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Assessment by finite element modeling of the interaction of multiple corrosion defects and the effect on failure pressure of corroded pipelines

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ABSTRACT

Determination of the failure pressure of pipelines containing multiple corrosion defects is critical to the integrity and safety of the pipeline infrastructure. In this work, finite element models were developed to determine the failure pressures of X46, X60 and X80 steel pipelines containing multiple corrosion defects with varied geometries and orientations by assessing the mutual interaction of the defects and the effect on pipeline integrity. Generally, the failure pressure of corroded pipelines decreases with the increasing interaction effect between corrosion defects. The interaction effect mainly depends on the mutual orientation of the defects and their geometry and spacing, rather than the steel grade. For longitudinally and circumferentially aligned corrosion defects present on a pipeline, the interaction effect between them does not exist when their spacing is larger than $2.5\sqrt{Dt}$ and $5.3\,t$, respectively, where D and t are diameter and wall thickness of the pipeline. As a result, the multiple defects can be assessed individually. Compared to circumferential corrosion defects, the longitudinal defects are associated with a larger spacing where the interaction effect between corrosion defects exists. The circumferential spacing of corrosion defects has a less impact on the failure pressure of corroded pipelines compared with the longitudinal spacing. For pipelines containing overlapped corrosion defects, the failure pressure is lowered, compared to that in the presence of a single top layer defect only. An increase in the depth of either top or bottom layer corrosion defect reduces the failure pressure of the pipeline. The increased length of the defect also increases the interaction effect between the overlapped defects, lowering the failure pressure of the pipeline.

1. Introduction

Pipelines have been the most effective and efficient method for transportation of oil and gas from production sites to their markets and end users. Statistics showed that corrosion was one of the primary mechanisms resulting in pipeline failure [1,2]. Generally, the presence of corrosion defects on pipelines introduces risk to the structural integrity. At the same time, a pipeline containing corrosion defects can continue to operate if the maximum allowable operating pressure (MAOP) passes the reliability assessment by determining the failure pressure of the corroded pipeline by various models [3–5]. Particularly, American Society of Mechanical Engineers (ASME) B31G standard [6], a computer code named "modified B31G" [7,8] and the DNV-RP-F101 standard [9] have been used widely to determine the failure pressure of pipelines containing corrosion defects.

The corrosion defects on pipelines are usually categorized into three types, i.e., a single defect, interacting multiple defects and complexly shaped defects [9]. In the past decades, efforts have been made to model and assess the single defect on pipelines, and various standards and engineering mathematical codes for defect assessment have been developed and validated by experimental testing, numerical calculations and field burst tests. Xu and Cheng [10] developed a finite element (FE) based model to predict failure pressures of X65 and X80 steel pipelines containing a single corrosion defect with varied depths. It was found that the defect induced a local stress concentration, which was increased with the increasing depth of the defect (while its width was unchanged). A quantitative relationship between failure pressures of corroded pipelines and the defect depth was developed. Su et al. [11] developed a FE model to predict failure pressure of corroded pipelines by considering internal pressure, the pipe steel grades and geometries of corrosion defects. The results indicated that, for short and deep corrosion defects, the failure pressures were sensitive to the corrosion width. Thus, the effect of defect width on the failure pressure of the pipeline should be considered in assessment methods. The analysis results were in agreement with many experimental testing data. Generally, for corrosion defects with similar depth, length and width, the

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alignment with the longitudinal or circumferential direction does not affect obviously the failure pressure of the pipeline. However, at a given depth, if the defect length and its width are greatly different, the orientation of the defect, i.e., longitudinally or circumferentially, would apparently influence the failure pressure. The defect length influences the failure pressure more greatly than the width at a given depth [10–12]. Moreover, the failure pressure of corroded pipelines is not nominally proportional to the ratio of the defect depth to the pipe wall thickness [12].

Analysis of the interaction of multiple corrosion defects is expected to provide more accurate and reliable prediction of the failure pressure of pipelines as corrosion defects are usually present in clustering and/or within a sufficiently close spatial distance [13–17]. For example, Chiodo and Ruggieri [18] predicted the failure pressure of corroded pipelines containing multiple axial defects based on plastic instability analysis. In addition to the defect size and orientation, the interaction between corrosion defects influenced remarkably the failure pressure of the pipelines. Cerit et al. [19] conducted FE analysis, combined with uniaxial tension loading tests, to determine the stress distribution at semi-elliptical corrosion pits on steels and high-strength aluminum alloys. They found that the pit aspect ratio, i.e., the ratio of the pit depth to its width, was a main parameter affecting the stress concentration factor. A simple equation was proposed to calculate the stress concentration factor depending on characteristics of pit parameters. Furthermore, Cerit [20] found that the stress concentration factor developed at corrosion defects was closely related with the profiles of two layers of overlapped pits (defects).

Investigations on multiple corrosion defects on pipelines have resulting in establishment of the interaction rules, such as CW rule [21], DNV-RP-F101 code [9], 6WT rule [22] and 3WT rule [23], as listed in Table 1. These rules and code were used to determine if an interaction existed between corrosion defects based on calculation of the strength of pipeline steels at the corrosion defects with specific geometrical factors. When the interaction effect was identified between two adjacent defects, they would not be treated as two single defects. As a result, conventional fitness-for-service assessment methods, such as ASME B31G, modified B31G, etc., cannot be used for defect assessment. Generally, the failure pressure of corroded pipelines decreases when multiple corrosion defects interact each other [15].

