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TECHNICAL NOTE

Numerical model for estimating time-dependent reliability of a corroding pipeline over its lifetime

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Abstract
This work aims to evaluate time-dependent reliability of a pipeline under corrosion impact over its lifetime. A finite element corrosion model was proposed, and an empirical power low model is also used and coupled with a probabilistic model for evaluating reliability index about a limit state function. The failure probability of structure was determinate for deferent corrosion rate (low, moderate and high rates), considering corrosion depth. Form method and Monte Carlo simulation are used for evaluating the structure reliability. The impact of applying both effect of corrosion and residual stress is shown which is appears a significant failure probability of the studied pipeline. The found results are analyzed and discussed.

Keywords Finite element · Reliability · Corrosion · Residual stress · Mechanical behavior · Pipeline

Introduction

The pipelines are the most used tools for conveying hydrocarbons (oil and gas). In Algeria, the tow kind of pipelines is habitually exploited to use them as welded and seamless tubes. For conveying gas, Algeria uses a pipeline network length that is over 9677 km with a diameter of 40 in. up to 48 in., and for transporting oil, they used a length of 9946 km with a varying diameter of 20 in. up to 34 in. (TRC 2018). Many significant problems can delay the pipelines' structure both onshore and within the subsea zones; corrosion is considered one of the major causes that can seriously affect these kind of structures (Velázquez et al. 2009; Rajabipour and Melchers 2013).

The defect causes thinning of the pipe wall and decreases the pipe's ability to resist internal pressure. If large enough, two distinctive failure modes can affect the pipeline, i.e., a small leak and burst (Pidaparti and Rao 2008; Eiber and Kiefner 1986). When the defect enters the wall of a pipe, at that moment, a small leak will appear, but a burst occurs if the remaining ligament of the pipe wall is severed (i.e., collapsing) due to internal pressure before the defect enters the pipe wall. The damages caused by burst are generally more severe than those of leakage (ASME 1995; Veritas 2010).

To estimate the length of service provided by the pipelines, several reliability calculation models are applied, where it is necessary for deterministic models of capacity to be established and coupled with probabilistic models to better manage the service life and safety of such structures which is still a challenging task (Melchers 1999; Xie 1998; Zhang and Zhou 2013).The importance of systems for predicting pipelines' reliability, in general, can be evidenced by the large number of papers in the existing literature in recent years. We can cite, for example, the works of Timashev and Bushinskaya (2015), Teixeira et al. (2008), Li et al. (2009), Velázquez et al. (2017), Motta et al. (2017), Liu et al. (2017) and Shuai (2017).

Studying the corrosion impact on the experimental plane appears to be very difficult and very expensive in terms of time, precisely among the essential objectives of numerical studies. In general, it is the saving of time that is offered by these methods, in spite of the complexity of the obtained results that is actually the major drawback presented by these methods. On the other hand, we find that a large number of research laboratories in the world are focusing on the numerical tools to perform research on its usefulness and power (Rajabipour and Melchers 2013; Cerit et al. 2009).

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In fact, numerical approaches can model the corrosion effect on pipeline's integrity using finite element. Hence, it can be also used for evaluating the probability of failure of the studied structure (pipes). The aim of the present study is to use and show the utility of the numerical method by modeling corrosion phenomena using finite element models. So, in this work, an empirical model was proposed to estimate the time-dependent reliability of pipelines transporting hydrocarbons. A probabilistic model was coupled with the empirical proposed model to evaluate the reliability evolution with deferent corrosion rates under the service pressure effects with and without residual stress.

Mechanical model

Corrosion model

Corrosion is considered a significant threat which can affect severely the pipeline's integrity. Regarding corrosion effects, several models are used by researchers to study it (Netto 2009; Vanaei et al. 2017; Cheng and Chen 2017; Chiodo and Ruggieri 2009; Majid et al. 2010, 2012; Zhou and Huang 2012; Zhu and Leis 2012; Ma et al. 2013; Fekete and Varga 2012; Alamilla et al. 2013; Abdalla Filho et al. 2014; Nahal and Khelif 2013, 2015) but the power model constitutes one of the most empirical models which is used to describe the corrosion evolution in time such as uniform corrosion, localized corrosion and corrosion fatigue, or even time-dependent for fracture toughness estimation (Romanov 1957; Li and Mahmoodian 2013; Katano et al. 2003). Several works applied the power corrosion model as it is considered indispensable for understanding the corrosion behavior (CSA 2007; DNV 2004; Lee and Pyun 2002; Lee 2005). ASME B31G (1995) also developed a model which is widely used, and it should be mentioned that Kiefner and Vieth (1990a, b) have modified the ASME B31G code to reduce conservatism. For a stochastic corrosion field, the time-dependent depth $e_{lc}(t)$ and length $l_{lc}(t)$ of corrosion defect can take the form (Kiefner and Vieth 1990b):

