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# RELIABILITY ASSESSMENT OF CORRODED PIPELINES CONSIDERING THE REAL CORROSION PROFILE

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**Abstract.** *The use of computational tools to assess the structural integrity of pipelines with corrosion defects has made significant progress in recent years. These tools can evaluate pipelines models with simple idealized corrosion defects or pipelines with complex corrosion defects. Although the evaluations through the computational tools are accurate, their input data for the construction of the geometric model and the material properties have a certain degree of uncertainty that must be considered when assessing the structural integrity of the pipelines. The reliability analysis of corroded pipeline has been studied for the last 30 year and today is considered in standards code and is used in practice. But almost the totally of the literature in this issue is focused in defects with uniform depth, called idealized defects. In the present work the reliability analysis of corroded pipelines will be studied considering the real remain wall thickness profile of the pipe in the corrosion region (river bottom profile). In this work, the reliability analysis of the corroded pipelines will be performed using the FORM (First-Order Reliability Method). The structural integrity assessment (internal pressure capacity) will be computed via nonlinear numerical simulation (FEM – finite element method) of 2D axisymmetric pipelines models. The objective will be to compare the probability of failure using two geometries, the first will consider idealized defects and the second model will consider the river-bottom profile of the corrosion defect. The results shown that the consideration of the RBP can increase the reliability index between 10% and 40%.*

**Keywords:** *River-Bottom Profile, Reliability, FORM, Failure Pressure, Finite Element Analysis*

## 1. INTRODUCTION

The use of computational tools to assess the structural integrity of pipelines with corrosion defects has made significant progress in recent years. These tools can evaluate pipelines models with simple idealized corrosion defects (Motta et al., 2017) or pipelines with complex corrosion defects (Pimentel et al., 2015). Although the evaluations through the computational tools are accurate, their input data for the construction of the geometric model and the material properties have a certain degree of uncertainty that must be considered when assessing the structural integrity of the pipelines. The reliability analysis of corroded pipeline has been studied for the last 30 year and today is considered in standards code and is used in practice. But almost the totally of the literature in this issue is focused on idealized defects. In the present work the reliability analysis of corroded pipelines will be studied considering the real remaining wall thickness profile of the pipe inn the corrosion region.

Input parameters such as outside diameters (OD), wall thickness (t), maximum defect depth (d), defect length (L), specified minimum tensile strength (SMTS), specified minimum yield stress (SMYS) and design pressure ( $P_d$ ) have uncertainties linked to their measurements. In this work, a reliability analysis of pipelines with corrosion defects will be performed using the FORM simulations (First-Order Reliability Method), for that, we will consider the parameters mentioned above as random variables. The objective will be to compare the failure probability using two models, the first will be the creation of 2D axisymmetric pipelines models with simple defects and evaluated using Finite Element Methods (FEM) (Rodrigues et al., 2017) and the second model will use the 2D axisymmetric ducts with river-bottom profile corrosion defect and will also be evaluated using the Finite Element Method (FEM) (Cabral et al., 2019).

## 2. FAILURE PRESSURE THROUGH FINITE ELEMENT ANALYSIS

The failure pressure that will be used in the reliability analysis was obtained through simulation with two-dimensional finite elements analysis. Two types of defects will be evaluated, the first being idealized defects, where the entire corrosion region has the same depth, with the maximum defect depth being, as shown in Figure 1 (Rodrigues et al., 2017). The second is complex defects, using a river-bottom profile, as shown in Figure 2 (Cabral et al., 2019).

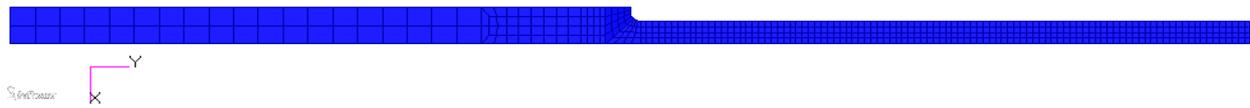


Figure 1. Two-dimensional model of the axisymmetric pipelines with idealized corrosion defect.

