23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

ASSESSMENT OF DNV-RP-F101 METHOD IN ESTIMATING THE FAILURE PRESSURE IN CORRODED PIPELINES

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Abstract. *Pipelines are efficient means to transport oil, natural gas, ethanol and derivatives. As they are in direct contact with the soil, buried pipelines may be subjected to corrosion defects. Corrosion is one of the most common causes of pipeline damage. Once the defect has been detected, the associated failure pressure must be evaluated. The objective of this work is to evaluate the degree of conservatism of the method of DNV-RP-F101 code for corroded pipes when subjected to internal pressure for different dimensions of corrosion defects. The adopted methodology estimates the failure pressure for pipes containing wall-reduction corrosion defects. These analytical results are compared to numerical results provided by finite element analyses. In order to validate the numerical model, experimental results provided by Choi et al. (2003) will be used. In that work, seven API-X65 pipes containing wall reduction defects with varying length, width and depth have been burst by internal pressure. Due to its conservativeness, the rectangular geometry has been adopted for the defect, and its variables are length, depth or width. Also, the ASME B31G semi-empirical method has been used to estimate failure pressures of corroded pipes to provide support for the analyses using the DNV method. In general, for long defects, the DNV method provides accurate results when compared to finite element analysis results. However, such results are less conservative than those provided by the ASME B31G. Considering short defects, it appears that results depend on the defect depth. Further investigation is required.*

Keywords: *pipelines, corrosion defects, DNV-RP-F101 method, ASME B31G method, finite element analysis.*

1. INTRODUCTION

Pipelines are used to transport petroleum and derivates. Pipelines efficiently run through different types of terrain from production sites in order to supply consumers. Over time, they become susceptible to damage. There are several causes for defects in pipelines. They can occur at the time of the construction of the pipeline or throughout its operation. Among the many defects that can occur in pipelines, the most common form is corrosion. Corrosion defects are responsible for affecting the lifetime of a pipeline, causing small leaks that are difficult to detect due to the small amount of oil being lost, and even complete rupture. Thus, this paper aims to contribute to the field of pipeline engineering in order to overcome the potential risk that pipelines present to the natural balance by preventing damage and minimizing the risks of environmental disasters and financial losses.

Corrosion is a common form of degradation in pipelines that reduces the strength of a pipeline. It is the transformation of a metal or metal alloy due to its chemical or electrochemical interaction in a given exposure environment. It may occur on the inner and outer surfaces of the pipe, the foundation material, the welding seam, the circumferential welding and/or the associated heat affected area. The pipeline, like other metal structures, deteriorates over time. In this case, the loss of metal in the cross section will result in a reduction of the operation efficiency and the safety of the pipe (Cosham et al., 2007).

When evaluating corrosion, the effect of its continuous growth should be considered to determine if a corroded region should or should not be left in service. After inspection, the need for intervention in order to carry out repairs to ensure continued use of the system is determined. Therefore, measures such as an appropriate inspection program should be adopted to prevent the growth of corrosion (DNV-RP-F101, 2004).

Assessment methods are needed to determine the severity of such defects when they are detected in pipelines. Corroded pipelines should be evaluated with respect to the maximum allowable pressure. Thus, once the corrosion is observed, the failure pressure for that situation should be evaluated, calling for assessment methods to determine the severity of these defects. To assess the failure pressure in corroded pipelines, among the different methodologies found in literature, we can name the ASME criteria (American Society of Mechanical Engineers), or B31G method, Rstreng0.85dL (Modified B31G method), the RPA (Rectangular Parabolic Area) method, or 0.85dL modified, the DNV-RP-F101 (Det Norske Veritas) method or DNV method, and finally, the PCORRC method.

This paper aims at assessing the degree of conservatism of the DNV-RP-F101 method in estimating the failure pressure for corroded pipelines when subjected to internal pressure load for different dimensions of corrosion defects.

