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Comparative study of assessment methods to predict the hydrostatic collapse of subsea pipelines with interacting corrosion defects

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Abstract. Assessing corroded subsea pipelines' structural integrity and risk management is a current challenge for the offshore industry. Corrosion defects are commonly distributed randomly along the subsea pipeline, leading to interactions between neighboring defects. Interacting corrosion defects play an important role in the evaluation of the collapse response of these pipes. So, this paper investigates the hydrostatic collapse of subsea pipelines with interacting corrosion defects through numerical analyses based on finite element models. The PIPEFLAW system, developed by the PADMEC (High-Performance Processing in Computational Mechanics) research group at UFPE (Federal University of Pernambuco), is used to generate 3D FE models and perform nonlinear analyses automatically. The analyses include subsea pipelines with dual corrosion defect configurations. A comparative study is carried out to estimate the collapse prediction, and different semi-empirical methods available in the literature are used together with a novel approach introduced in recent research. This approach subdivides the corrosion zone into sub-defects with an equivalent length, width, and depth. The findings demonstrate that this methodology performs better than traditional evaluation methods for predicting the collapse pressure of subsea pipelines with interacting corrosion defects. Thus, the novel approach contributes to more accurate and less conservative assessments and may become a practical tool for the integrity assessment of corroded pipelines in offshore environments.

Keywords: Subsea pipelines; Collapse Hydrostatic; Corrosion; Interacting defects.

1 Introduction

Subsea pipelines play an essential role in offshore hydrocarbon transport systems, enabling the continuous flow of oil and gas from subsea wells to processing facilities. Leakage from these systems may lead to operational downtime, significant economic losses, and environmental disasters [1]. In addition, anomalies such as corrosion pose serious threats to the safe operation of these pipelines [2].

Several theoretical, experimental, and numerical studies have been conducted to understand the collapse behavior of corroded subsea pipelines [3–9]. Among these efforts, the study of Netto *et al.* [4–6] stands out, as it analyzes different shapes and dimensions of isolated defects and proposes an empirical equation to estimate the collapse pressure associated with a single corrosion defect. More recent advances have incorporated elliptical geometries into the idealization of defects, resulting in new empirical formulations that better represent the conditions observed in the field [10].

In addition to isolated defects, the interaction between multiple corrosion defects has been the subject of investigation in recent years, since the proximity of corrosion defects can reduce the collapse capacity of subsea pipelines. Studies have explored this interaction through numerical simulations [9,11,12]. Wu *et al.* [12] proposed a formulation for predicting the collapse of pipelines with dual corrosion defects.

More recently, D'Aguiar *et al.* [13] presented a methodology for assessing collapse pressure with complex corrosion representing the corrosion region in sets of sub-idealized defects. For each sub-defect, the collapse capacity is evaluated by an empirical model, and the critical one is taken as the estimate for the collapse pressure

of the corroded pipe under consideration.

Given this context, this study aims to compare different semi-empirical methods available in the literature for predicting the collapse pressure of subsea pipelines with interacting corrosion defects. Specifically, the applicability of the novel approach proposed by D'Aguiar [13] is evaluated, aiming to understand its accuracy and limitations in comparison to traditional methodologies.

2 Finite element analyses

This study utilizes the PIPEFLAW system for Finite Element Analysis (FEA). Developed by the PADMEC (High-Performance Processing in Computational Mechanics) research group at the Federal University of Pernambuco (UFPE, Brazil), PIPEFLAW is a computational tool based on MSC.PATRAN software [14], which integrates several modules for automated FE model generation and nonlinear analysis using the commercial software ANSYS [15].

The discretization pattern adopted is described in detail by Cabral *et al*. [16,17]. The accuracy and precision of the models generated by PIPEFLAW have been demonstrated in several previous studies [9,11,13,16–21], including those conducted by D'Aguiar *et al*. [11,13] , which validated the PIPEFLAW system using experimental data from the literature for corroded subsea pipelines. The results indicated that PIPEFLAW accurately predicts the collapse of subsea corroded pipelines, with errors of less than 10% relative to experimental data, considering both single and interacting corrosion defects. A typical mesh generated by PIPEFLAW can be seen in Fig. 1 for an isolated rectangular defect [11].