The methods available for assessment of multiple corrosion defects on pipelines suffered from a number of problems. For example, the modeling results were validated with data obtained from a specific grade of pipeline steel, and did not include the steel strength in determination of the interaction rule. Therefore, the influence of the grade of the pipe steel on the interaction effect between corrosion defects has remained unknown. Moreover, there has been so far rare investigation on overlapped corrosion defects, which are the typical type of corrosion defects observed on pipelines in the field [24]. Without this knowledge, analysis of the fitness-for-service of pipelines would not be reliable as the overlapped corrosion defects can dominate the determination of failure pressure of the pipelines.

In this work, FE based models were developed for assessment of API X46, X60 and X80 steel pipelines containing multiple corrosion defects, which were either longitudinally aligned, circumferentially aligned or overlapped each other. The size of the corrosion defects and the grade of pipeline steels were considered to evaluate the interaction effect between adjacent defects. The critical spacing between defects with various orientations was determined, enabling assessment if an interaction effect existed to affect the failure pressure of the pipeline. The reliability of the models was verified by experimental data collected from literature. The failure pressures of pipelines containing multiple corrosion defects were determined. It is anticipated that this work develops a promising methodology for reliable assessment of the interaction effect between multiple corrosion defects, and for accurate determination of the failure pressure of corroded pipelines, with considerations of the defect geometry and orientation, as well as the steel grade.

Table 1
Various rules governing the interaction effect of multiple defects present on pipelines, where S_L^{Lim} is the maximum longitudinal spacing, S_C^{Lim} is the maximum circumferential spacing, D is the pipe diameter, t is pipe wall thickness, L_1 and L_2 are lengths of corrosion defects, and w_1 and w_2 are widths of corrosion defects.

Interaction rules	Longitudinal limit S_L^{Lim}	Circumferential limit S_C^{Lim}
CW rule [21]	$S_L^{Lim} = \min(L_1, L_2)$	$S_C^{Lim} = \min(w_1, w_2)$
DNV-RP-F101 code [9]	$S_L^{Lim} = 2.0\sqrt{Dt}$	$S_C^{Lim} = \pi\sqrt{Dt}$
6WT rule [22]	$S_L^{Lim} = 6t$	$S_C^{Lim} = 6t$
3WT rule [23]	$S_L^{Lim} = 3t$	$S_C^{Lim} = 3t$

2. Numerical modeling

2.1. Initial and boundary conditions

FE analyses in this work were performed using a software ANSYS 15.0, with a general-purpose FE modeling package for numerically solving a variety of mechanical problems. Three-dimensional (3D) FE models were developed, enabling determination of the failure pressure of pipelines containing multiple corrosion defects which were oriented either longitudinally, circumferentially or overlapped each other. An eight-node SOLID185 element that was able to calculate plasticity, stress stiffening, large deflection and large strain was used for modeling. Locking and hourglass controls for SOLID 185 were set as the default setting of ANSYS. To reduce the numerical computation, one quarter of a pipe including corrosion defects was modeled considering the symmetrical nature of the assembly, as shown in Fig. 1a.

Symmetrical constraints were applied on the planes to be modeled. Displacement in Z direction of the uncorroded end was also constrained. The length of the pipe was sufficient to avoid the effect of boundary conditions on the corroded area.

Fig. 1b–d shows the mesh refinement applied on the corrosion defects to ensure reliable simulation. The uncorroded area on the pipe was under coarse meshing to reduce computation. A mesh density analysis was conducted to determine the appropriate meshing sizes for different defects, as shown in Fig. 2. The mesh sizes were 8 mm and 10 mm in circumferential and longitudinal directions, respectively. The maximum and minimum element sizes of the corroded region were 3 mm and 1 mm, respectively. The corrosion defects have a smooth edge, with a radius equaling to the defect depth, to avoid a high stress concentration.

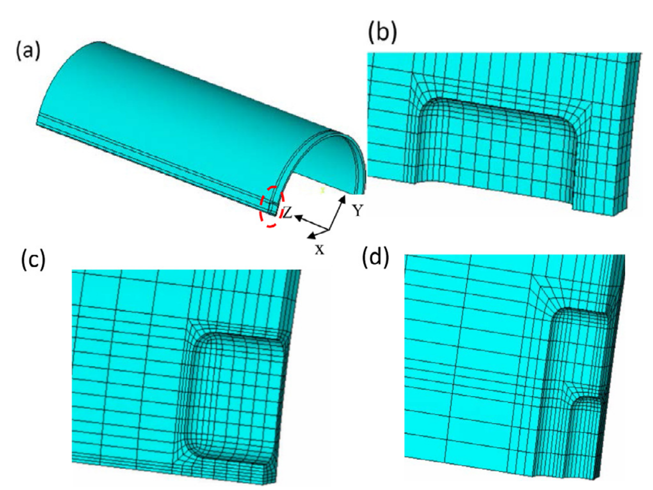

Fig. 1. 3D modeling of a pipe containing corrosion defects (a) a quarter model, (b) meshes of a longitudinal corrosion defect, (c) meshes of a circumferential corrosion defect, (d) meshes of two overlapped corrosion defects.