The technical basis for the formulation of this defect evaluation method in corroded pipelines was created from a project guideline developed in cooperation between BG Technology and DNV (Det Norske Veritas), along with other organizations and sponsors, including PETROBRAS. The methodology used evaluates corroded pipelines. The DNV method employs the ultimate strength rather than the yield strength as a failure mechanism controller. The methods provided in the DNV-RP-F101 document are intended to be used in case of corrosion defects on carbon steel pipes (not applicable for other components).

The DNV-RP-F101 document provides recommendations for assessing pipelines containing corrosion defects when they are subjected to internal pressure alone, and to internal pressure combined with longitudinal compressive stresses in the following combinations of load/stress and defects: internal pressure for single defect, interacting defects and complex defects, unlike the internal pressure approach combined with the longitudinal compressive stress for single faults alone. The evaluation process is only applicable to steel pipelines that are expected to fail by plastic collapse. To calculate the work pressure, the DNV method estimates the eroded pipeline failure pressure based on a safety factor. However, this factor is not in the scope of this study.

In this paper, only pipelines containing a single corrosion defect and subjected only to internal pressure are evaluated. Details not covered in this study are not discussed here, and the reader can find them in the DNV-RP-F101document (DNV-RP-F101, 2004). To assess the failure pressure of the corroded pipelines, a parametric analysis study is conducted. In this case, the failure pressure estimated by the DNV method will be compared to the solutions provided by the B31G method and by finite element analyses.

Furthermore, a study of the configuration of the required finite element mesh is carried out. As benchmark, a study by Choi *et al*. (2003) is adopted as reference where experimental full scale tests were performed on API-X65 steel pipelines containing seven different defect geometries.

2. SEMI-EMPIRICAL METHODS

The semi-empirical methods employed in this work to estimate the failure pressure of single corrosion defect pipelines subjected to internal pressure are ASME B31G and DNV-RP-F101. The former considers short and long defects, and presents different formulations for each one as follows in equations (1) to (4).

For short defects:

$$l \leq \sqrt{20.D.t} \tag{1}$$

$$P_f = 1{,}1 \,.\, \sigma_{ys} \,.\, \left(\frac{2t}{D}\right) . \left[\frac{1-\left(\frac{2}{3}.\frac{a}{t}\right)}{1-\left(\frac{2}{3}.\frac{a}{t}.\left(\sqrt{1+0{,}8.\left(\frac{l^2}{D.t}\right)}\right)\right)}\right] \tag{2}$$

For long defects:

$$l > \sqrt{20.D.t} \tag{3}$$

$$P_f = 1{,}1.\, \sigma_{ys}.\left(\frac{2t}{D}\right).\left(1-\frac{a}{t}\right) \tag{4}$$

where P_f is the failure pressure, σ_{ys} is the material´s yield strength, l and a are the defect´s length and depth, respectively, and D and t are the outer diameter and wall thickness of the pipe, respectively. It is to be observed that the defect´s length l does not have any influence on the failure pressure of long defects.

Next, equations (5) to (8) describe the procedure for single corrosion defect pipeline failure pressure estimation according to the DNV-RP-F101 method:

$$P_{sw} = F.P_f \tag{5}$$

$$F = F1\,.\,F2 \tag{6}$$

$$P_f = \sigma_u.\frac{2.t}{(D-t)}.\left[\frac{1-\left(\frac{a}{t}\right)}{1-\left(\frac{a}{t}\right).Q^{-1}}\right] \quad (7)$$

$$Q = \sqrt{1+0{,}31.\frac{l^2}{D.t}} \quad (8)$$

where P_{sw} is the operational pressure, P_f is the failure pressure, σ_u is the material´s ultimate strength, *D* and *t* are the outer diameter and wall thickness of the pipe, respectively, and *l* and *a* are the defect´s length and depth, respectively. Further, *Q* is named corrosion factor while *F* is the safety factor comprised of a modeling factor *F1* and an operational factor *F2*.

3. FINITE ELEMENT MODELING

The effectiveness of a finite element mesh in computing the residual strength of corroded pipelines to estimate the failure pressure is assessed in this section. Numerical results are compared to experimental results provided by Choi *et al*. (2003). The ANSYS® program is used to perform finite element analyzes. The finite element used to model the problem is the 20 node three-dimensional isoparametric element (SOLID 186). The modeled pipeline is made of API-X65 steel, a standard material used for oil and gas pipelines, where API stands for American Petroleum Institute (API, 2000). The rectangular corrosion defect has length (*l*), width (*c*) and depth (*a*) as shown in Fig. 1.