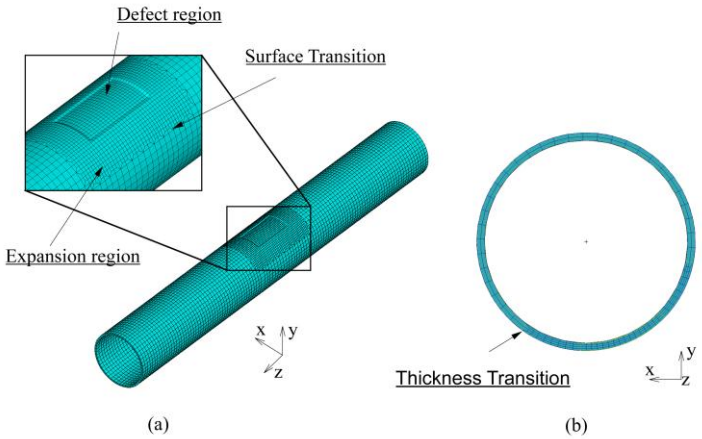


Figure 1. Mesh automatically generated by PIPEFLAW for a single defect: (a) External discretization and (b) Cross section of the middle of the pipe (center of the corrosion defect) [11].

3 Semi-empirical approaches

Semi-empirical methods are commonly employed to estimate the collapse pressure of corroded pipelines. These approaches typically represent corrosion defects using simplified geometric profiles, which approximate the actual irregular profile. As illustrated in Fig. 2, the most frequently adopted shapes include constant-depth (rectangular), elliptical, and parabolic shapes.

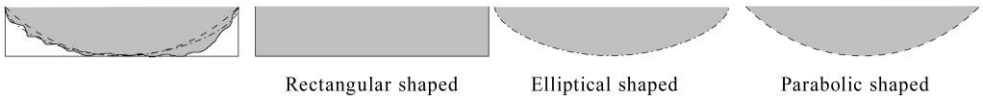


Figure 2. Schematic diagrams of idealized shapes

According to DNV [22], corrosion defects can be classified into three categories: single, interacting, and complex-shaped defects. A single defect is defined as one that does not interact with neighboring defects. Interacting defects occur when adjacent defects are close enough to interact, either axially or circumferentially. Complex defects consist of colonies of interacting defects or a single defect for which its real detailed profile is

obtained through inspection tools.

This study conducts a parametric analysis to compare collapse pressure predictions obtained from different semi-empirical methods available in the literature. The methods evaluated include: the approach proposed by Netto [4,6], developed for single defect with idealized rectangular shape; the model by Wu *et al*. [12], which accounts for interacting defects with simplified rectangular geometry; and the recent method introduced by D'Aguiar *et al*. [13], which incorporates detailed geometric profiles to assess complex-shaped corrosion.

3.1. Single corrosion defect

Netto, Ferraz, and Botto [6] and Netto [4] combined experimental and numerical efforts to investigate the collapse response of subsea pipelines with single corrosion defects. They pointed out that the geometry of the corrosion defect, its localization in the surface of the pipeline (internal or external), and its position relative to the ovalized cross-section influence the collapse capacity.

Netto [4,5] include a procedure for estimating collapse pressure based on experimental data and numerical results. The procedure focused on the most practical range of geometric parameters, specifically narrow and long defects. This methodology yielded the following equation:

$$\frac{P_{cor}}{P_{co}} = \left[\frac{1-\frac{d}{t}}{1-\frac{d}{t}\left(1-\left(\frac{c}{\pi D}\right)^{0.4}\left(\frac{l}{10D}\right)^{0.4}\right)}\right]^{2.675} \tag{1}$$

where P_{cor} is the collapse pressure of the corroded pipe, and P_{co} is the collapse pressure of the intact pipe, D is the nominal outer diameter, t is the thickness of the pipe, d is the corrosion depth, c is the corrosion circumferential width, and l is the corrosion length.