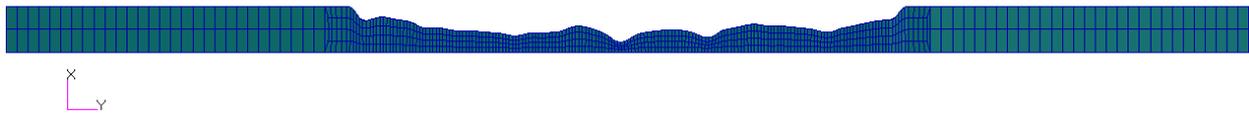


Figure 2. Two-dimensional model of the axisymmetric pipelines with corrosion defect of river-bottom profile.

### 2.1 Loads and boundary conditions

The models are loaded with internal pressure and their boundary condition is end-capped pipe (Figure 3 e 4). For the idealized model, the constraint at the end of the defect represents the symmetry of the model on the X axis, to decrease the computational cost.

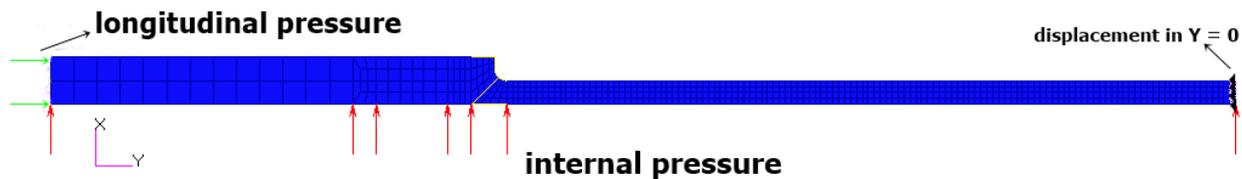


Figure 3. Loads and boundary conditions for pipelines with idealized corrosion defect.

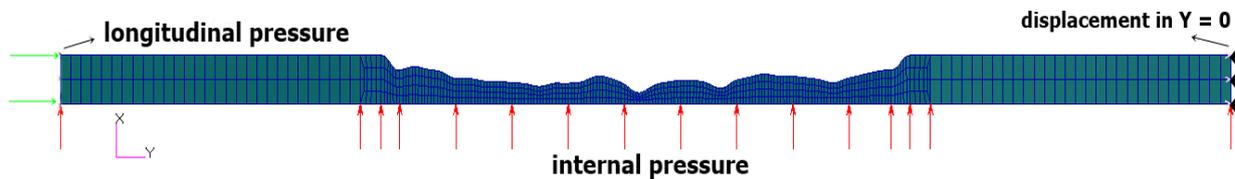


Figure 4. Loads and boundary conditions for pipelines with river-bottom profile corrosion defect.

### 2.2 Material curve

According to the tests performed on specimens presented in Souza (Souza et al. 2007), the yield and ultimate stresses are presented in Table 1 and Figure hh.

Table 1 - Material properties

Specimens	$\sigma_y$	$\sigma_u$	$\sigma_{true}$	$\epsilon_{true}$
<b>TS04</b>	355.70	539.20	547.79	0.014
<b>TS05</b>	285.10	428.50	443.05	0.033
<b>TS10</b>	362.30	557.30	557.30	0.033

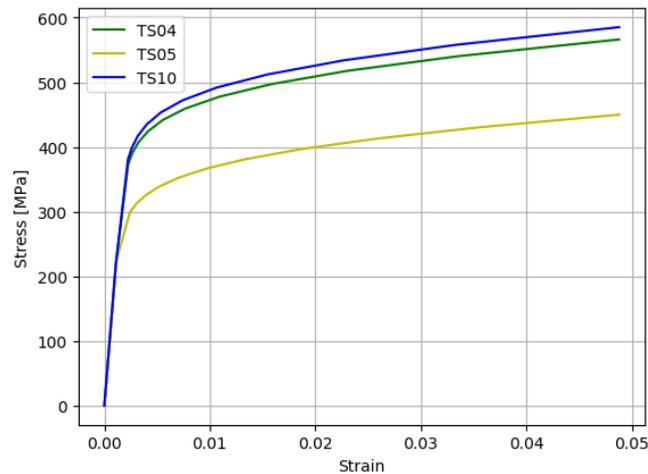


Figure 5 - Representation of material curves.