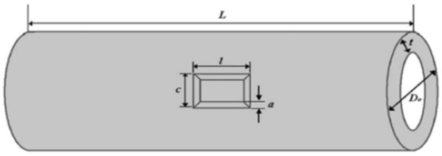

Figure 1. Pipeline with a rectangular shaped corrosion defect
Source: Choi *et al.* (2003)

Considering the symmetry of the pipeline and a centered defect, the finite element model consists of one-fourth of the damaged structure subjected to appropriate boundary conditions. The pipeline is loaded with internal pressure only. The analysis performed is nonlinear, resolved incrementally, leading the pipe to yielding. The material properties are Young's modulus, E = 203 GPa, Poisson's ratio, ν = 0.3, yield strength σ_{ys} = 468 MPa, and ultimate strength, σ_u = 673 MPa according to Choi *et. al* (2003).

Mesh configuration and refinement significantly affects the final result. As expected, the higher the degree of refinement, the more precise the solution will be. In the study of the appropriate configuration of the finite element mesh, two different mesh models were built; namely, a structured mesh and a non-structured mesh. Analyses were performed for the seven different defects that have undergone full-scale experimental tests, whose parameters and failure pressure estimates results are provided by Choi *et al*. (2003). In case the reader wants further information, details not provided here can be found in the original article referenced here. In the study, the pipeline is 2.3 meters long, and has an outer diameter of 762 mm, and a wall thickness of 17.5 mm. In the first case considered, the DA defect has the following dimensions: 200, 50 and 4.4 mm in length, width and depth, respectively. Figure 2 shows the two examples of finite elements mesh for the DA defect.

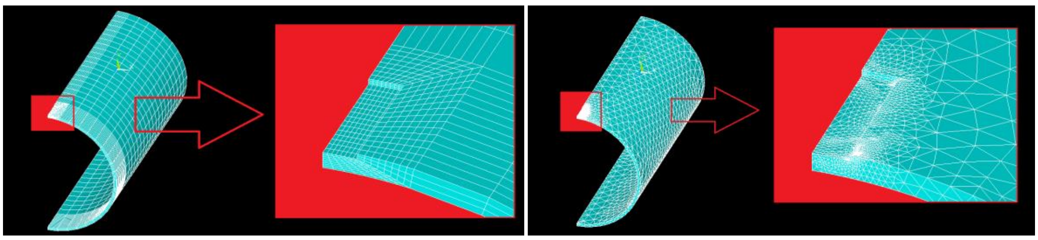

Figure 2. Typical structured and non-structured finite element meshes, and defect meshing details

According to DNV-RP-F101 method, failure will occur due to plastic collapse, and the failure pressure formulation is related to the ultimate strength of the material. Thus, the incrementally nonlinear analyses are performed until the first point in the model reaches this level of stress, when it is considered that failure has occurred. Fig.3 shows the stress distribution in the defect area for both structured and non-structured meshes, respectively, of the first specimen examined (DA).

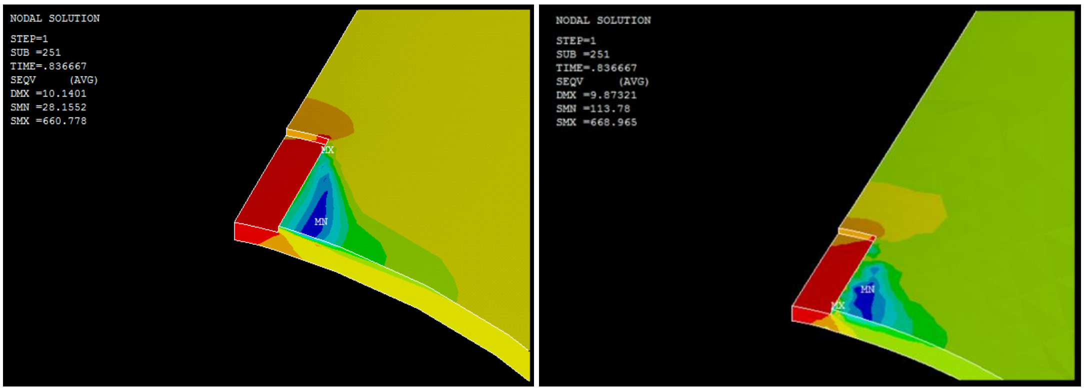

Figure 3. Comparison of structured and non-structured meshes stress distributions in the DA specimen defect

