An investigation on the collapse pressure prediction of subsea pipelines with realistic corrosion defects

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Abstract. Subsea pipelines are widely used for oil and gas transportation, but they are susceptible to failure mostly due to corrosion. Corrosion in pipelines typically results in defects of varying depths and complex shapes. Computational simulation using the finite element (FE) method is one of the most efficient and accurate way for assessing the integrity of corroded subsea pipes. This paper evaluates the collapse response of subsea pipelines with realistic corrosion defects. The study uses the PIPEFLAW system - developed by the PADMEC (High-Performance Processing on Computational Mechanics) research group from Federal University of Pernambuco - which automates FE model generation and performs nonlinear analyses. After validation based on the experimental tests available in the literature, the effect of realistic corrosion defects on the collapse pressure of subsea pipelines is analyzed in detail. The FE realistic solutions are compared against results obtained using a semi-empirical method and numerical results obtained considering idealized FE models. It is observed that the non-uniformity of defects is an important factor affecting the collapse response of pipes. In addition, the idealized geometry of the corrosion defects, especially when considering constant depth, leads to an excessively conservative prediction of the hydrostatic collapse.

Keywords: Subsea pipelines; Corrosion; Collapse response.

1 Introduction

Predicting the hydrostatic collapse of subsea pipelines is one of the main aims for designing new pipelines or reassessing lines in operation [1]. Corrosion is a leading cause of offshore pipeline failure [2]. Several authors have carried out theoretical, experimental, and numerical studies to evaluate the collapse of subsea pipes with geometric idealized corrosion defects under external pressure [3–11].

Netto et al. [1,2] evaluated the collapse response considering different shape and size of corrosion defects and proposed an empirical equation to estimate the collapse pressure of pipes with a single idealized corrosion defect. More recently, a new empirical equation has been provided to predict the collapse pressure of corroded pipelines considering an elliptical geometry to the defects [3].

The literature mentioned is fundamental to understanding the influence of the geometry of the corrosion defect on the failure mechanisms and collapse modes. However, corrosion is a complex and random electrochemical reaction process [12], and results based on corrosion defects with geometric idealized may be overly conservative. So far, there has been rare investigation on subsea pipes with irregular-shaped or complex-shaped defects.

In this work, three-dimensional FE models are created to simulate the collapse of corroded pipelines with a more realistic geometry of the localized corrosion profiles. The collapse pressure predictions are compared to the numerical and analytical results obtained for pipes with idealized corrosion defects.

2 Finite element analyses

Numerical analyses are performed using the PIPEFLAW system [4], developed by the PADMEC research group at the Federal University of Pernambuco (UFPE, Brazil). PIPEFLAW is a tool based on the MSC.PATRAN [5] program that allows the automatic generation of finite element models of pipelines with idealized and complex corrosion defects. This system has been ascertained to be accurate and reliable in previous studies available in the literature [4,6–11].

2.1 Model generation and discretization

The meshes used in this paper are considered 3D hexahedral solid elements generated by the PIPEFLAW system. More details of the automatic generation process are described in Cabral et al [4,6].

2.2 Load and boundary conditions

The FE models analyzed here are subjected only to external pressure. The pipeline modeling length is kept 10 times the diameter to avoid the boundary effects on the accuracy of the collapse analyses. The symmetrical boundary conditions are imposed to fix the displacements in the longitudinal direction (Fix *Z*) at the ends of pipes. Moreover, the displacements in *θ* direction are restricted to prevent rigid body motion. Figure 1 shows the loads and boundary conditions applied.