### 2.3 Mesh and stopping criteria

The element used in the finite element mesh is a quadrilateral of bilinear order, which has four nodes. The stopping criteria were adopted:

1. When the Von Mises stress in a single node in a radial direction, within the defect region, exceeds the true ultimate tensile stress.

### 2.4 Axisymmetric element evaluation

The use of axisymmetric modelling and analysis in computer simulation is extremely fast when compared to 3D analysis and with good accuracy, as shown in Table 2. On the other hand, the results are more conservative, and the stresses and strains are greater than for 3D elements.

Table 2 - Failure pressure

Specimens	$P_f$ (Ideal)	$P_f$ (RBP)	$P_f$ (Exp.)
<b>TS04</b>	10.12	11.88	12.06
<b>TS05</b>	8.21	9.63	10.13
<b>TS10</b>	11.85	12.16	12.63

## 3. RELIABILITY ANALYSIS

The methodology applied in the reliability analysis uses FORM simulations, which is a semi-probabilistic method that uses the Taylor expansion of the failure function, linearizing the limit state equation.

- Definition of random variables:  
As mentioned, the random variables were:  $P_{int}$ ,  $t$ ,  $d$ ,  $L$ ,  $OD$ ,  $\sigma_y$ ,  $\sigma_u$ .
- Limit state function definition (G):

$$G(OD, t, d, L, \sigma_y, \sigma_u, P_{int}) = P_{mef} - P_{int} \quad (1)$$

$$P_{int} = 1.02 \times P_d \quad (2)$$

$$P_d = \frac{2 \times S \times t}{OD} \quad (3)$$

$$S = 0.72 \times E \times SMYS \quad (4)$$

Where  $P_{mef}$ ,  $P_d$ ,  $t$ ,  $d$ ,  $L$ ,  $\sigma_y$ ,  $\sigma_u$ ,  $S$ ,  $OD$ ,  $E$  and  $SMYS$  are respectively pressure obtained by finite element analysis, design pressure, wall thickness, maximum defect depth, defect length, yield stress, ultimate stress, allowable stress, weld joint factor and specified minimum yield strength of the pipe.

In Table 1 the random variables, the type of distribution, the mean and covariance of the random variable, given by the Equation 5.

Table 1. Random variables and their distributions.

Variables	Distributions	Mean	CoV
$P_{int}^{(1)}$	Gumbel	$1.05 \times P_d$	3.0%
$OD^{(2)}$	Normal	Nominal	3.0%
$t^*$	Normal	Nominal	3.0%
$d^*$	Normal	Measured value	CoV(d)
$\sigma_y^*$	Normal	$1.08 \times SMYS$	4.0% ou 8.0%
$\sigma_u^*$	Normal	$1.09 \times SMTS$	3.0% ou 6.0%
$L^*$	Normal	Measured value	5%

<sup>(1)</sup>(Veritas, 2017), <sup>(2)</sup>(Ahammed & Melchers, 1996).

$$CoV = \frac{StD}{m} \quad (5)$$

Where  $StD$  is the standard deviation and  $m$  is the sample mean.

The covariance of the maximum defect depth was calculated considering the type of instrument used to perform the inspection (UT – ultrasonic technology or MFL – magnetic flux leakage). In this work we adopted UT measurements, therefore, the calculation of the standard deviation follows Equation 6.

$$StD[d/t] = \frac{\sqrt{2} \times acc\_abs}{t \times \Phi^{-1}\left(0.5 + \frac{conf}{2}\right)} \quad (6)$$

Where,  $acc\_abs$  is the absolute depth accuracy,  $t$  is the wall thickness,  $\Phi^{-1}$  is the inverse of the cumulative distribution function of a standard normal variable and  $conf$  is the confidence level. In that paper  $acc\_abs$ ,  $conf$  assume the values of 0.25 e 0.9, respectively.

The probability analysis was performed for three specimens (TS04, TS05, TS10) (Souza et al., 2007), the Table 2 shows the values of the means assigned to the random variables. The other three tubular specimens were removed from a pipeline called ORBEL I.

Table 2. Dimensions of the tested specimens, transverse tensile specimens and their defect depth profiles.