In Tab. 1 shows failure pressure values obtained by the experimental test of Choi *et al*. (2003), as well as the corresponding values estimated by the semi-empirical methods ASME B31G, DNV-RP-F101, and by finite element analyses employing the two different mesh models. The table also shows percent errors of each method with respect to the experimental values, regarded as reference values.

Table 1. Comparison between failure pressure estimates by B31G, DNV, FEA and experimental results (P_{TEST}).

Pipe	Failure pressure (MPa)					Percent Error			
	P_{TEST}	P_{B31G}	P_{DNV}	P_{FEA} Structured Mesh	P_{FEA} Non-Structured Mesh	P_{B31G}/P_{TEST}	P_{DNV}/P_{TEST}	P_{FEA}/P_{TEST} Structured Mesh	P_{FEA}/P_{TEST} Non- Structured Mesh
DA	24.11	21.62	28.87	25.10	25.10	10.3%	19.7%	4.1%	4.1%
DB	21.76	19.17	24.60	23.20	23.40	11.9%	13.0%	6.6%	7.5%
DC	17.15	16.20	17.17	20.70	18.40	5.5%	0.1%	20.7%	7.3%
LA	24.30	21.35	28.70	25.10	25.10	12.1%	18.1%	3.3%	3.3%
LC	19.80	18.08	21.97	20.70	20.90	8.7%	11.0%	4.5%	5.6%
CB	23.42	19.17	24.60	24.30	24.10	18.1%	5.0%	3.8%	2.9%
CC	22.64	19.17	24.60	25.00	23.60	15.3%	8.6%	10.4%	4.2%

L = 2.3 m, D_o = 762 mm, t = 17.5 mm.

An overall analysis of these results allows these authors to say that results provided by ASME B31G method are always conservative. On the contrary, results provided by DNV-RP-F101 method are non-conservative, which provides further motivation for the present study to assess such method. Further, regarding finite element analysis results, values are also non-conservative with respect to the experimental ones for both structured and non-structured meshes. Considering percent error values, these are averagely smaller when non-structured meshes are employed. This might indicate that non-structured meshes are more suitable for pipeline failure pressure analysis.

4. NUMERICAL ANALYSIS

This section describes a parametric study of failure pressure estimate for corroded pipelines with different defect dimensions to assess the applicability of the DNV-RP-F101 method. This is an attempt to establish if the method is sufficiently conservative to be safely used in industry. Results provided by ASME B31G method and by finite element analyses are used as reference values to assess the results provided by the DNV-RP-F101 method. ASME B31G method has been chosen for being widely known as a conservative method, while the finite element method may provide accurate results given appropriate meshes are employed.

The pipeline considered in the current analyses is 2.0 meters long, and has an outer diameter of 508 mm, and a wall thickness of 12.7 mm, and it is made of API-X65 steel whose strength properties are yield stress σ_{ys}= 448 MPa, and tensile strength σ_u= 531 MPa. The different rectangular corrosion defects present variable length (l), width (c) and depth (a). The defects in the study are characterized as isolated rectangular corrosion defects with depth variations that correspond to the ratio of 20%, 40%, 60% and 80% of the thickness of the original pipe wall. For the parametric analyses, defects are classified as short or long according to the ASME standard. Defects vary in length while maintaining their width constant for the four different defect depths considered.

