On the collapse propagation of thick-walled dented submarine pipelines

Michele A.L Martins[1], Caroline F.M. Netto[2], Theodoro A. Netto[2]

[1]*Laboratory of Scientific Computing and Visualization, Federal University of Alagoas*
Av. Lourival Melo Mota, Tabuleiro do Martins, Maceió-AL, Brazil
micheleagra@lccv.ufal.br
[2] *Subsea Technology Laboratory, Federal University of Rio de Janeiro*
Av. Athos Silveira, 149 - CT, Rio de Janeiro-RJ, Brazil
ferraz.caroline@lts.coppe.ufrj.br, tanetto@lts.coppe.ufrj.br

Abstract. Subsea pipelines are prone to structural instabilities, with collapse being the most critical failure mode, especially in deep-water environments. An eventual collapse can be rapidly propagated, damaging kilometers of the pipeline, with catastrophic impacts. In addition to high pressures, any damage that may occur due to impact, excessive bending, corrosion, and other causes during pipeline transport, installation and operation, can reduce the collapse and propagation pressure of the structure. Static buckling of pipelines under external pressure is a well-established subject in the literature and classical theories such as Timoshenko's provide reasonable estimates of the buckling threshold under some conditions. The accuracy of these predictions is particularly good for long, thin tubes, but when it comes to damaged thick-walled pipelines, there is a gap of knowledge and a lack of information regarding the post-buckling behavior of such pipes. Thus, this work aims to present a comprehensive study on the collapse propagation of thick-walled dented submarine pipelines based on experimental analysis, numerical models and a parametric study to cover several scenarios of interest.

Keywords: Propagating collapse; thick-walled pipelines; dynamic propagation.

1 Introduction

The industry faces significant challenges in oil and gas production at ultra-deep waters. Subsea pipelines operating in these harsh environments are subjected to extreme pressures, demanding robust design and operational considerations. As a minimum requirement, a subsea pipeline must be designed to account for various potential failure modes and relevant conditions expected throughout its operational life (e.g. installation loads, operational loads, and accidental conditions such as object drop or impact). Focusing on structural design, as external pressure becomes the most critical design load, one of the most important aspects to consider is buckling instability. The loss of stability can often result in two catastrophic outcomes: local buckling and buckle propagation. In such cases, the pipe loses its circular cross-section, undergoes excessive deformation, and the buckle can propagate along the pipeline. Without proper arrest of buckle propagation, this can lead to catastrophic pipeline collapse.

Understanding the conditions leading to buckling and propagation is essential to prevent or mitigate the consequences of these failures. Therefore, it is important to determine the collapse pressure, as well as understand the post-collapse behavior and to quantify the buckle propagation pressure. To better understand and describe the post-collpase and buckle propagation behavior of thick-walled dented pipelines, this work presents numerical model analysis together with a parametric study encompassing several relevant design variables, such as diameter-to-thickness ratio, dent geometry, material properties, and damage symmetry.

2 Buckling and collapse propagation of pipes under external pressure

The buckling of pipelines under external pressure is a well-established subject, with numerous studies published over the past century (Fairbairn [1], Tassoulas *et al.* [2], Kyriakides *et al.* [3]). These studies aim to deepen the understanding of the mechanics governing buckling and collapse propagation in subsea pipelines. Various factors, including combined loads (Corona [4], MacDonald *et al.* [5]), plasticity effects (Corradi *et al.* [6], Fatt [7]), installation methods (Estefen [8], Haghighi [9], Sriskandarajah *et al.* [10]), damages and imperfections (Fan *et al.* [11], Ong *et al.* [12], Park and Kyriakides [13]), manufacturing processes (Kyriakides *et al.* [14]), and corrosion (Netto *et al.* [15], Netto [16]), significantly influence both the buckling pressure and collapse propagation pressure.

