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Nonlinear finite element analysis of collapse and post-collapse behaviour in dented submarine pipelines

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ABSTRACT

The venture of oil and gas exploration into deeper waters has increased drastically in these recent years, as the shallow water fields approaching exhaustion. Large diameter pipelines installed in these areas are exposed to the severe pressure loading resulting from the water depth and any pre-installation damages sustained during transportation or pipelay and may reduce the collapse and buckle propagation resistance drastically. This work focuses on the utilisation and application of the finite element method as a robust and practical engineering tool to establish a methodology for analysing the effects of initial imperfections in the form of dents of various shapes and sizes on pipelines, sustained prior to pipelay, to determine the collapse pressure and buckle propagation pressure which can result in costly abandonments and unnecessary replacements. Comparison between the available theoretical closed-form simplified solutions available via 2D ring analogy, the experimental test conducted by various researchers on steel tubes, empirical formulations from past works and the analysis results obtained from this research were conducted, by incorporating the material plasticity, residual stresses and external pressure. The methodology employed herein provides a relatively realistic and practical assessment tool for computing the collapse and buckle propagation pressures of dented large-diameter submarine pipelines.

1. Introduction

The production of oil and gas from offshore fields are becoming very important with explorations moving further away from the shallow water into the deep water region. The main means of transporting these commodities from the wells are pipelines. Their use has increased over the past years due to their cost and energy saving features. The oil and gas flow through these pipelines from wellheads and manifolds at seabeds to platforms, ships or onshore facilities. Major oil and gas pipelines have typical diameters in the vicinity of 36–64 in., with typical diameter-to-thickness ratio of 40–80, and are designed to withstand the installation loads, operational loads and some one-off accidental design conditions such as object drop or impact. As a result of these severe conditions, the design of pipelines must consider these loading, during its construction, installation and in operation. The primary design load is the external pressure, due to the water depth, bending, thermal, fatigue, tension, compression, concentrated forces and impact loads. One of the most important aspects to be taken into account during pipeline design is the buckling phenomenon. Buckling on a pipeline occurs globally and locally. The local buckling or collapse can occur on a pipeline when the external pressure reaches the load carrying capacity of the pipeline. In this case, the pipe loses the roundness of its circumference, common during pipelay process especially at the sagbend region due to bending which may result in dents, coupled with external pressure, may cause the collapse to propagate globally across the pipe span, finally resulting in major reduction in fluid-carrying capacity. In the design of submarine pipelines, it is vital to determine the collapse pressure and the buckle propagation pressure. The current design codes and recommended practices available provide guidelines and selection criteria on the design collapse pressure and the diameter-to-thickness ratio (D/t) of pipelines for safe installation and operations. However, this may be inadequate when dealing with pipes with specific geometric imperfections or damages sustained during the laying, transportation or fabrication process. One countermeasure is the use of buckle arrestor rings, which is possible during the initial stage prior to pipe-laying. With current advent in computing power and its application to numerical methods, namely finite element methods, have opened up an opportunity for some further research into the determination of local collapse of pipes and the understanding of post-collapse behaviour of buckling propagation under external hydrostatic pressure present at great depths, and omit all unnecessary costs on abandonment and replacement of damaged pipes.

1.1. Buckling and collapse of pipes

The local buckling or collapse can occur on a pipeline when the external pressure reaches the load carrying capacity of the pipeline. This is especially more serious in absence of internal pressure, i.e. in an empty pipeline. In this case, the pipe looses the roundness of its circumference, common during pipelay process especially at the sagbend region due to bending which may result in dents, coupled with external pressure, may cause the collapse to propagate across the pipe span, finally resulting in loss of fluid-carrying capacity. This phenomenon has been reported and studied as far back as in 1858 by Fairbairn [1], where collapse experiments were conducted on cylindrical tubes to study the contributions of diameter-to-thickness (D/t) ratios and span length (L) of these tubes. This was then followed by the thin ring analogy by Levy [2] who concluded the critical external pressure applied circumferentially required to collapse this thin ring as:

$$P_{CR} = \frac{3EI}{r^3} \quad (1)$$

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Notation

D	pipe outer diameter
t	wall thickness
ν	Poisson's ratio
E	elastic modulus
E_T	tangent modulus
r	pipe radius
I	area moment of inertia
P	external pressure
P_{CR}	critical pressure
P_C	collapse pressure
P_o	yield pressure
P_P	propagation pressure
σ_o	material yield stress
σ_{UTS}	ultimate tensile stress
WD	water depth
ρ	density
f_o	initial ovality