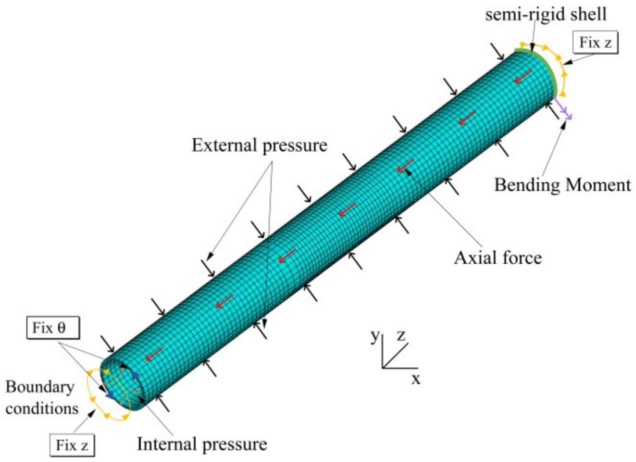


Figure 1. Loads and boundary conditions in the pipeline allowed by PIPEFLAW [12]

2.3 Nonlinear analyses

The nonlinear finite element analyses are performed using the commercial ANSYS software [13]. Riks method (arc-length algorithm) [14] was adopted to provide the full equilibrium solution and predict the collapse.

2.4 Material properties

The modified Ramberg-Osgood (R-O) model, defined by Gong et al. [15], is adopted in this paper. The mechanical properties of the material used in validation examples are as follows: $E = 200$ GPa, $\sigma_y = 198.2$ MPa, $n = 8.9$, $E' = 2400$ MPa, $\sigma_{0.5} = 252.8$ MPa (yield stress at a strain of 0.5%).

2.5 Validation

Seven experimental tests and numerical calculations carried out by Gong et al. [3] are used to validate the accuracy of the automatic procedure for FE modeling and simulation. Figure 2 shows the typical PIPEFLAW FE models with different corrosion defects.

(a) Elliptical defect TD10

(b) Rectangular defect – TD12

Figure 2. FE model automatically generated by the PIPEFLAW program.

Table 1 presents the dimensions of the investigated pipes - the outer diameter (*D*) and the wall thickness (*t*) – and the geometric defects parameters for each pipe - length *(l),* depth (*d*), and circumferential width (*c*). The predicted results of the collapse pressure are also listed in Table 1: present solution (PIPEFLAW FE) and reported solutions in [3]. The results predicted by the PIPEFLAW FE simulations are in excellent agreement with the experimental data. The maximum relative error is less than 3%.

Table 1. Geometric properties and comparison of collapse pressure between experimental tests and FE analyses.

Specimen	Defect Shape	*D* (mm)	*t* (mm)	*l/D*	*d/t*	*c/πD*	Exp.[3] (MPa)	FE[3] (MPa)	FE PIPEFLAW (MPa)
TD1	Elliptical	89.08	4.50	1.0	0.3	0.05	22.40	22.31	21.75
TD2	Elliptical	89.01	4.50	1.0	0.4	0.05	21.78	21.60	21.32
TD3	Elliptical	88.89	4.50	1.0	0.5	0.05	19.87	20.33	20.34
TD4	Elliptical	89.00	4.50	1.0	0.6	0.05	18.29	18.68	18.41
TD9	Elliptical	88.94	4.50	1.0	0.6	0.025	20,13	19.92	19.89
TD10	Elliptical	89.00	4.50	1.0	0.6	0.075	17,19	17.79	17.27
TD12	Rectangular	89.03	4.50	1.0	0.3	0.05	20.45	20.54	20.92

3 Realistic corrosion defects

In this section, FE models are developed to represent corroded pipelines with realistic and idealized shapes. The idealized FE models are simplified by elliptical and rectangular geometries, considering the maximum corrosion depth, as demonstrated in Figure 2.

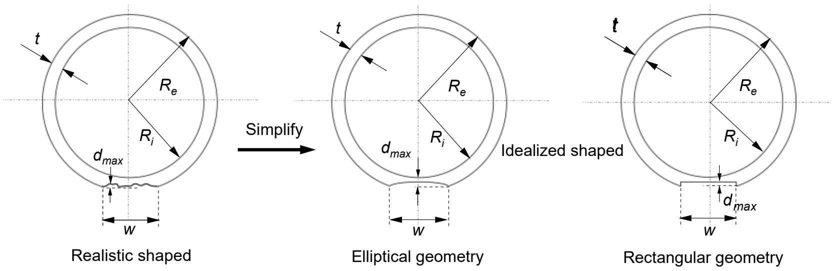


Figure 2. Realistic and idealized shaped corrosion defect (Adapted from [16])

