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New Equation for Failure Pressure Estimation on Curved Pipelines

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Abstract. The present work aims to assess the influence of the curvature of the axis of corroded pipelines in their failure pressure. Corrosion is one of the major causes of incidents in pipelines, whose integrity is usually assessed through semi-empirical methods. When corrosion occurs in curves of pipelines, the literature on the influence of the pipeline curvature in the remaining pipeline strength is very limited. The use of curved pipelines arises from the need to overcome topological obstacles, being a solution commonly used to implement adjustments to segments of pipelines. The use of curves in pipelines is even more evident on off-shore pipelines, in which the installation process causes bending and curvature to the originally straight pipeline. The present study will simulate and obtain failure pressure in curves of corroded pipelines using Finite Element Analysis (FEA) provided by the PIPEFLAW software developed by PADMEC research group from UFPE. The results obtained will be compared to those found by using Lorenz Factor (LF) and Nepo Factor (NF), a newly proposed alternative factor to Lorenz Factor for failure pressure estimation on curves of corroded pipelines.

Keywords: curved pipeline, corrosion defect, Finite Element Method, Nepo Factor, Lorenz Factor.

1 Introduction

The calculations of failure pressure on corroded pipelines have always been one of the most important issues in structural integrity analysis. The use of curved pipelines occurs in several different occasions like pipeline construction, installation, topological and geometrical adversities and hydraulic conections, and requires specific calculations for its application to be done. The use of Finite Element Method (FEM) has been used as an accurate and precise tool, but it is expensive, which requires advanced softwares in order to automatize the process of modeling and analysis as stated by Cabral [1]. For curved pipelines, studies are limited and lacking, with some of the few ones available by Bubenik and Rosenfield [2], Lee [2] and Nepomuceno [3], regarding the use of a factor for 90° elbows, burst strength in subsea gas pipeline elbows and FEM automatic modeling and analysis for curved corroded pipelines, respectively.

With this in mind, the formulation of a new equation based on FEM results may be the solution for both accuracy, that lacks on empiric models, and speed, that lacks on full FEM models. This new equation, called Nepo Factor (NF), is based on the Lorenz Factor (LF) proposed by Bubenik and Rosenfield [2], accessed through the work written by Lee [2], using the same variables, but applying them in a way that the results are closer to those based on full FEM model.

The NF may be used as an alternative option to LF, since it is more accurate, and full FEM, since it is faster. It is important to notice that the use of full FEM modeling and analysis still is indicated for research and practical purposes since it is the most accurate method, which should not be fully replaced by the use of Nepo Factor.

2 Format instructions Methodology

To evaluate the behavior of corrosion in curves of pipelines, a series of parametric study was performed using three different approaches: fully FEM, LF and NF. The LF and NF results are based on the result of failure pressure in straight pipes via FEM, to compare the factors results to the FEM ones. This work uses the same parameters as Nepomuceno [3] in order to have reference values to compare and validate the results obtained. Table 1 below presents the parameters used: cross section diameter (Rm), wall thickness (t), defect depth (d), defect width (w), defect length (l), front fillet radius (FR), and top fillet radius (TR).

Table 1. FEM modeling parameters

R_m	t	d	w	l	FR	TR
0.3556	0.00635	0.00381	0.054	0.092	0.002286	0.006858

In order to access the NF results, a parametric study will be conducted. The parameters to be changed are: cross section diameter, wall thickness, and defect width. For each parameter, two values were considered as indicated in Tab.2. For each situation, 10 models were generated (five intrados, five extrados, which will be explained in section 2.2, and five curvature radius variations ranging from 0.955 to 2.865 m). A total of 60 models will be analyzed. Additionally, 6 straight corroded pipeline models, one for each parameter modification, were generated and analyzed in order to LF and NF be applied.

This was possible due to the PIPEFLAW software, provided by the research group PADMEC from Universidade Federal de Pernambuco – UFPE, that generates and analyzes automatically finite element models of straight corroded pipelines, and due to Nepomuceno [3] that generated a methodology for curved pipelines modeling using PIPEFLAW associated to Python codes. The parameters modifications are shown in the Tab. 2 below:

Table 2. Modified models parameters

Parameter	Value
Wall Thickness	0.00585
	0.00685
Cross Section Diameter	0.3056
	0.4056
Defect Width	0.049
	0.059

The results obtained by the 60 curved models are compared to those obtained by applying different LF and NF to results obtained by the 6 straight models. Graph and tables will show the final results comparing fully FEM, LF and NF.