Several studies have also focused on thick-walled pipes. Zhang and Pan [17] investigated the collapse of thick-walled subsea pipelines with imperfections subjected to external pressure using the finite element method. The authors examined the effects of the ovality and the thickness eccentricity on the collapse pressure and suggested new collapse pressure formula which includes both the ovality and thickness variation of the imperfect pipe. They also highlights that the formula presented at the DNVGL-ST-F101[18] underestimates the collapse pressure when the diameter-to-thickness ratio is less than 20. Once collapse of thick pipes is dominated by yielding, Corradi *et al*. [6] argued that available theories on the imperfection sensitivity of thin shells are not applicable to thick pipes and that current empirical formulas are conservative. Their research contributed to understanding the impact of imperfections on the load-bearing capacity of thick-walled pipes, concluding that ovality is the most critical imperfection, while other effects can be treated as secondary corrections.

The buckling pressure of a thin-walled pipe with linear-elastic material can be derived from the classical method as eq. (1), which considers an infinite span pipe under plane strain condition:

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

where E is the Young Modulus and ν is the Poisson's ratio of the pipe material, t is the pipe thickness and D_0 is the mean external diameter. This is still within the elastic buckling limits and does not consider material yield stress and hardening effects. Considering the imperfection, the collapse pressure of pipes with initial ovality can be given by eq. (2):

$$P_{co} = \frac{1}{2}\left\{(P_0 + \mu P_c) - [(P_0 + \mu P_c)^2 - 4P_0P_c]^{\frac{1}{2}}\right\} \tag{2}$$

$$P_0 = 2\frac{\sigma_0 t}{D_0}, \tag{3}$$

$$\begin{gathered} \mu = 1 + 3\Delta_0\frac{D_0}{t}, \\ , \end{gathered} \tag{4}$$

$$\Delta_0 = \frac{D_{\max} - \mathrm{D}_{\min}}{D_{\max} + \mathrm{D}_{\min}}, \tag{5}$$

where P_0 is the yield pressure, σ_0 is the yield stress, Δ_0 is the pipe ovalization and $D_{\max}$ and $\mathrm{D}_{\min}$ are the pipe cross section maximum and minimum diameters of the ovalized pipe, respectively. The classic formula presented above do not fully consider the material and geometrical nonlinear properties.

For thin-walled pipes that buckle elastically, such formula can be used to predict the collapse pressure. However, for thick-walled pipes, the main failure modes are plastic buckle and collapse, thus such prediction will not be realistic. To adequately analyze the collapse of thick-walled pipelines, several studies have been conducted that focus specifically on these conditions (He *et al.* [19]). Additionally, numerical models and simulations can be employed to provide more accurate predictions of the collapse behavior, accounting for factors like material plasticity and complex geometries.

Once buckle has occur, under certain conditions, it can be propagated through the pipe span. Regarding the buckle propagation, Kyriakides (1994) [14] conducted several experimental analysis and concluded that the development of the buckle propagation occurs when the pipe is subjected to the action of a sufficiently high external pressure and when the buckle is be initiated somewhere along the length of the structure. The lowest pressure at which an initiated buckle will propagate is defined as the propagation pressure of the pipe. Thus, a propagating buckle can occur at pressures $P_p < P < P_{co}$.

3 Numerical model

To enhance our understanding of the behavior of thick-walled, dented pipelines under external pressure, we developed and validated a finite element model. This model is designed to predict both local buckling and buckling propagation pressures resulting from external pressure loads. Utilizing this model, we conducted several parametric analyses to investigate the behavior of the pipes and the impact of initial damage deformations along with key design parameters on pipe collapse.

The employment of a numerical model is critical for accommodating the complexities involved, including material plasticity, excessive deformation, contact, imperfections, variations in wall thickness, and residual stresses. Numerical treatment of these factors allows for a more accurate prediction of buckling limit states in thick, dented pipelines. The developed finite element model incorporates non-linearities in contact, material, and geometry, which are crucial for precise predictions.