$$e_{lc}(t) = (k_{uc} + \alpha_{lc}\Delta k_{lc})t^n,$$
$$l_{lc}(t) = \gamma_{lc}(k_{uc} + \alpha_{lc}\Delta k_{lc})t^n$$

where $e_{lc}(t)$ and $l_{lc}(t)$ represent the localized corrosion depth and length, γ_{lc} is the length-to-depth ratio, k_{uc} and n are the corrosion constants, α_{lc} is the localized corrosion fraction, and Δk_{lc} represents the specific rate of localized corrosion.

Finite element model

In this work, a geometric model of corroded pipeline was developed under the software using finite element modeling (Fig. 1). The pipeline dimensions to be modeled are given

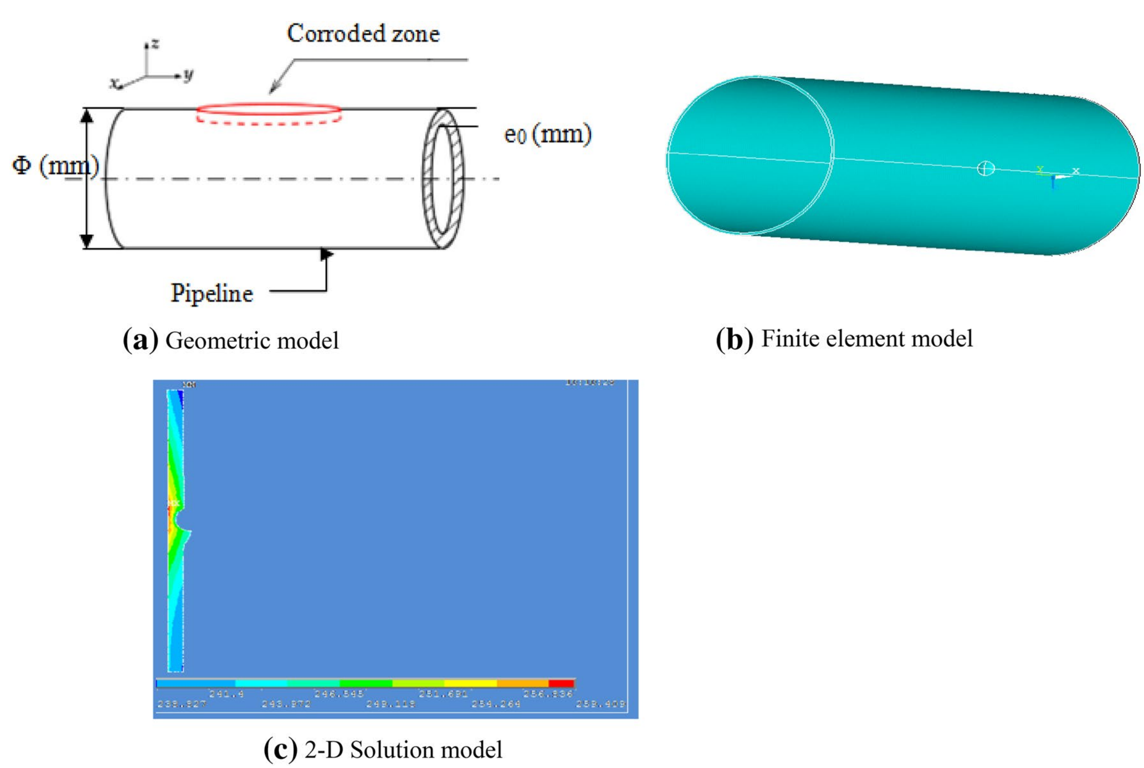

Fig. 1 Pipeline geometry and finite element model

Table 1 Pipeline's dimensions

Parameter	Type/value
Pipeline	API 5L X70
Yield strength (F_y)	485 Mpa
Outer diameter (D)	508 mm
Pipeline wall thickness (e_0)	9.5 mm
Ultimate strength	520 Mpa
Poisson's coefficient (ν)	0.3
Young's modulus (E)	206 GPa
Service pressure	4 bar

in Table 1. In this study, the finite element model of the corroded pipeline is simplified to a 2-D axisymmetrical model.