The study consists of estimating pipeline failure pressures (P_f) for the many different corrosion defects to assess the degree of conservativeness of the DNV method. One hundred different geometry defects, considering variation in length and depth, are used in the study. Details of the defect dimensions are given in Tab. 2, as well as the respective values of failure pressure estimated by B31G, DNV and the finite element methods. For brevity, only results for 24 defects out of the 100 total analyzed are presented.

Table 2. Failure pressure estimate by B31G, DNV and FEA.

Analysis	Defect geometry				Defect type (ASME criteria)	P_f (MPa)		
	l (mm)	*c* (mm)	*a* (mm)	*a/t* (%)		B31G	DNV	FEA
57	300	150	2.54	20	SHORT	22.20	23.85	27.3
58	300	150	5.08	40	SHORT	19.57	19.76	24.0
59	300	150	7.62	60	SHORT	16.70	14.72	17.8
60	300	150	10.16	80	SHORT	13.57	8.34	10.6
61	320	160	2.54	20	SHORT	22.15	23.74	27.3
62	320	160	5.08	40	SHORT	19.47	19.55	23.6
63	320	160	7.62	60	SHORT	16.58	14.46	17.3
64	320	160	10.16	80	SHORT	13.43	8.11	10.2
65	340	170	2.54	20	SHORT	22.11	23.63	27.3
66	340	170	5.08	40	SHORT	19.39	19.36	23.5
67	340	170	7.62	60	SHORT	16.47	14.23	16.9
68	340	170	10.16	80	SHORT	13.31	7.92	9.8
69	360	180	2.54	20	LONG	19.71	23.54	27.4
70	360	180	5.08	40	LONG	14.78	19.19	23.2
71	360	180	7.62	60	LONG	9.86	14.02	16.6
72	360	180	10.16	80	LONG	4.93	7.75	5.9
73	380	190	2.54	20	LONG	19.71	23.45	27.2
74	380	190	5.08	40	LONG	14.78	19.04	22.9
75	380	190	7.62	60	LONG	9.86	13.84	16.3
76	380	190	10.16	80	LONG	4.93	7.61	9.2
77	400	200	2.54	20	LONG	19.71	23.37	27.2
78	400	200	5.08	40	LONG	14.78	18.90	22.7
79	400	200	7.62	60	LONG	9.86	13.68	16.0
80	400	200	10.16	80	LONG	4.93	7.47	5.9

In general, the B31G and DNV methods results are conservative with respect to the finite element method. That is, mostly the failure pressure values provided by those methods are lower than those provided by finite element analysis. However, this is not necessarily true for the deepest defects, that is, those which are 80% of the thickness of the pipe wall.

Among the 100 defects considered, 68 are short defects while the remaining 32 are long defects. An overall idea of the degree of conservativeness of a semi-empirical method might be provided by an average percent error with respect to reference values. Tab. 3 provides these average error values for B31G and DNV methods with respect to FEA (finite element analysis) for short and long defects.

Table 3. 1 Average 2percent error values for short and long defects.

	B31G/FEA	**DNV/FEA**
SHORT: 68 defects	12%	16%
LONG: 32 defects	29%	6%
100 defects	**18%**	**13%**

Results in Tab. 3 show that, considering all 100 defects, B31G method results are 18% smaller than FEA results, while DNV method results are 13% smaller than FEA results. When separating short and long defects, a general conclusion cannot be reached. For short defects, results show that DNV method is more conservative than B31G method whereas, for long defects, B31G is much more conservative.

Figures 4a to 4d show failure pressure variations with defect lengths for depth-to-thickness ratios of 20%, 40%, 60% and 80%, respectively, calculated by the three methods. These curves represent the results of the one hundred analyses performed, and allow for a better understanding of the behavior of the DNV-RP-F101 method with respect to the ASME B31G method and the finite element method.