Input files for the analysis were generated using a parametric generator, allowing for variations in pipe geometry (including ovalization) and mesh densities. The geometry under study was a 2220 mm axisymmetric pipe with a diameter of 219.1 mm and an initial ovalization of 0.0008. We considered several geometric parameters in our parametric study: the diameter-to-thickness ratio (D/t), spherical dent diameter ratio (d/D), and dent displacement ratio (δ/D). Figure 1 illustrates all the parameters considered.

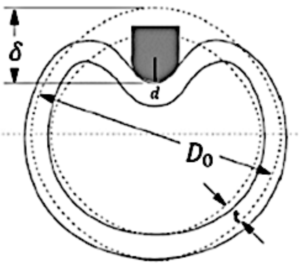

Figure 1. Cross section of the dented pipe

We examined three different diameter-to-thickness ratios (10.6, 15.3, and 19.7), two spherical dent diameter ratios (0.4 and 1.6), and two dent displacement ratios (0.2 and 0.4). The material was assumed to be a J2-type elastoplastic with isotropic hardening. The material properties, defined in Tab. 1, were determined from a uniaxial tensile test conducted at the Subsea Technology Laboratory at the Federal University of Rio de Janeiro.

Table 1. Material properties of the pipe

Property	Value
E [MPa]	193796.43
ν	0.3
σ_0 [MPa]	474.45

The simulation process encompassed denting, collapse, and buckle propagation, using ABAQUS [20] version 6.14-1 on a Core i7-processor computer. The model accounted for symmetry in the x, y, and z directions with boundary conditions that restricted circumferential displacements, allowing only longitudinal ones. Solid elements (C3D27R, 27-node brick elements with reduced integration) were employed for the pipe, while indenters and the modeled vessel were simulated using rigid bodies and R3D4 3D quadrilateral discrete rigid bi-linear elements. All contact interactions between the pipe and indenters, as well as internal face self-contacts, were managed using surface-to-surface and smooth contact definitions in ABAQUS.

The analyzed pipe section was discretized into 30 elements in the axial direction and 20 in the circumferential direction. A finer mesh was used for the section containing the dent, roughly one tube diameter in length. The analysis followed three steps: indentation, indentation unload, and static analysis. The denting process involved incrementally prescribing the displacement of the rigid indenter until the desired depth was reached, followed by its incremental unloading. Subsequently, a pressure load was applied to the dented tube by introducing a volumetric flow rate into a fluid cavity between the pipe and a modeled rigid vessel. Figure 2 depicts the sequence of events considered.

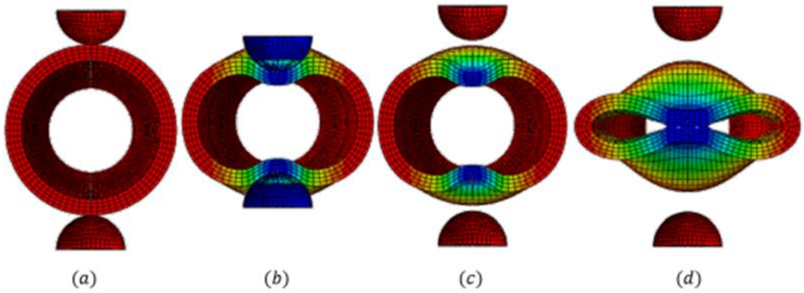

Figure 2. Analyses steps: (a) initial configuration; (b) indentation; (c) indentation remove; (d) pipe colapse and propagation

This methodical approach allowed us to capture the full range of the pipe's response from initial buckling to post-buckling behavior and ultimately, collapse propagation across the pipe span.

4 Results

A comprehensive parametric study was conducted to assess the influence of various parameters, including the diameter-to-thickness ratio, spherical dent diameter ratio, and dent displacement ratio, on the behavior of the pipes. Table 2 summarizes the cases analyzed. The relationship between pressure and volume variation effectively describes the collapse behavior of these pipes. This study also explores how such imperfections influence the buckling and propagation pressures.