Table 2 lists the geometric parameters used in the FE analysis of corroded pipes (Adapted from [17]). The

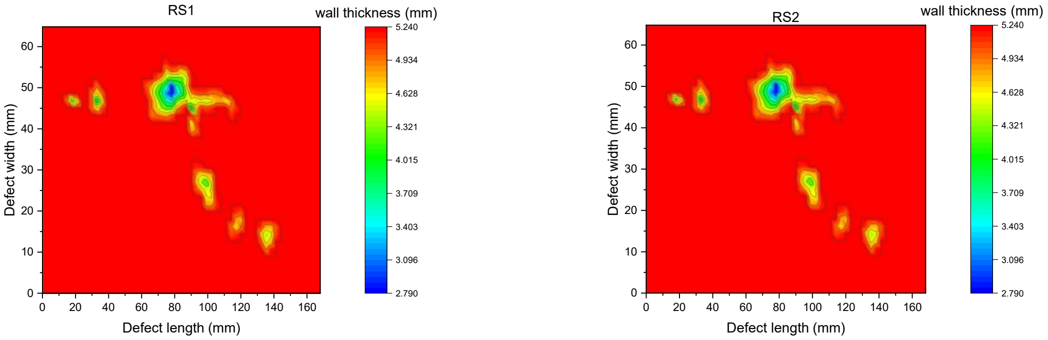
X65 steel grade is adopted, and the fit parameters for the stress-strain curve are listed [3]: E = 207 GPa, σ_y = 410 MPa, n = 13, E' = 3047 MPa, $\sigma_{0.5}$ = 450 MPa.

Table 2. Geometric characteristics of pipe and defects

Specimen	D (mm)	t (mm)	Δ_0 (%)	l (mm)	d_{max} (mm)	d_{mean} (mm)	c (mm)
RS1	135	5.24	0.1	134,40	2.620	0.04	64.80
RS2	135	5.24	0.1	168.00	2.440	0.04	64.80
RS3	135	5.24	0.1	236.00	2.620	0.06	80.00
RS4	210	8.20	0.1	142.00	3.400	1,63	117.00

The PIPEFLAW system requires mapping the corrosion points and their remaining wall thicknesses to generate FE models of the pipelines with realistically shaped corrosion defects. More details on the realistic model generation process are available in [11].

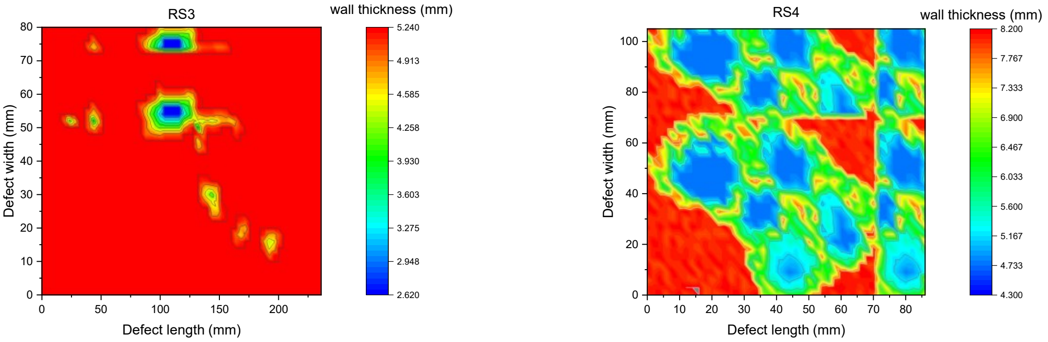
Figure 3 and Figure 4 shows the contour plots generated from the corroded region mapping data for specimens. In the cases illustrated, the maximum value found in the thickness matrix of corrosion zone points is the nominal thickness of the pipe wall (t), and the minimum thicknesses are equivalent to t-d_{max}.



(a) Specimen RS1

(b) Specimen RS2

Figure 3. Contour plot generated from the corrosion data (RS1 and RS2).



(a) Specimen RS3

(b) Specimen RS4

Figure 4. Contour plot generated from the corrosion data (RS3 and RS4).

