting shape. Note that only visible pitting defects via the naked human eye were measured and recorded. However, the test results of scanning electron microscopy (SEM) indicated that there are some very shallow holes, which are difficult to be detected by naked eye. The statistical histogram of pitting depth and pitting diameter were obtained based on these measured data, and the pitting morphology was carefully inspected using SEM, which provided basic information for numerical simulation in Part II. The mass loss per unit length caused by corrosion was also obtained after the buckling test of pipe. The corroded region of pipe was cut by the wire electrical discharge machining (WEDM) and then the weight of the corroded pipe segment was obtained using an analytical balance (JMA30002, the measuring range is 3 kg and the accuracy is 0.01 g). An intact pipe segment with 5 cm depth was used as a benchmark to calculate the weight of the pipe segment free of corrosion, and the approximate mass loss caused by corrosion was obtained from detailed measure scheme in Section 3.3.

2.2. Measuring the out-of-roundness and thickness variation of the test pipes

To capture the accurate profile of pipe, the RA7320 PACMM was used. The measuring range of RA7320 is 2 m, with the point repeatability accuracy 0.03 mm and the spatial length accuracy 0.042 mm. To map the pipe profile, a fictitious reference cylinder was constructed based on at least 6 random reading from the outside surface of pipe (more than 40 points were adopted in the measuring process) and then a Cartesian coordinates system was constructed as shown in Fig. 2. The center coordinate and radius of such fictitious cylinder (R_C) can be easily obtained using the software PC-DMIS based on the least square methods [42]. The scanning function of PACMM allows the user to obtain the profile of pipe, and the measured data are provided as a set of Cartesian coordinates (x_i, y_i), each corresponds to a measured point on the external surface of the pipe. Based on this information, the deviation of each point in radius from the fictitious reference cylinder can be determined, which are shown in Section 3.1. Typically, a circumferential scan was taken every 50 mm (dL) along the axial direction of pipe and about 80 points were recorded in each cross section. The

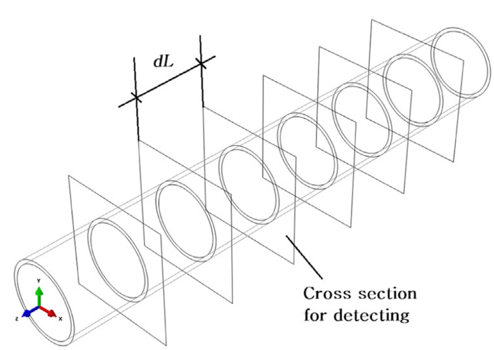

Fig. 2. Schematic of circumferential scan scheme.