Ultimate External Pressure Capacity of Deepsea Dented Pipeline with Combined Axial Compressive Force

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Abstract: As a common defect of deepsea pipeline, dents will weaken the residual strength of the pipeline. In this paper, nonlinear finite element method is adopted to investigate the collapse failure of deepsea dented pipeline under the combined external pressure and axial compressive force. The influence of the axial compressive force on the collapse pressure of dented pipelines with different diameter-thickness ratio and dent depth are investigated based on numerical simulation. It is concluded that relative large axial compressive force will reduce the collapse pressure capacity significantly for deep dent case.

1. Introduction

It is commonly accepted that dents can significantly weaken the external pressure bearing capacity of the deepsea pipeline, resulting in collapse failure of the pipeline. Furthermore, the pipeline is inevitably subjected to axial compressive force during operation due to the temperature difference. In recent years, researchers and engineers around the world developed various specification for evaluating residual strength of dented pipelines. Codes such as ASME B31.8[1] and API 579[2] give evaluation method based on dent depth or strain, but they are only applicable to onshore pipelines where internal pressure is the control load. Although the influence of axial force and bending moment on the failure internal pressure of pipeline is considered in the DNV-RP-F101[3], the failure mode of the pipeline is still the burst failure dominated by internal pressure. Based on the plastic upper and lower limit theory and Mises yield criterion, Mohareb et al.[4-9] derived the analytical solution of the ultimate bending moment of the intact pipe under the combined internal pressure, axial force and bending moment. Park and Kyriakides et al.[10] proposed a Universal Collapse Resistance Curve (UCRC) based on the numerical result. Bai et al.[11] studied the buckling failure law of pipelines with small diameter-thickness ratio under the combined external pressure, bending moment and axial tension by establishing the finite element model of thick-walled pipeline. Most researchers focused on intact pipelines as well as internal pressure dominated conditions. Therefore, it is of great significance to carry out the research on the collapse failure of dented pipeline under the combined external pressure and axial compressive force.

2. Finite element model

In order to save computing resources, 1/4 pipe model is adopted for calculation, as shown in Figure 1. MPC constraints are established between the pipe end face and the central reference point, and the boundary conditions and axial force are applied to the pipe end through the reference point.
Ramberg-Osgood constitutive equation was used to simulate the plastic deformation behavior of the material, as shown in equation (1)[12]. In this research, API X60 is selected as the pipe material, which is commonly used in offshore oil and gas development. The parameters for API X60 pipe steel and FEM are shown in Table 1[13]. In addition, the initial imperfection of pipes in terms of wave-type is also considered in numerical analysis[14,15], which in the form of the combination of the first two orders of eigenvalue buckling modes when pipe is subjected to bending load. The imperfection amplitude is set to 3% t (generally between 1% t and 12% t) according to previous research[16], as shown in Figure 2.

\[ \varepsilon = \frac{\sigma}{E} + \alpha \left( \frac{\sigma}{\sigma_y} \right)^n \]  

where \( \varepsilon \) and \( \sigma \) are strain and stress, \( E \) is Young’s modulus, \( n \) is strain hardening exponent, \( \sigma_y \) is yield strength, \( \alpha \) is material constant, \( \mu \) is Poisson's ratio, respectively.

| Model | Length \( L/\text{mm} \) | Outer Diameter \( D/\text{mm} \) | Diameter-thickness ratio \( D/t \) | \( E/\text{MPa} \) | \( \mu \) | \( \sigma_y/\text{MPa} \) | \( \alpha \) | \( n \) |
|-------|----------------|-----------------|----------------|---------------|-----|----------------|-----|-----|
| Pipe  | 3180           | 318             | 13.5           | 19.9          | 24.2 | 209000         | 0.3 | 1.48 | 18.99 |
|       | 29.2           | 33.6            |                |               |      |                |     |      |      |