The FE results are compared to the results obtained from the semi-empirical equation proposed by Netto [2], defined as:

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

where P_{cor} is the collapse pressure of the corroded pipe, and P_{co} is the collapse pressure of the intact pipe. This equation was calibrated for a combination of parameters. More details are available in Netto [2].

The collapse pressure of the intact pipe (P_{co}) can be calculated using the DNV [18] equation, as follows:

$$\left(\frac{P_{co}}{P_{el}}-1\right)\left(\frac{{P_{co}}^2}{{P_y}^2}-1\right) = f_o\frac{D}{t}\frac{P_{co}}{P_y} \tag{2}$$

in which P_y us the yield pressure and P_{el} is the elastic buckling pressure estimated respectively as:

$$P_y = f_y\,\alpha_{fab}\,\frac{2t}{D} \tag{3}$$

$$P_{el} = \frac{2\,E\left(\frac{t}{D}\right)^3}{1-\nu^2} \tag{4}$$

where f_y is the yield stress, ν is the Poisson coefficient, and α_{fab} is the fabrication factor (adopted 0.85).

Figure 5 illustrates the FE model automatically generated by PIPEFLAW program for specimen RS4. The FE meshes automatically generated based on the mapping data for specimens is appropriate.

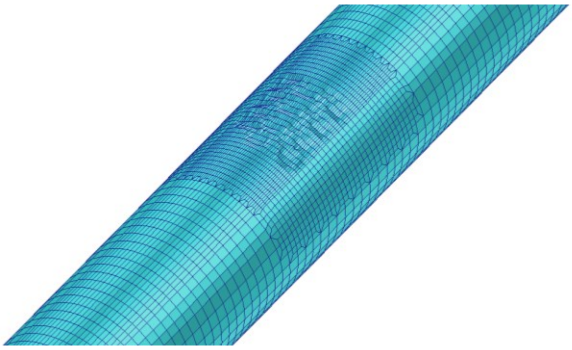


Figure 5. FE model of pipe with realistic corrosion defect (Specimen RS4).

Figure 6 summarizes the collapse pressure obtained numerically (realistic and idealized forms) and from the semi-empirical equation proposed by Netto [10]. The collapse pressure is calculated analytically based on the maximum and mean depth of the defect.

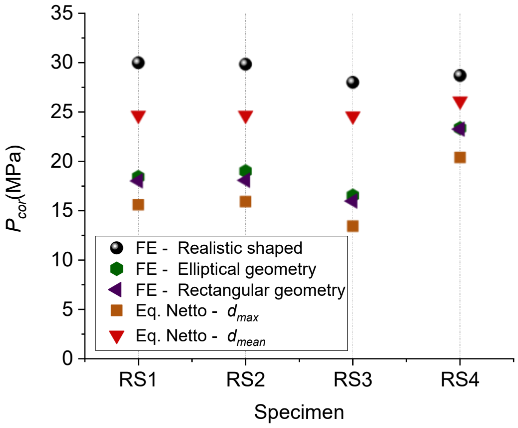


Figure 6. Summary of the collapse pressure results obtained.

As expected, the results obtained from the defect's idealization are conservative and in favor of safety. There was no significant difference between the idealized FE models (elliptical and rectangular) for these cases. However, FE models with elliptical geometry possess larger collapse pressure. Previous studies [3] have observed that the larger the defect size, the more significant the difference between elliptical and rectangular models.

The collapse pressure calculated from the Netto equation [2] based on the mean depth showed good agreement with the realistic FE results. In contrast, the collapse pressure calculated based on the maximum defect depth is excessively conservative but agree well with the idealized FE results.

4 Conclusions

In this work, based on numerical analyses initially validated from experimental results, it is possible to evaluate the hydrostatic collapse of subsea pipelines with idealized and realistic corrosion defects. The main conclusions of this study are:

- The non-uniformity of realistic defects is an important factor affecting the collapse response of pipes, confirming the highly conservative predictions of idealized models.
- The equation proposed for Netto [2] is consistent and agrees well with numerical results. Additionally, the results show that it is reasonable to calculate the collapse pressure based on the mean depth of the defect. However, additional studies must be conducted to evaluate its applicability, considering other cases of realistic corrosion defects.

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