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Residual bending capacity for pipelines with corrosion defects

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ABSTRACT

Residual bending capacity for corroded pipelines in the presence of axial force and internal pressure can be determined analytically assuming a full plastic failure mode for the pipeline. In this paper, a set of closed-form analytical solutions for residual bending capacity are developed for pipelines with idealized corrosion geometries, namely, constant-depth, elliptical, and parabolic corrosions. It is shown that pipelines with idealized elliptical or parabolic corrosion yield higher bending resistance than that of constant-depth, with the difference between elliptical or parabolic corrosion particularly significant for the case of deep and wide corrosion. It is further pointed out that the simplification of the actual corrosion geometry by constant-depth, as commonly assumed in current code assessment of corroded pipelines, will inevitably underestimate the residual strength of the pipe, especially for the case of deep and wide corrosion. Finally, the experimentally measured bending moment is adopted to validate the proposed analytical solutions in this paper.

1. Introduction

Pipelines, which serve as the arteries of the oil and gas industry, have been widely accepted as one of the most economical ways of transporting oil and gas over long distances. Pipelines are usually subjected to complex combination of bending moment and axial force in addition to internal pressure. Intensive research has been conducted in the last 30 years on bending capacity of intact pipelines combined loadings. Bouwkamp and Stephen (1973) initially conducted seven full-scale steel pipeline specimens for Alaska pipeline Service Company. Each pipeline was subject to the combination of bending moment, axial force and internal pressure. Six steel pipeline specimens with different diameter to wall thickness ratio ranging from 18 to 102 were carried out by Sherman (1976) to study their bending capacity and failure behavior. Schneider (1998) focused on the experimental and theoretical behavior of two large-scale pressurized pipelines with sleeve using four-point bending under combined loadings. Based on maximum distortional energy density yield criterion, pipelines subject to the combination of bending moment, axial force and internal pressure are investigated analytically and numerically by Limam, Lee, Corona, and Kyriakides (2010), Mohareb (2003), Ozkan and Mohareb (2009), and Sadowski and Rotter (2013). Recognizing the important influence of corrosion on the bending capacity of pipelines, Bai and Hauch (2001) attempted to extend their research on intact pipelines to corroded pipelines, and corresponding analytical solutions under the combination of bending moment, axial force and internal pressure were developed for pipelines affected by the constant-depth corrosion, which were later adopted by the American Bureau of Shipping (ABS, 2006) for strength assessment of corroded pipelines. Chen, Li, Chai, and Zhou (2010), Kim, Oh, Park, and Hasegawa (2006), Meshii and Ito (2012), and Oh, Kim, and Park (2009) introduced the net-section-collapse analysis to evaluate the residual bending capacity of pressurized pipelines with corrosion defects.

The current assessment method for corroded pipeline under combined loadings is mostly based on the assumption of uniform depth in circumferential direction. However, the assumption will cause conservative loading capacity prediction on pipeline with practical corrosion defect. To fill this gap, the residual bending capacity for pipelines with various idealized corrosion shapes i.e. constant-depth, elliptical and parabolic shapes in the presence of axial force and internal pressure are investigated in this paper. The proposed analytical solutions presented as universal nondimensional equations are suitable for corrosion allowance limit design and residual strength assessment of pipelines.

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2. Basic assumptions and equations

2.1. Basic assumptions

In order to make the analytical solution of bending capacity for corroded pipeline tractable, the following assumptions are introduced:

(i) The internally pressurized pipeline is thin-walled with a large diameter-to-wall-thickness ratio. Radial stress and shear stresses are ignored.
(ii) Corrosion defects are idealized as infinitely long in the longitudinal direction and symmetrical with respect to the bending plane of the pipe. The actual corrosion shapes is simplified into well defined idealized corrosion shapes i.e. constant-depth ($a(\theta) = a_0$), elliptical ($a(\theta) = a_0\sqrt{1-(\theta/\beta)^2}$) and parabolic ($a(\theta) = a_0(1-\theta/\beta)^2$), where $a(\theta)$ is the corrosion depth as a function of an angular coordinate θ with respect to y-axis; a_0 is the corrosion depth at the corrosion centerline where it is also maximum depth; β is the corrosion half angle representing the half corrosion width. The three distinct idealized corrosion shapes are shown schematically in Fig. 1.
(iii) The cross-section of the pipeline is assumed to be circular and remains circular throughout the deformation for both original and corroded pipelines.
(iv) The material for the pipeline is assumed to be uniform and follows an elastic-perfectly plastic stress–strain relationship.
(v) The plastic deformation can be fully developed without the local buckling of the pipeline wall. A section remains plane both before and after bending so that a plastic neutral axis exists and divides the cross-section into compressive and tensile regions. Both compressive and tensile regions would reach to compressive and tensile limit strengths at the same time.