This procedure can be used as an effective tool to predict the collapse pressure of subsea pipelines with single corrosion defects (rectangular geometry). However, the equation has been calibrated for specific defect parameters, as follows [4,5]:

Shallow defects:	Moderately deep defects:	Deep and narrow defects:
$\left(0.1 \leq \frac{d}{t} \leq 0.2, \frac{c}{\pi D} \leq 0.1\right)$	$\left(0.2 < \frac{d}{t} \leq 0.4, \frac{c}{\pi D} \leq 0.1\right)$	$\left(0.4 < \frac{d}{t} \leq 0.6, \frac{c}{\pi D} \leq 0.2\right)$

For moderately deep defects, the maximum value of $\frac{c}{\pi D}$ is $0.15 - 0.25\frac{d}{t}$, whereas for deep and very narrow defects, it should be limited to 0.10-0.125$\frac{d}{t}$. In addition, further details can be found in Netto [4,5].

3.2. Interacting corrosion defects

Wu *et al.* [12] studied the collapse of subsea pipelines with interacting corrosion defects based on nonlinear finite element simulations. They provide the formulation for the collapse prediction of pipelines with identical dual corrosion defects. Their expression is a function of the geometric features and the axial and circumferential defect spacing, as described below:

$$\frac{P_{cor}}{P_{co}} = g\left(\frac{d}{t}, \frac{c}{\pi D}, \frac{L}{10D}\right) \cdot h\left(\frac{S_l}{D}, \frac{S_c}{\pi D}\right) \tag{2}$$

where P_{cor} is the collapse pressure of the corroded pipe, and P_{co} is the collapse pressure of the intact pipe. Based on finite element analyses, the functions related to the geometry of corrosion defects $g\left(\frac{d}{t}, \frac{c}{\pi D}, \frac{L}{10D}\right)$ can be expressed as:

$$g\left(\frac{d}{t}, \frac{c}{\pi D}, \frac{L}{10D}\right) = \left(b_1 + b_2\left(\frac{d}{t}\right)^{b_3} \cdot \left(\frac{c}{\pi D}\right)^{b_4} \cdot \left(\frac{l_c}{10D}\right)^{b_5}\right)^{b_6} \tag{3}$$

where $b_1 = 1.29$, $b_2 = 14.9$, $b_3 = 1.73$, $b_4 = 0.56$, $b_5 = 0.6$, and $b_6 = -0.99$.

Subsequently, the function to the axial and circumferential defect spacing $h\left(\frac{S_l}{D}, \frac{S_c}{\pi D}\right)$ in Eq. 2 can be obtained:

$$h\left(\frac{S_l}{D},\frac{S_c}{\pi D}\right)=\frac{\left(c_1+c_2\left(\frac{S_l}{D}\right)+c_3\left(\frac{Sc}{\pi D}\right)+c_4\left(\frac{S_c}{\pi D}\right)^2\right)}{\left(1+c_5\left(\frac{S_l}{D}\right)+c_6\left(\frac{S_c}{\pi D}\right)+c_7\left(\frac{S_c}{\pi D}\right)^2\right)} \tag{4}$$

where $c_1 = 0.9$, $c_2 = 0.42$, $c_3 = -7.08$, $c_4 = 19.65$, $c_5 = 0.44$, $c_6 = -8.25$, and $c_7 = 22.87$.

Equation 2 is applied only to a specific range of parameters: $\frac{d}{t} \leq 0.6$, $\frac{c}{\pi D} \leq 0.6$, $\frac{L}{10D} \leq 1$, $\frac{S_l}{D} \leq 5$, and $\frac{S_c}{\pi D} \leq 0.4$. Furthermore, Wu *et al.* [12] assessed the accuracy of this formulation for the collapse pressure of pipelines with multiple corrosion defects. They used equivalent parameters and obtained results with acceptable conservatism.

3.3. Complex corrosion defect

D'Aguiar *et al*. [13] introduced a novel approach aimed at reducing the conservatism of existing semi-empirical methods for predicting the collapse pressure of subsea pipelines corroded under external pressure. This approach is classified as a Level 2 approach for pipeline integrity assessment, according to the industry's usual categorization, which considers a detailed geometric corrosion profile.