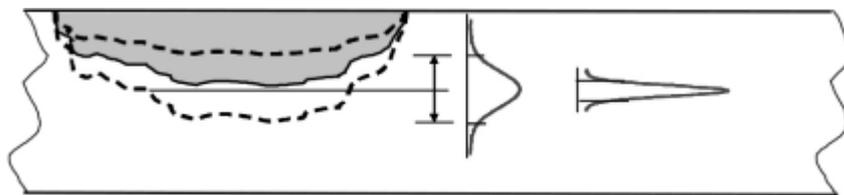
Specimens	OD (mm)	t (mm)	d (mm)	$\sigma_y$ (MPa)	$\sigma_u$ (MPa)	L (mm)
TS04	457.70	6.23	3.27	355.70	539.20	2750.00
TS05	457.70	6.04	2.71	285.10	428.50	2750.00
TS10	457.10	6.09	2.80	362.30	557.30	2750.00

Source: data obtained from Souza (Souza et al., 2007b).

### 3.1 Variation of the remaining defect thickness

The thickness of the idealized defect and the defect with river-bottom profile will be disturbed in uniform throughout the entire defect region, as shown in Figure 1. Disturbance of defect thickness Figure 1.

Figure 1. Disturbance of defect thickness.

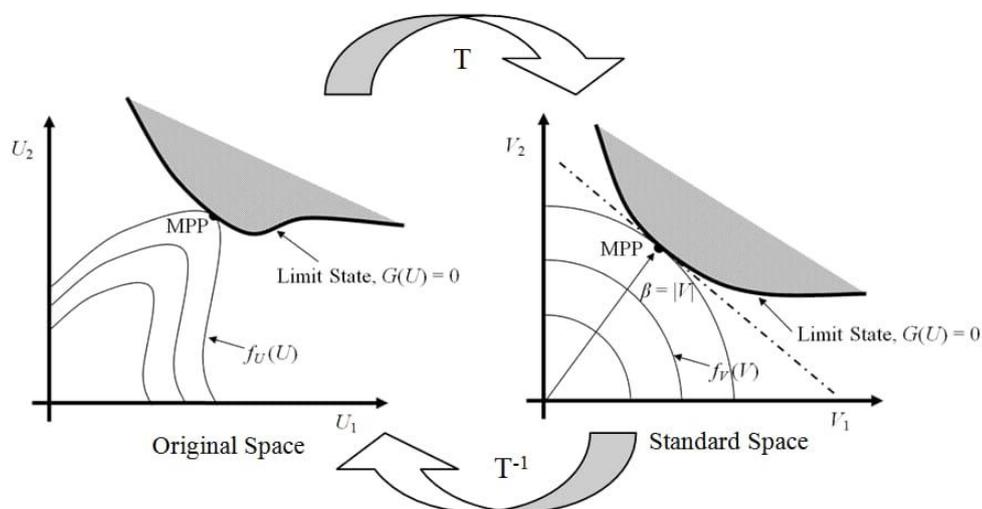


Source: data obtained from DNV RP F101 (Veritas, 2017).

### 3.2 First order reliability method (FORM)

FORM approximates the problem around the most probable failure point (MPP) with an equivalent basic problem by transforming the original random variable space ( $U$ ) into a standard reduced space ( $V$ ), using the Nataf transformation ( $T$ ) (Melchers & Beck, 2018a). A graphical interpretation of the method is shown in Figure 2. The MPP ( $V^*$ ) is the shortest distance point from the limit state ( $G(U) = 0$ ) to the origin of the standard space ( $V$ ). The minimum distance  $\beta = |V^*|$  is called the reliability index. The standard reduced space is a space of equivalent standard normal distribution of uncorrelated random variables, i.e.,  $V_i(V)$  is the standard normal distribution (zero mean and unity standard deviation). In the standard space the limit state is linearly approximated around the MPP.

Figure 2. Graphical interpretation of the form procedure.



In the standard space  $P_f$  is approximated by  $\Phi(-\beta)$ , where  $\Phi$  is the cumulative distribution function of the standard normal distribution. The opposite procedure could be used to approximate the reliability index from the  $P_f$  value

(obtained via MC, for instance). To find the MPP any optimization method can be applied. In this work, an the HL-RF iterative algorithm, called HL-RF from Hasofer, Lind, Rackwitz and Fiessler (Hasofer & Lind, 1974; Rackwitz & Flessler, 1978), is used. The gradient of G with respect to the random variables in the standard space ( $\nabla G$ ) is used in the optimization process to find the MPP. The MPP, ( $V^*$ ) can be obtained as  $V^* = \beta\alpha$ , in which  $\alpha$  is the unitary vector of the gradient  $\nabla G$ , that can also be used to evaluate the importance of each random variable in the problem.