3. **Influence of axial compressive force on the collapse pressure**

Pipes of five different diameter-thickness ratios from 13.5 to 33.6 are taken into account in the numerical analysis. Indenter loading depth \( \delta_m \) varies from 0 to 0.2\( D \), where \( D \) is pipe outer diameter, and axial compressive force \( F_c \) varies from 0 to \( F_{co} \). \( F_{co} \) is the ultimate axial force of intact pipe, expressed as \( 2\pi R_m \sigma_0 \), where \( R_m \) is pipe mean radius. The sensitivity analysis is carried out to investigate the influence of axial compressive force on the collapse pressure of dented pipeline. In order to understand the variation of collapse pressure with axial compressive force under various dent depth conditions more clearly, the collapse pressure variation curve under three relative shallow dent conditions and three relative deep dent conditions are plotted in Figure 3 and Figure 4 respectively. The collapse pressure \( \bar{P}_{co} \) herein is normalized by the collapse pressure of intact pipe calculating via FEA.
As shown in Figure 3, for intact pipe ($\delta_m/D = 0$) and pipes with shallow dent ($\delta_m/D = 0.02, 0.05$), when the pipe diameter-thickness ratio is small ($D/t = 13.5, 18.9, 24.2$), the normalized collapse pressure first increases and then decrease with the increase of the axial compressive force. When the axial compressive force is about $0.5P_{co}$, the collapse pressure reaches the peak value, and it is also noted that the collapse pressure of the pipes under axial compressive force are larger than the collapse pressure of the pipe under single external pressure. When the
The diameter-thickness ratio of the pipe is relatively large ($D/t = 29.2, 33.6$), the normalized collapse pressure remains basically unchanged with the increase of the axial pressure. Therefore, for the shallow dent depth cases ($\delta_m/D \leq 0.05$), the axial compressive force will not endanger the ultimate external pressure bearing capacity of the pipeline. For a pipeline with a large wall thickness ($D/t \leq 24.2$), the axial compressive force will even strengthen its ability to resist external pressure.

As shown in Figure 4, for the pipe with a relative deep dent, the variation of the collapse pressure of the pipeline with different diameter-thickness ratios is presented. Noted that the collapse pressure

Figure 4. Effect of axial compressive force on collapse pressure of pipeline with deep dent ($\delta_m/D = 0.1, 0.15, 0.2$)

As shown in Figure 4, for the pipe with a relative deep dent, the variation of the collapse pressure of the pipe with different diameter-thickness ratios is presented. Noted that the collapse pressure
generally remains unchanged with the axial compressive force when the axial compressive force is less than \( 0.5F_{co} \). However, when axial compressive force reaches \( 0.5F_{co} \), the collapse pressure of the dented pipe drops promptly with the increasing of axial compressive force. Therefore, when the dent depth reaches a certain level \( (\delta_n / D \geq 0.1) \), the large axial compressive force will have a great impact on the ultimate external pressure capacity of the pipeline.

4. Conclusions
In this paper, the three-dimensional numerical model for elastoplastic collapse failure of deepsea dented pipelines is established. The ultimate external pressure bearing capacity of pipelines with a variety of different diameter-thickness ratios and dent depth is calculated, and the influence of axial compressive force on the collapse pressure of the pipeline is analyzed. The main conclusions can be drawn as follows:

1) When the dent depth is small, the presence of the axial compressive force does not endanger the external pressure bearing capacity of the pipeline. With the increase of the axial compressive force, the collapse pressure increases firstly and then decreases, but is always greater than the collapse pressure under single external pressure condition, and the smaller the diameter-thickness ratio of the pipe, the more obvious this trend is. When the axial compressive force is \( 0.5F_{co} \), the collapse pressure reaches the peak value.

2) When the dent depth is large, under the condition of small axial compressive force, the collapse pressure of the pipe remains generally unchanged with the increasing of the axial compressive force. When the axial compressive force reaches \( 0.5F_{co} \), the collapse pressure decreases promptly.

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