To simulate damage, indentations were applied to mimic the type of damage that might occur on the pipeline's outer circumference during transportation, reeling, or other pipelay operations, as well as from collisions or equipment drops. Different sizes of dents were simulated using two diameter ratios ($d/D = 0.4$ and $d/D = 1.6$) and two displacement ratios ($\delta/D = 0.2$ and $\delta/D = 0.4$). The analysis involved a static step to apply the indentation, followed by a second step to remove the indenter, leaving the pipe with residual stresses from the damage. A third step involved applying a gradual external pressure load via a fluid flux, leading to pipe collapse.

As expected, the results indicate that increased ovalization - resulting from larger dent displacements and indenter diameters - significantly reduces the buckling pressure. This relationship is depicted in Figs 3, 4, and 5, which show graphical results for all three diameter-to-thickness ratios examined.

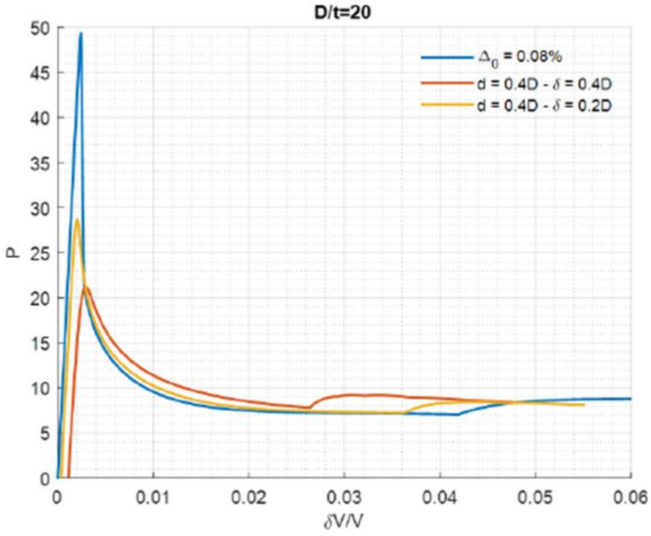

Figure 3. Pipe volume variation due to external pressure load application for $D/t = 19.74$

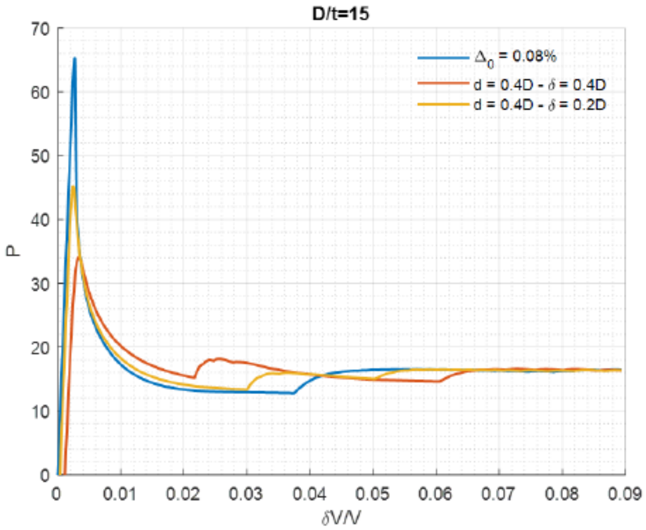

Figure 4. Pipe volume variation due to external pressure load application for $D/t = 15.32$

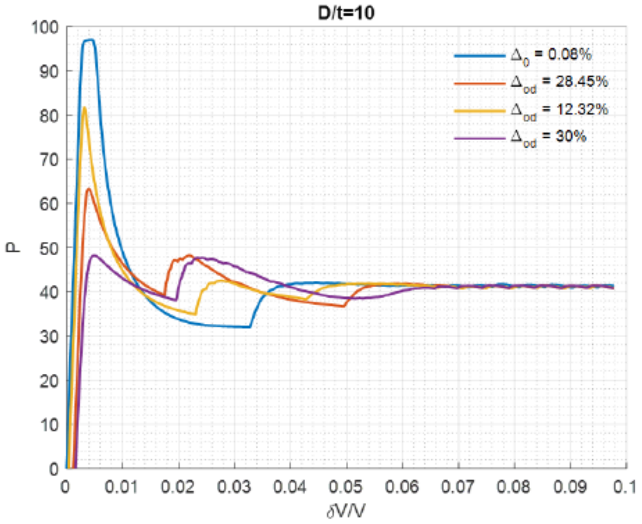

Figure 5. Pipe volume variation due to external pressure load application for $D/t = 10.64$

