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Prediction of the collapse pressure for thick-walled pipes under external pressure

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ABSTRACT

Collapse behavior of offshore pipelines under external pressure is a primary concern for ultimate limit state design criteria of structural integrity. In this work, finite element analyses of the collapse behavior for long, moderately thick-walled steel pipes under external hydrostatic pressure were performed. The effects of initial ovality, yield stress and yield anisotropy on the collapse pressure were investigated. Besides, 441 finite element models of thick-walled pipes with practical configurations were constructed and analyzed using Python (the programming language within the finite element software package ABAQUS). A simplified equation for predicting the critical plastic collapse pressure was given and recommended for calculating the pressure capacity of thick-walled pipes. The accuracy of the simplified equation was verified by the experimental results from other researchers.

1. Introduction

The demand for various sources of energy has been steadily increasing. Oil and gas, as the main sources of energy, in the shallow-waters are fast depleting, while the exploration of deep-water oil and gas reserves obtains more attention. The integrity of current pipelines should be significantly improved. A single-wall steel pipe is a typical pipeline used to transport oil and gas from offshore reserves. Under the external hydrostatic pressure, the pipelines are vulnerable to local buckling, and the occurrence of propagating buckle can result to huge economic loss.

Thick-walled pipes, with diameter-to-thickness ratios in the range of 12.5–30, are widely used in risers and pipelines. Long, relatively thick-walled tubes under external pressure experienced a limit pressure type of instability [1]. Except for the tube configuration, the limit pressure is very sensitive to initial geometric imperfections, particularly initial ovality. As early as 1975, Palmer and Martin [2] began to study the buckle propagation due to the large external pressure in submarine pipelines. Detailed parametric studies of the collapse pressure were done by Yeh and Kyriakides [3]. Hoo Fatt [4] derived analytical solutions for the elastic buckling and plastic collapse pressures of a non-uniform cylindrical shell. The proposed solutions are extensions of the solutions for the elastic–plastic collapse of a linear elastic, perfectly plastic cylindrical shell subjected to uniform external pressure. Estefen [5] conducted the theoretical and experimental research on the collapse behavior of intact and damaged deepwater pipelines and considered the effect of reel-lay installation method on the pipelines. Finite element studies on pipe collapse due to external pressure, bending and tension were performed by Bai et al. [6]. However they provided overly conservative estimates for considering the initial yield pressure as the critical pressure. The importance of initial imperfection and inelastic behavior of tube material was pointed out by Corona and Kyriakides [7]. Netto [8] proposed the simple equation for the estimation of the collapse pressure of corroded or worn pipes, and the prediction correlated very well with the experiments. In addition, Limam et al. [9] concluded that the manufacturing process could induce inelastic anisotropy to the tubes. The main characteristic of the anisotropy was that the yield stress in the circumferential direction was different from that in the axial direction.

The collapse behavior of thick-walled pipes is strongly influenced by outer diameter-to-thickness ratio D/t, material properties, such as yield stress and strain hardening parameters as well as initial imperfections. Initial ovality is one of the main initial imperfections affecting the collapse behavior under external pressure. The initial ovality Δ_0 is expressed by the following equation [7]

$$\Delta_0 = \frac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}}, \quad (1)$$

where $D_{\max}$ and $D_{\min}$ are the maximum and minimum diameters at a cross-section, respectively.

According to the mechanics of buckling and collapse of long pipes under external pressure, the buckling of thinner pipes is

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determined by the elastic behavior of the pipe material, and thicker pipes used in deeper water buckle and collapse in the plastic range. Early studies on the collapse behavior of pipes under external pressure were well outlined by Timoshenko and Gere [10], which was based on their classical design formulation for a long, circular cylindrical shell.

The buckling pressure of a thin-walled pipe with linearly elastic material can be derived from the classical method as the following formula [10]

$$P_{el} = \frac{2E}{1-\nu^2}\left(\frac{t}{D_0}\right)^3, \tag{2}$$

where D_0 is the mean diameter and ν is the Poisson's ratio of the pipe material.

Considering the imperfection, the collapse pressure of pipes with initial ovality can be given by [10]

$$P_c = \frac{1}{2}\{(P_p + \mu P_{el}) - [(P_p + \mu P_{el})^2 - 4P_pP_{el}]^{1/2}\}, \tag{3}$$

where P_p is the yield pressure that can be given by:

$$P_p = 2\sigma_y \frac{t}{D_0}, \tag{4}$$

and

$$\mu = 1 + 3\Delta_0 \frac{D_0}{t}. \tag{5}$$

However the classic formula mentioned above did not fully consider the material and geometrical nonlinear properties. For pipes which buckle elastically, Timoshenko's design formula can be used to predict the collapse pressure, but for thick-walled pipes, the main failure modes are plastic buckle and collapse, therefore an updated simplified formula is necessary for the latter case.