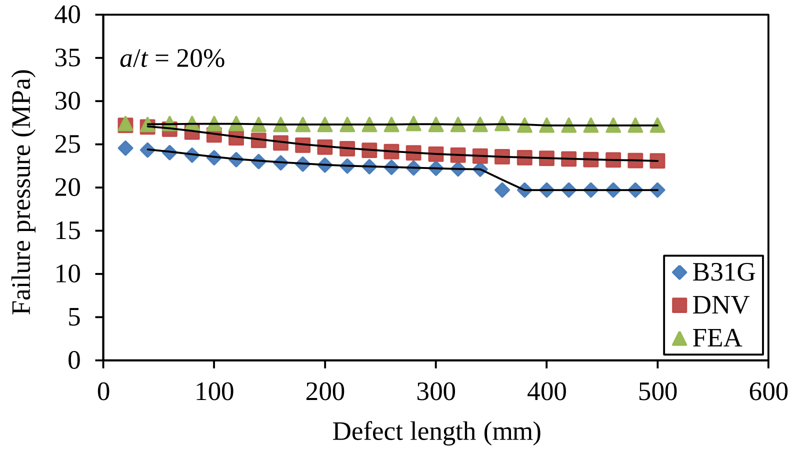

Figure 4a. Failure pressure versus defect length for a/t = 20%

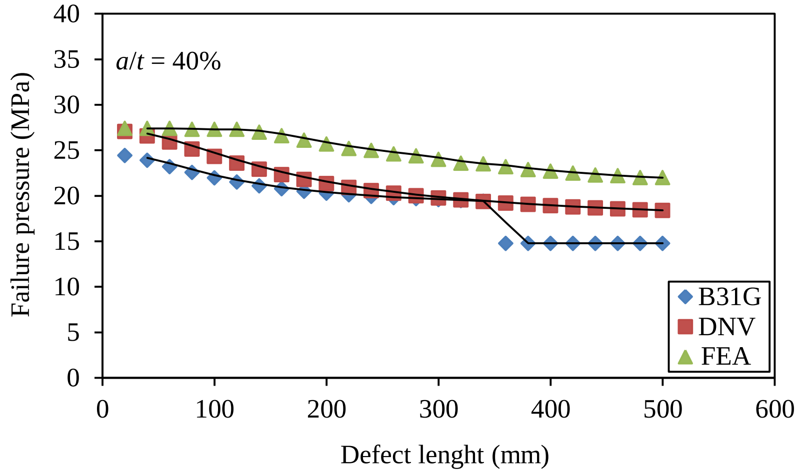

Figure 4b. Failure pressure versus defect length for a/t = 40%

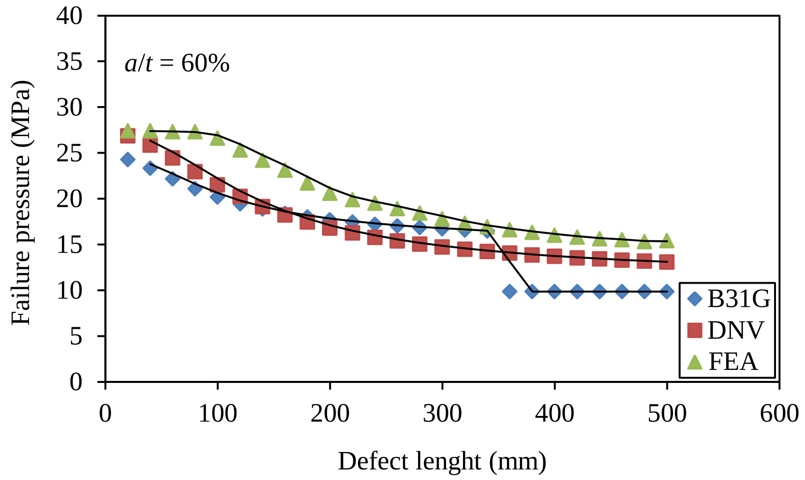

Figure 4c. Failure pressure versus defect length for a/t = 60%

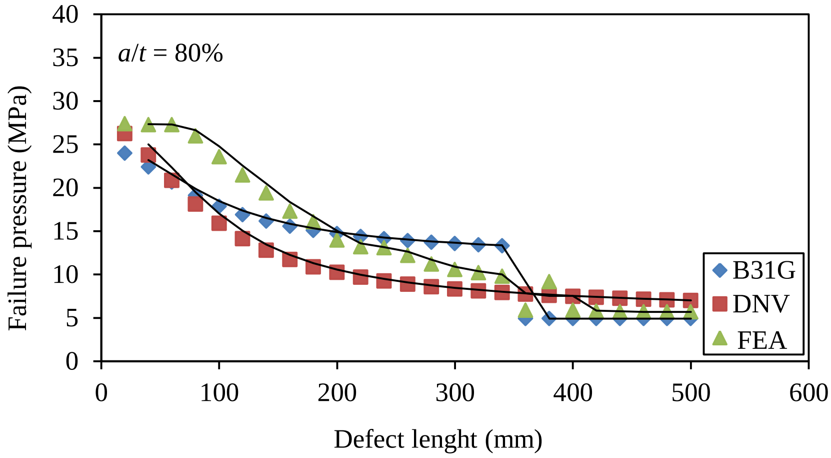

Figure 4d. Failure pressure versus defect length for a/t = 80%

The points plotted on the graphs correspond to the estimate failure pressure of the corroded pipeline for a given length of defect. The defects vary in 20 mm increments in length, according to the analysis. Without exception, the curves suggest a decreasing behavior of the function. It is observed that for a progressive increase in the defect length, the results show decreasing values of the failure pressure. That is, the longer the defect, a smaller internal pressure is required to cause failure. Also, failure pressure tends to decrease when the defect becomes deeper, which is also an expected behavior since less wall thickness is left to sustain loading. Furthermore, it can be observed that the curves become steeper with the increase in the depth of the defect. Thus, it is concluded in the study that the variation in thickness, *a*, and the length, *l*, of the defect considerably influence the failure pressure.

In the curves corresponding to failure pressure values estimated by DNV-RP-F101, it is observed that the values decrease in a uniformly distributed manner. This is a clear demonstration that the only expression for failure pressure of the DNV-RP-F101 method is sufficient to handle all lengths of defects. The same behavior is not observed in the B31G method. Curves show there is a rise in the separation threshold between a short defect and a long defect, with a constant behavior in the long defect. This is justified by the formulation that disregards the length of the defect as a dependent variable in estimating failure pressure for corroded pipelines.

Analyzing the results as whole, for the different depths of defect, it is observed that for very shallow defects (*a/t* = 20%), the finite element method showed very little variation in the failure pressure estimate values. It can also be seen that there is a change in the trend for the failure pressure values when the defect depth is 80% of the thickness of the pipe. Due to this identified change in behavior, it is suggested that other depths be investigated.