2.2. Basic equations

When pipelines subjected to combined bending moment, internal pressure and axial force, the stress state of a piece of the pipeline is assumed to be biaxial shown in Fig. 2, as commonly assumed in thin-walled theory, with large circumferential stress, σ_θ and longitudinal stress, σ_z. While the radial stress, σ_r and shear stresses are small relative to the longitudinal or circumferential stress components.

Fabrication processes of pipelines often induce strength anisotropy in the pipelines. Considering such strength anisotropy, the following equation is employed to describe the interaction

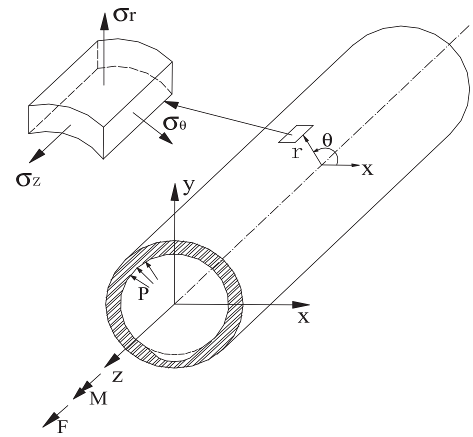

Fig. 2. Stress components acting on pipeline element.

between the longitudinal stress and the circumferential stress (Galambos, 1998):

$$\frac{\sigma_z^2}{\sigma_{zl}^2} - 2\alpha\frac{\sigma_z\sigma_\theta}{\sigma_{zl}\sigma_{\theta l}} + \frac{\sigma_\theta^2}{\sigma_{\theta l}^2} = 1 \quad (1)$$

in which σ_z is the longitudinal stress; σ_θ is the circumferential stress; σ_{zl} is the longitudinal stress limit; $\sigma_{\theta l}$ is the circumferential stress limit; α is a strength anisotropy factor. Fig. 3 shows the interaction curves for strength anisotropy factors commonly used in the industry, namely $\alpha = 0.45$, 0.50 and 0.55 respectively. Note that $\alpha = 0.5$ in Eq. (1) leads to the von Mises yield criterion.

Eq. (1) is adopted to analyze the interaction relation for pipelines subjected to combined bending moment, axial force and internal pressure. To that end, Eq. (1) can be solved to get the following expressions for the longitudinal tensile and compressive stress limits, σ_t and σ_c.

$$\sigma_c = \alpha\sigma_{zl}\frac{\sigma_\theta}{\sigma_{\theta l}} - \sigma_{zl}\sqrt{1-(1-\alpha^2)\left(\frac{\sigma_\theta}{\sigma_{\theta l}}\right)^2} \quad (2)$$

$$\sigma_t = \alpha\sigma_{zl}\frac{\sigma_\theta}{\sigma_{\theta l}} + \sigma_{zl}\sqrt{1-(1-\alpha^2)\left(\frac{\sigma_\theta}{\sigma_{\theta l}}\right)^2} \quad (3)$$

The resultants of force and bending moment acting on the pipeline can be obtained through the integral of the stress limits defined by σ_c and σ_t over the cross-sectional compressive and tensile areas. Since the circumferential stress σ_θ is primarily related

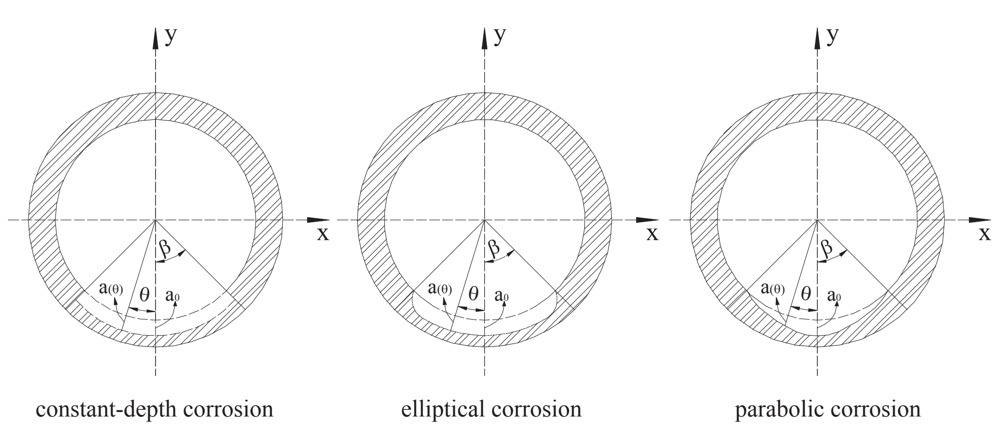

Fig. 1. Three idealized corrosion shapes.