2.1 Finite Element Method

As stated by Cabral [4], the FEM has been proved to be a great method to predict remaining strength in corroded pipelines, but the generation of proper computational models can take several days. This problem was solved by using the PIPEFLAW software, which automatically generates models of straight pipelines with ideal corrosion defects, associated with Python software, produced by the author, in order to modify the straight model into a curved one. More details regarding the FEM mesh and PIPEFLAW's automatic generation procedure can be found in Cabral [4]. The straight models generated by PIPEFLAW were validated by previously published works from Motta [5].

2.2 Lorenz Factor

Lee [2] says in his work that Bubenik and Rosenfield [2] have previously assessed corroded 90° elbows pipes and created an equation for the theoretical elastic stress distributions around the circumference of 90° curved pipelines, using curvature radius (Rb), cross section diameter (Rm) and defect position angle (α):

$$LF = \frac{{}^{R_b}/_{R_m} + {}^{\sin\ }/_{2}}{{}^{R_b}/_{R_m} + \sin\alpha}, \tag{1}$$

According to Lee [2] "The Lorenz Factor (LF) calculates the increase or decrease in the nominal stress in a curved pipeline relative to a straight one", as shown in the Fig. 1 below, in which σ_H is the nominal stress:

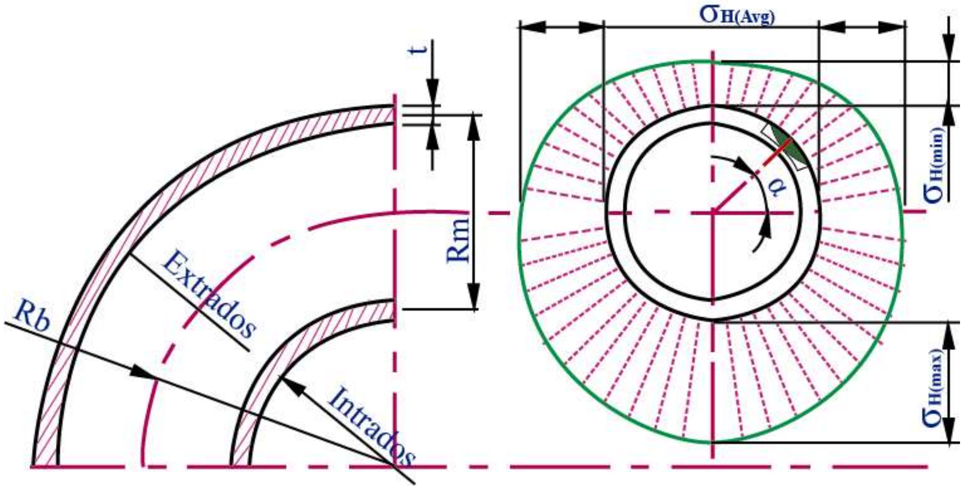

Figure 1. Nominal stress distribution in a 90º curved pipeline

The LF is used to obtain failure pressure on corroded curved pipelines. In figure 1 it is exposed that the Extrados and Intrados positions of the defect are the minimum and maximum values of nominal stresses, respectively. There is a big gap between LF and FEM results, as it is exposed by Nepomuceno [3], which motivated the Nepo Factor to be developed.

2.3 Nepo Factor

As will be shown the application of the LF to obtain the failure pressure in curves of corroded pipelines can give results there are very conservative or non-conservatives. Thus, the Nepo Factor (NF) was developed by modifying the Lorenz Factor eq. (1), in order to have results closer to the FEM ones. The equation is show below in two forms, one using LF as part of it, and one independent of LF:

$$NF = LF \times \left[1 + \frac{\sin\alpha}{4 \times {}^{R_b}/_{R_m}}\right] \tag{2}$$

$$or\ NF = \frac{{}^{R_b}/_{R_m} + {}^{3}/_{4} \times \sin\alpha + \frac{\sin^2\alpha}{8 \times {}^{R_b}/_{R_m}}}{{}^{R_b}/_{R_m} + \sin\alpha}. \tag{3}$$

Both LF and NF should be used as follows:

$$FP_c = FP_s/F, \tag{4}$$

in which FPc is the failure pressure of the curved pipeline, FPs is the failure pressure of the straight pipeline and F is LF or NF.