5. CONCLUSIONS

Corrosion defects that occur in oil and gas pipelines may grow to a level that may be enough to compromise the safety of the structure. Therefore, the careful design and maintenance of pipelines is essential. In this paper, an approach with the DNV-RP-F101 method was followed in order to analyze the degree of conservatism in the estimated failure pressure for corroded pipelines when subjected to internal pressure for different dimensions of corrosion defects.

As a particularity, the method presents a different approach, by using the tensile strength rather than the yield strength, as a failure control criterion. To evaluate the remaining strength in corroded pipelines, among the different methodologies, the B31G method, also known as ASME criterion, was chosen as a parameter. It was selected for being the pioneer and therefore a more conservative method.

For the pipeline being studied, analytical methods were compared to numerical computational solutions obtained by the Finite Element Method (FEM), using the ANSYS® program, in the estimation and behavior of the failure pressure in the parametric study. The finite element method is employed as a comparison reference for, as well as being accurate, it allows the assessment of the semi-empirical methods used.

In the study, it was concluded that the variation of the thickness, *a*, and the length, *l*, of the defect considerably influence the rupture pressure. The width of the defect, *c*, however, has a negligible effect on the rupture pressure.

The failure pressure tends to decrease when the defect becomes deeper. The DNV method showed similar variation among different defect depths. However, for very shallow defects the finite element method showed little variation in the estimated values of failure pressure.

In general, the failure pressure estimates obtained by semi-empirical methods were found to be conservative when compared to the numeric computational simulations via the finite element method. The DNV method provides accurate results, however, by separating the analysis of short and long defects, it was observed that the DNV method is less conservative than the B31G method for long defects. In the case of short defects, further investigation is required.

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