Following the initial buckling, the continuous increase in pressure leads to buckle propagation, where the collapse spreads rapidly across the pipe span. The propagation pressure (P_p) is considerably lower than the collapse pressure (P_{co}), and it is monitored by observing the volume changes in the fluid-filled cavity. This behavior is clearly illustrated in Fig. 6 for a pipe with a $D/t = 10.64$; $d/D = 0.4$ and $\delta/D = 0.4$.

A notable observation from the results is that despite different levels of imposed ovalization and damage size, the propagation pressure remains consistent, indicating that it represents the minimum energy required to promote buckle propagation after the opposite faces of the pipe contact each other. Particularly in the post-buckling phase, after the pressure drops due to buckling, it reaches a minimum level and then begins to rise again as the inner surface of the pipe contacts. The buckle then propagates at a nearly constant pressure throughout the pipe span. This phenomenon, well documented in the literature, was confirmed for pipes with D/t ratios of 15.32 and 19.74.

An interesting feature observed in the results for the $D/t = 10.64$ pipe (Fig. 5) is that following buckle occurrence and pressure drop, the pipe undergoes additional energy deformation before propagation occurs. This additional energy is necessary to achieve the correct cross-sectional configuration for propagation, resembling a 'dog bone' shape. Following this, a new zone of instability is observed, and the pressure again drops, eventually reaching the level required to propagate the buckle. It is important to note that even under conditions of significant denting, the propagation pressure remains consistent, demonstrating the robustness of this dynamic propagation model under various damage scenarios.

The comprehensive data from these studies are presented in Tab. 2, which details the geometric parameters of the pipe and modeled cases, including the initiation pressure (P_i) and propagation pressure (P_p).

Table 2. Geometric parameters of the pipe and modeled cases

Case	D_0 [mm]	D/t	δ/D	d/D	P_i	P_p
1	219.1	19.74	0.0	0.0	49.38	8.75
2	219.1	19.74	0.2	0.4	28.67	8.64
3	219.1	19.74	0.4	0.4	21.14	8.64
4	219.1	15.32	0.0	0.0	65.30	16.37
5	219.1	15.32	0.2	0.4	45.13	16.37
6	219.1	15.32	0.4	0.4	34.05	16.37
7	219.1	10.64	0.0	0.0	97.05	41.41
8	219.1	10.64	0.2	0.4	81.21	41.41
9	219.1	10.64	0.4	0.4	63.22	41.41
10	219.1	10.64	0.4	1.6	48.18	41.41

5 Conclusions

This paper aimed to enhance the understanding of the destabilizing effects of external pressure on pipelines. Finite element models, combined with a parametric study, were developed to assess the significance of various design variables and conditions concerning the collapse of thick-walled pipes with dents. Such dents can typically occur during fabrication, transportation, installation, or even during the operation stage. The study highlights the critical role of these variables in influencing the mechanical stability of pipelines.

Further extensive parametric analyses are currently ongoing to draw more robust conclusions. Future work will include the examination of different indenter shapes, a broader range of variations in the d/D and δ/D ratios, comparisons between isotropic and kinematic hardening laws, and the analysis of non-symmetric damaged cross-sections.

A deeper understanding of pipeline behavior under these conditions can lead to safer design practices and more cost-effective solutions in the event of damage. Proper assessment of buckling and comprehensive risk analysis can prevent the unnecessary abandonment of damaged pipes. Conversely, identifying severely dented pipes with the potential for catastrophic failure allows for timely removal from operation, thereby enhancing overall safety and integrity.

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