The approach proposed by D'Aguiar *et al.* [13] shares conceptual similarities with the Effective Area Method [23], commonly used to estimate the burst pressure of pipelines under internal pressure. Both methodologies aim to approximate complex corrosion profiles using simplified and equivalent defect representations that can be incorporated into semi-empirical expressions. The author's [13] decompose the corroded surface into equivalent sub-defects, each characterized by a representative depth, width, and length. The procedure follows the steps described below:

1. The corroded region is discretized into sub-defects of varying dimensions.
2. The total number of sub-defects, N, is established based on the discretization points used to describe the corrosion profile. For realistic defects, this is typically derived from in-line inspection data.
3. For each sub-defect, the equivalent depth is determined from the estimated material loss volume and the corresponding equivalent length (l_{eq}) and width (c_{eq}).
4. The collapse pressure associated with each sub-defect is calculated using a semi-empirical formulation applicable to idealized isolated defects. D'Aguiar et al. [13] adopt the method proposed by Netto [4,5] (Eq.1).
5. The critical collapse pressure of the corroded section is defined as the minimum among the collapse pressures computed for all sub-defects.

Further details on the development and implementation of this approach can be found in the work of D'Aguiar *et al*. [13].

4 Comparative study

The novel approach proposed by D'Aguiar *et al*. [13] can predict collapse pressure relatively accurately for realistic corrosion defects. Here, based on numerical analyses, a comparative study is developed to prove that the present approach can be applied to predict the collapse pressure of subsea pipelines with interacting corrosion defects.

4.1. Extending the application range of novel approach

The finite element models of pipelines with two corrosion defects, as rigorously validated in D'Aguiar *et al*. [21], are used to verify the applicability of the novel approach proposed by D'Aguiar *et al*. [13], for subsea pipes with interacting corrosion defects. The pipe attributes of the pipeline are presented in Tab. 1. The fixed geometric parameters of corrosion defects are: $c/\pi D$ =0.3, l/D =1.0. Here, two different defect depths are used: d/t =0.3 (shallow defect) and d/t =0.5 (deep defect).

Table 1. Material properties and geometric parameters of the pipe.

E (GPa)	E' (MPa)	σ_y (MPa)	$\sigma_{0.5}$ (MPa)	N	D (mm)	D/t	Δ_o (%)
207	3047	410	450	13	323.85	20.4	0.1

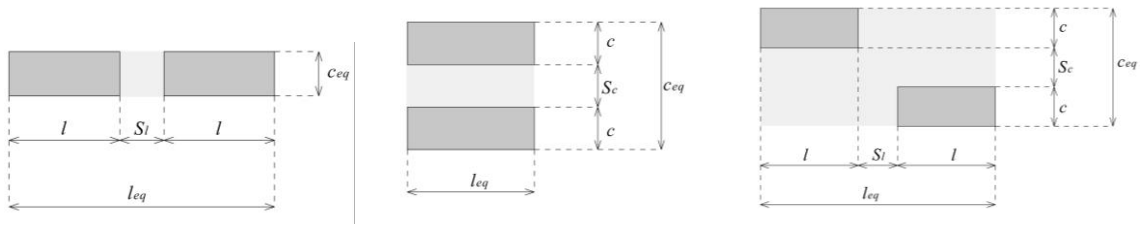
This paper focuses on dual identical corrosion defects (rectangular geometry) aligned longitudinally, circumferentially, and diagonally on the pipe's external surface, respectively. Table 2 presents the corrosion defect configuration with three categories of alignments. The normalized distances between defects, S_l/t (longitudinal distance) and $S_c/\pi D$ (circumferential distance), are specified for each configuration.

In addition, the novel approach results are compared against the ones obtained by the equation proposed by Netto [4,5] to predict the collapse pressure for a pipeline with a single corrosion defect (Eq. 1), and those obtained by the formulation developed by Wu *et al*. [12] for a pipeline with identical dual corrosion defects (Eq. 2). In Netto's equation, the corrosion defects are simplified into a single equivalent corrosion defect, as illustrated in Fig. 3.

In present study, the collapse pressure of the intact pipe (P_{co}) is obtained from formulation by the DNV [24] (P_{co} = 28.02 MPa).

Table 2. Corrosion defect configuration with different alignment.