3 Results

Given the conditions stated in the methodology, some results are observed. The NF has shown a conservative behavior when compared to FEM and values for failure pressure were much more accurate than LF presents. The mean of the difference between FEM and NF was 0,22 and the variance was 0,04, while the mean of the difference between FEM and LF was 0,62 and the variance was 0,12. The Tab. 3 below list all failure pressures, including those of straight pipelines for LF and NF calculations:

Table 3. Failure Pressures

Parameter	Value	FPs (MPa)	Method	FPc (MPa)										
				Intrados (I)						Extrados (E)				
				Rb	955	1432	1910	2387	2865	955	1432	1910	2387	2865
wall thickness	0.00585	10,29	FEM		9,36	9,92	9,79	10,00	10,04	11,29	11,04	11,04	10,79	10,79
			LF		7,98	8,86	9,25	9,48	9,62	11,88	11,41	11,15	10,99	10,88
			NF		8,79	9,43	9,70	9,84	9,92	10,89	10,75	10,66	10,60	10,56
	0.00685	14,8	FEM		12,78	13,74	14,00	14,32	14,11	16,20	15,74	15,52	15,45	15,18
			LF		11,49	12,75	13,31	13,63	13,84	17,09	16,41	16,04	15,81	15,65
			NF		12,65	13,57	13,95	14,15	14,28	15,66	15,46	15,34	15,25	15,19
Outside Diameter	0.3056	14,14	FEM		12,63	13,20	13,44	13,63	13,67	15,99	14,76	14,53	14,49	14,49
			LF		11,51	12,49	12,94	13,19	13,36	16,06	15,48	15,17	14,97	14,84
			NF		12,49	13,18	13,47	13,62	13,72	14,89	14,71	14,60	14,52	14,46
	0.4056	11,32	FEM		9,75	10,70	10,96	11,18	11,22	12,45	12,28	12,11	11,92	11,88
			LF		8,33	9,49	10,00	10,29	10,47	13,28	12,70	12,39	12,19	12,06
			NF		9,30	10,20	10,55	10,74	10,85	12,02	11,88	11,78	11,70	11,65
Defect Width	0.049	12,76	FEM		11,25	11,79	12,00	12,52	12,25	13,84	13,57	13,34	13,15	13,20
			LF		9,90	10,99	11,48	11,75	11,93	14,73	14,15	13,83	13,63	13,49
			NF		10,90	11,70	12,03	12,20	12,31	13,50	13,33	13,22	13,15	13,09
	0.059	12,53	FEM		11,04	11,52	11,76	12,00	12,00	13,53	13,24	13,06	13,00	12,96
			LF		9,73	10,79	11,27	11,54	11,72	14,47	13,89	13,58	13,38	13,25
			NF		10,70	11,49	11,81	11,98	12,08	13,26	13,09	12,99	12,91	12,86

Table 3 also presents good evidence of NF being more accurate than LF, since the results show that NF, not only is closer to FEM than LF, but also is more conservative, maintaining failure pressures majoritarily lower than FEM indicates. This can also be seen in the Fig. 2:

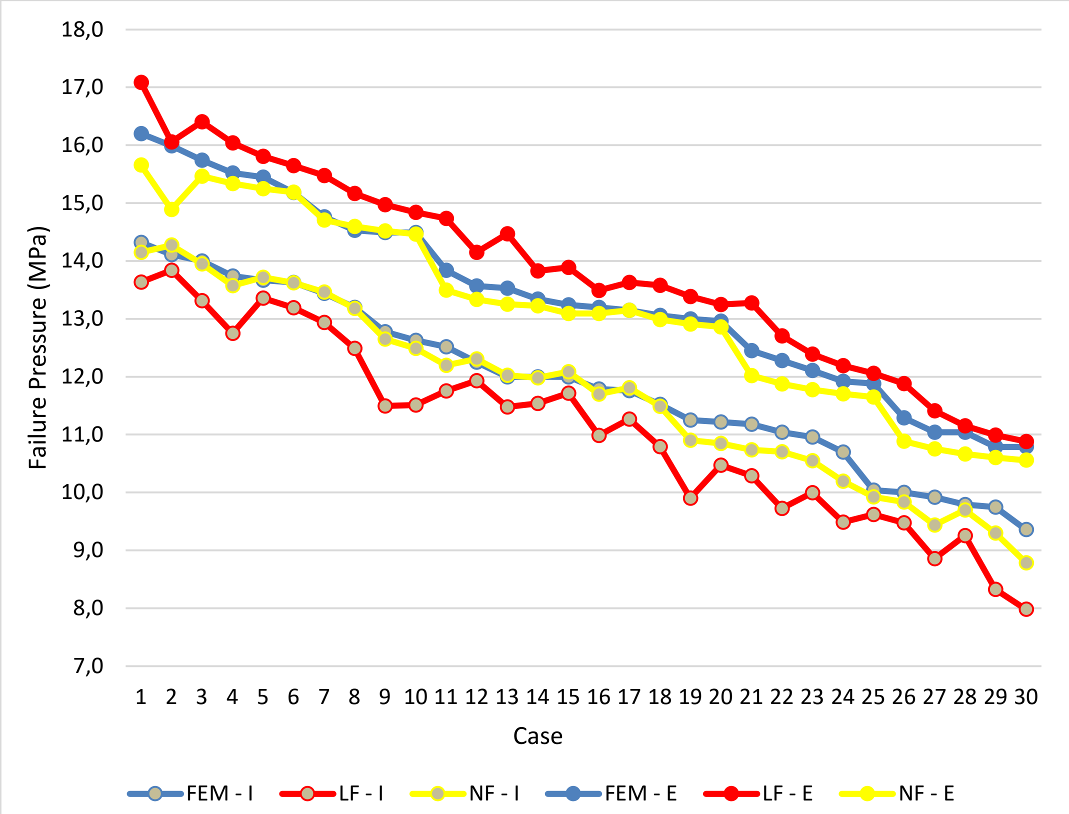

Figure 2. Failure pressures comparison

Figure 3 shows the behavior of a curved pipeline with different Rb/Rm proportions and through the different methods for failure pressure attaining. As expected, NF shows results closer to FEM and still conservatives, while LF's results

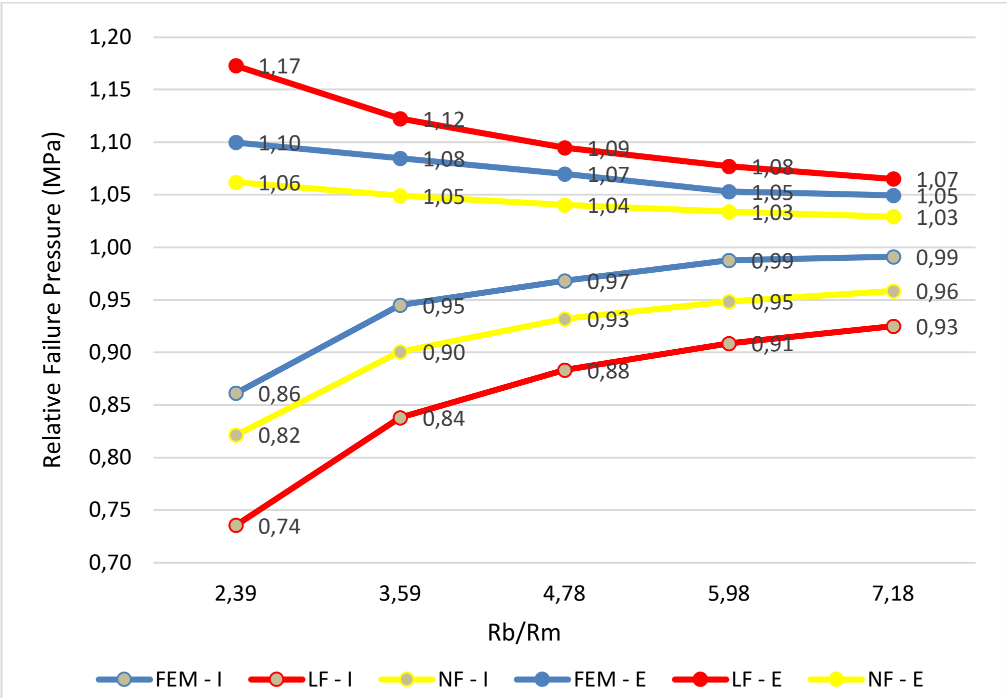

Figure 3. Curved pipeline failure pressure behavior

The relative failure pressure is calculated by dividing FPc by FPs. Thus, the relative pressure value of 1 represents the straight pipeline failure pressure.

4 Conclusions

In this work, the assessment of curved corroded pipelines, through finite element method and Lorenz Factor, was performed in order to validate Nepo Factor as an equation for failure pressure estimation in corroded curved pipelines. The obtained results suggest that Nepo Factor may be used as an alternative option to full FEM modeling and analysis and also is more accurate than LF. It is worth noting that NF should not be seen as a replacement to full FEM, but an additional method for curved pipelines failure pressure calculation and for validation of curved pipeline models.

In future works, it would be interesting to focus on studies regarding reliability methods applied to curved pipelines using FEM, LF and NF.

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