The  $P_f$  approximation obtained via FORM can be improved using a Second Order Reliability Method (SORM) (Melchers & Beck, 2018b). The SORM/FORM method has demonstrated to be very computationally efficient when compared to other approaches such as sampling based schemes. But it can provide inaccurate results in problems with non-Normal random variables and highly non-linear limit state functions. Besides that, problems with discontinuity may lead to convergence problems resulting in increased computation cost and/or inaccurate results.

#### 4. RESULTS

The results show that the analysis using pipelines models with idealized defects have a higher probability of failure than the use of pipelines with river-bottom profile defect, Table 3. These results were expected, considering that the idealized defect model is more conservative than the river-bottom profile.

Table 3. Failure probability and reliability index ( $\beta$ ).

Specimens	Failure prob. (RBP)	Failure prob. (Ideal)	Reliability index ( $\beta$ )(RBP)	Reliability index ( $\beta$ )(Ideal)
TS04	$1.251 \times 10^{-7}$	$1.207 \times 10^{-4}$	5.157521	3.671214
TS05	$8.563 \times 10^{-6}$	$5.128 \times 10^{-5}$	4.299382	3.884444
TS10	$1.951 \times 10^{-5}$	$2.771 \times 10^{-4}$	4.113173	3.453149

Although the results of the probability of failure obtained by analyzing models with an idealized defect are superior to those presented by the model with a river-bottom profile defect, they are very small, not reaching 0.05%.

The importance of each random variable in the probability is made through the gradient  $\nabla G$ . In Table 4, we see that the degree of importance for pipelines with idealized defects are:  $t > P_{int} > \sigma_u > OD > d > \sigma_y > L$ , for cases using pipelines with river-bottom profile defects the degree of importance of the random variables are  $P_{int} > \sigma_u > OD > t > d > \sigma_y > L$ .

Table 4. Influence of each random variable on failure probability.

Specimens	Defect	$P_{int}$ ( $\times 10^{-2}$ )	OD ( $\times 10^{-2}$ )	$t$ ( $\times 10^{-2}$ )	$d$ ( $\times 10^{-2}$ )	$\sigma_y$ ( $\times 10^{-2}$ )	$\sigma_u$ ( $\times 10^{-2}$ )	L ( $\times 10^{-2}$ )
TS04	RBP	-5.898	-3.127	2.275	-0.0046	-0.4893	3.853	-0.5540
	Ideal	-3.655	-2.710	6.100	-1.1311	0.0049	3.180	0
TS05	RBP	-5.634	-2.847	2.273	-0.0038	0.3421	3.741	-0.2358
	Ideal	-3.740	-2.743	5.978	-1.1848	0.0062	3.192	0
TS10	RBP	-5.748	-2.772	2.282	-0.0274	0.2543	3.069	-0.1135
	Ideal	-3.559	-2.700	6.251	-1.1980	0.0394	3.211	0

#### 5. FINAL REMARKS

The consideration of uncertainties for the structural evaluation of pipelines has a positive financial impact and reduces the environmental risks related to leaks, these factors are of great importance for the oil and gas industry. In addition, the data collected through reliability analysis reduces the cost of unnecessary maintenance, increasing accuracy between the time for carrying out maintenance.

For the cases analyzed, the probabilities of failure are low. However, it is noted that the type of analysis performed in the prediction of failure pressure significantly influences the probability of failure. The idealized cases proved to be less reliable than the analyzed cases with river-bottom profile defect. For the latter, wall thickness was the fourth most influential random variable in failure probability, while internal pressure was the most influential variable. For idealized

cases, wall thickness was the most influential random variable in failure probability, while internal pressure was the second most influential variable.

For future work, the methodology developed in appendix E of DNV RP F101 and the use of variation of each point of the remaining thickness of the river-bottom profile defect independently must be considered.

## 6. ACKNOWLEDGMENT

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