Considering large deflection, small strain kinematics and elastic–plastic material behavior, Kamalarasa and Calladine [11] developed a complicated analysis method for plastic buckling and collapse of long pipes under external pressure, but the analysis requires numerical treatment due to the initially stable post-buckling behavior. Therefore, there is no simplified formulation available to predict the pressure capacity for thick-walled pipes conveniently with enough accuracy.

The aim in this study is to develop a simple, explicit strength formulation that can be used in load and resistance factor design checks of thick-walled tubes such as deepwater submarine pipelines. Hence, a predictive formula is developed for the collapse pressure of pipes with D/t ratios higher than 12.5, in which both the structural parameter and the initial imperfection were taken in accounted. 441 finite element models of thick-walled pipes with practical configurations were constructed and analyzed using Python [12–14], which can realize parametric modeling in ABAQUS. Based on the numerical results, the simplified equation for predicting the critical plastic collapse pressure was given and recommended for calculating the pressure capacity of thick-walled pipes. The accuracy of the simplified equation was verified by the experimental results from other researchers.

2. Finite element model

The pipe is modeled as the 3D quarter ring configuration with outer diameter D and wall-thickness t, including initial ovality and both longitudinal and transversal symmetry. The elastic–plastic large deflection analysis is carried out by means of the finite element program ABAQUS [15]. The element of C3D8R is used. By mesh convergence studies as done by An et al. [16], it is determined that a FE mesh consists of 40 elements in the circumferential direction and 4 elements in the radial direction.

The steel material properties are extracted from API 5L [17]. The stress–strain curve is fitted with the Ramberg–Osgood model defined as follows:

$$\varepsilon = \frac{\sigma}{E}\left[1 + \frac{3}{7}\left(\frac{\sigma}{\sigma_y}\right)^{n-1}\right]. \tag{6}$$

The effect of the material hardening parameter n, defined in Eq. (6), is relatively small for high values of n and the collapse pressure is normalized by the yield stress which reduces the effect of this parameter. The previous studies [3,12] showed that the models created with the material with hardening parameter equal to 13.6 can effectively capture the characteristic behavior and the normalized collapse pressure capacity. Therefore, in this study, the pipe is modeled using the material model with an elastic regime followed by an exponentially hardening behavior.

In the real world, no perfect system exists and all structural systems suffer from some type of imperfection. For the submarine pipes, the initial ovality which is the main geometrical imperfection should be applied to the FE models to enable the numerical models to capture the real response of the system. The initial ovailty parameter is defined as the following equation:

$$\Delta r = imp \times r_0 \cos 2\theta, \tag{7}$$

where *imp* is the value representing the imperfection amplitude. Moreover, the arc-length method is used for solving the problem.

Python, the programming language within the ABAQUS, is used to create and manage the parametric study's files. The applied external pressure can be set as the buckling pressure P_{el} calculated by Eq. (2), and the maximum increments of the analysis step should be adjusted according to the geometric parameters of the pipes to streamline the numerical analysis.

3. Parametric study

3.1. Influence factor of P_{cr}

Based on the above-mentioned studies on the pipes buckling and collapse under external pressure, the external pressure capacity of the pipe as a function of the influencing parameters can be represented as follows:

$$P_{cr} = f(D, t, \sigma_y, E, \nu, imp). \tag{8}$$

The Poisson's ratio is 0.3. Furthermore, to improve the efficiency of the results, the pipe parameters are non-dimensionalized and the collapse pressure is normalized by the yield pressure P_p. Based on the solutions proposed for the elastic buckling pressure, Eq. (8) can be further expressed as follows:

$$\frac{P_{cr}}{P_p} = f\left(\frac{D}{t}, \frac{\sigma_y}{E}, imp\right). \tag{9}$$

As shown in Fig. 1, the collapse pressures of imperfect tubes for various D/t are predicted by Eq. (3) and numerical method. The collapse pressure increases exponentially as the D/t decreases. In addition, particularly for thick-walled pipes (e.g. $D/t < 30$), the classical formulation cannot accurately predict the collapse pressure due to the plastic behavior.

The plasticity of pipe material plays a more significant role as the diameter-to-thickness ratio decreases. By the finite element method, the response results for the thick-walled pipes with different material assumption are shown in Fig. 2. Note that API 5L grade X52 steel with elastic modulus 207 GPa and yield stress 386 MPa is considered. Comparing the response curves between linearly elastic and inelastic materials, the response for elastic–plastic material exhibits a limited load (peak value of P_{cr}/P_{el}).