The expression presented in (1) above was further improved to consider an infinite span pipe under plane strain condition by Bryan in 1888 [3] given by:

$$P_{\mathrm{CR}} = \frac{2E}{1-\upsilon^2}\frac{1}{(D/t-1)^3} \tag{2}$$

This is still within the elastic buckling limits and does not consider material yield stress and hardening effects, thus a more comprehensive approach was required. Kyriakides and Corona [4] have shown from [5,6] that a more realistic P_C estimate for an initially ovalized pipe can be found to be

$$P_C = \frac{1}{2}\{(P_o+\psi P_C) - [(P_o+\psi P_C)^2 - 4P_oP_C]^{1/2}\} \tag{3}$$

where

$$P_o = \frac{\sigma_0 t}{R} = \frac{2\sigma_0 t}{D}$$

$$\psi = \left(1 + 3f_o\frac{D}{t}\right)$$

and

$$f_o = \frac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}}$$

Palmer and Martin [7] have derived simple estimates of propagation pressure, following the collapsed rigid plastic ring theory as follows:

$$P_P = \pi\sigma_o\left(\frac{t}{D}\right)^2 \tag{4}$$

This problem was also later solved by Steel and Spence [8] with an empirical formulation from numerous experimental tests carried out on cylindrical tubes of various sizes and materials to include the effects of strain hardening of pipe material and provided a good correlation to experimental, given by:

$$\frac{P_p}{\sigma_o} = \frac{4}{\pi}\left(\frac{2t}{D}\right)^2\left[1.0 + 2.07\left(\frac{2t}{D}\right)^{0.35}\left(\frac{E_t}{\sigma_o}\right)^{0.12}\right] \tag{5}$$

Another such empirical expression which provides good fit to experimental outcome was presented by Kyriakides [9] from his extensive research on the subject of pipeline collapse and post-collapse propagation of buckles on pipelines, given by:

$$P = 39.25\sigma_o\left(\frac{t}{D}\right)^{2.5} \tag{6}$$

In the design of submarine pipelines, it is vital to determine the collapse pressure and the buckle propagation pressure. The current design codes and recommended practices available from DNV [10] and API [11] provide guidelines and selection criteria on the design collapse pressure and the diameter-to-thickness ratio (D/t) of pipelines for safe installation and operations. This, however, may be inadequate when dealing with pipes with $D/t > 45$, pipes with geometric imperfections or damages in the form of dents sustained during the laying, transportation or fabrication process.

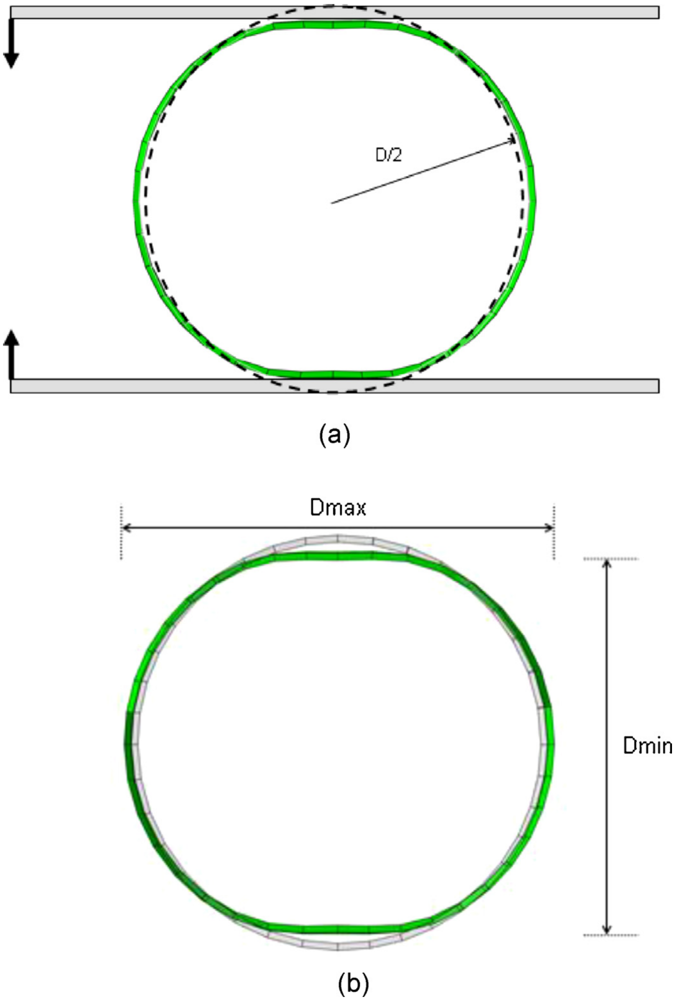

Fig. 1. (a) Initial imperfection in the form of forced flat denting on pipe section, and (b) ovality parameters definition [12].

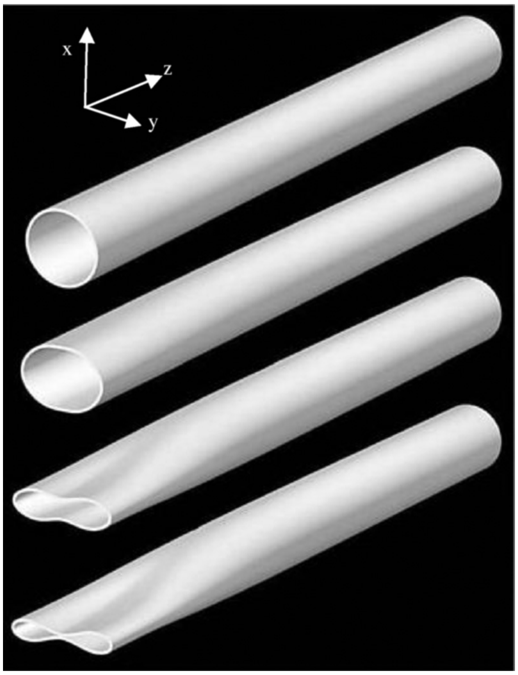

Fig. 2. Analysis sequence during denting, collapse and propagating buckle.