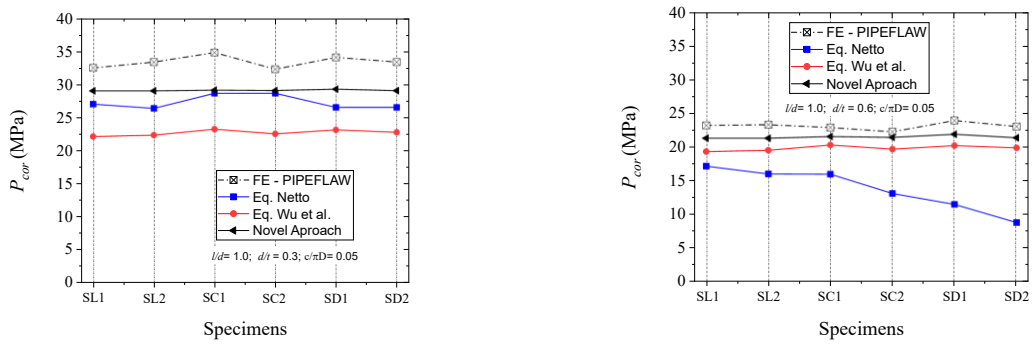
Specimen	Aligned type	S_l/t	$S_c/\pi D$
SL1	Longitudinal	20	-
SL2	Longitudinal	40	-
SC1	Circumferential	-	0.1
SC2	Circumferential	-	0.3
SD1	Diagonal	20	0.1
SD2	Diagonal	20	0.3



(a) (b) (c)

Figure 3. Simplification scheme for combining two corrosion defects into a single equivalent corrosion defect, considering various alignments: (a) longitudinal, (b) circumferential, and (c) diagonal.

Figure 4 presents the comparison between the collapse pressure obtained using FE numerical simulations via PIPEFLAW (reference), the collapse pressures predicted from the different semi-empirical approaches, and the novel approach proposed by D'Aguiar *et al.* [13]. This latter provides estimates closer to the numerical results, especially for cases with more severe defects (Fig. 4b). The results obtained using the expressions proposed by Netto [4,5] and Wu *et al*. [12] tend to be more conservative. Fig. 4b shows that Netto's equation underestimates collapse pressure more significantly as defect depth increases (d/t = 0.6), indicating its potential sensitivity to defect geometry. In this situation, it has a steeper decreasing trend than other approaches, particularly for SC and SD specimens, suggesting an overestimation of defect severity in these cases.



(a) (b)

Figure 4. Comparison of semi-empirical methods and the FE analyses for predicting the collapse pressure of pipelines with two corrosion defects: (a) $\frac{d}{t} = 0.3$ and (b) $\frac{d}{t} = 0.6$.

Figure 5 shows the distribution of the relative error for the three methods for assessing the collapse capacity of pipelines with corrosion defects. The relative error is calculated based on the reference results obtained via numerical simulations (3D FE – PIPEFLAW). The box plot allows for comparing the accuracy and dispersion of the relative errors of the evaluated approaches.

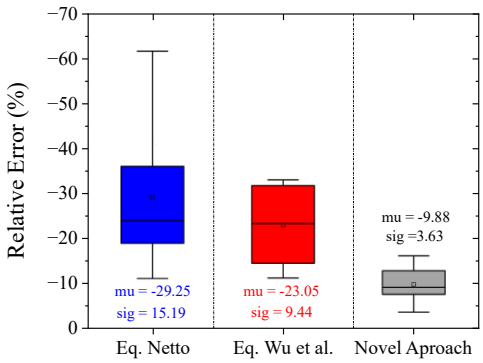


Figure 5. Distribution of Relative Error for the analyzed methods.

As previously noted, the semi-empirical equations of Netto [4,5] and Wu *et al*. [12] underestimate the collapse pressure, with mean percentage error values of -29.25% and -23.05%, respectively. In addition, both methods exhibit a significant dispersion of the results, evidenced by the standard deviations: 15.19% [4,5] equation) and 9.44% [12].

In contrast, the novel approach by D'Aguiar *et al.* [13] showed superior performance, with an average percentage error of −9.88% and low dispersion (standard deviation of 3.63%). These results demonstrate precision and accuracy in estimating the collapse capacity compared to traditional methods. The results show that the novel approach effectively predicts the collapse pressure in pipelines with interacting corrosion defects, highlighting its high potential for practical application for the assessment of pipelines with multiple defects in arbitrary corrosion configurations.

5 Conclusions

This paper highlighted the practical applicability of the novel approach proposed by D'Aguiar *et al.* [13] for predicting the collapse pressure in subsea pipelines with corrosion defects. The methodology demonstrated excellent performance in scenarios with interacting defects, significantly expanding its field of application. These findings underscore the potential of this approach as an accurate and robust tool for evaluating pipeline integrity in offshore environments.

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