For 2-D model, the element type was selected with six nodes having tow degrees of freedom at each node, and quadratic displacement which was well-applied to properly model the irregular zone (corroded area in our case). Regarding the boundary conditions, the pipe was blocked along the (*yy*) axis and it was free along the (*xx*) axis. In total, the corroded pipe model has 19,878 nodes with a maximum von Mises stress of 259.67 Mpa, with 5 mm of a corrosion depth and 4 bar service pressure.

The corroded pipe geometry model is presented in Fig. 1. The aim of this part of study is to view the corrosion impact on the pipeline's behavior.

Mechanical behavior

The objective of this section is to view the corroded pipeline's mechanical behavior evolution under the pressure service effect which is taken to be 4 bar. At this phase of study, the corrosion increases at each time by 1 mm, and each time the von Mises stress was calculated. The obtained result is shown in Fig. 2. A proportional relation was found between the stress and the corrosion depth.

According to the curve presented in Fig. 2, an empirical mechanic model can be proposed as follows:

$$\sigma(t) = 255.12 - 0.83d(t) + 0.34d^2(t),$$
$$d(t) = e_{\mathrm{lc}}(t) + l_{\mathrm{lc}}(t),$$

where $d(t)$ is the loss in the wall thickness over time (these relationships are only valid for the considered pipe dimensions).

Residual stress

When manufacturing pipelines using mechanical processes, chemical and heat treatments, residual stresses occur in most cases, this is usually due to an imbalance between material's external and internal conditions. Typically, a plastic deformation or a microstructural change in the material prevents previously applied external charges from discharging (Totten et al. 2002). Residual stresses can significantly affect the mechanical properties of materials and structural components, including fatigue life, distortion, dimensional stability, corrosion resistance, and brittle fracture (Rossinia et al. 2012). In recent decades, various quantitative and qualitative methods analyzing residual stresses have been developed. In general, a distinction is usually made between destructive and non-destructive techniques for evaluating residual stresses (Rendler and Vigness 1966). Gou and Zhang (2011) were able to define the residual stresses in pipelines, and it is given as follows:

$$\sigma_{\mathrm{Rs}} = 0.21\sigma_{\mathrm{y}},$$

where σ_{Rs} is the residual stress, σ_{y} is the yield strength, which is in our case 485 MPa for X70 steel material which constitutes the material of the pipeline of this study.

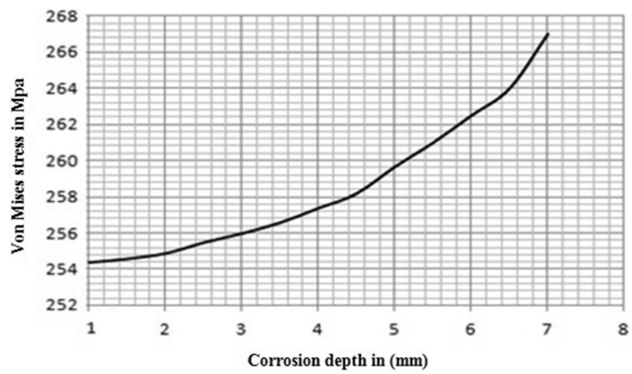

Fig. 2 von Mises stress evolution vs. corrosion depth for the corroded pipeline

Reliability analysis

The most widely used models for assessing pipelines' failure probability are ASME B31G, modified ASME B31G, DNV-99, etc., and the modified ASME B31G is the largely applied one in the existing standard industry (ASME 1995; Kiefner and Vieth 1990a, b). To evaluate failure probability, the Monte Carlo method is applied (Leira et al. 2016), which is based on random sampling of variables according to their distributions, so a large number of simulations is considered. Based on the theory of large numbers, the failure probability can be evaluated by the ratio of failing samples' number N_f and the samples' total number N: $P_{\mathrm{f}} = \frac{N_{\mathrm{f}}}{N}$. Hence, for calculating reliability index, FORM/SORM (Zhou 2011) (first-order reliability method/second-order reliability method) is usually used by researchers.

Limit state function

To evaluate the probability of failure of pipelines intended for conveying hydrocarbons (oil and gas) and assessing the corroded pipeline's reliability, a limit state function has been expressed as follows:

$$G(t) = \sigma_y - \sigma_V,$$

where σ_V is the Von Mises stress, σ_y is the yield strength, when $G(t) > 0$, the structure can fulfill its purpose; $G(t) < 0$ the structure (pipeline) will fail. By replacing the stress expressions, the limit state function became:

$$G(t) = \sigma_y - \delta\left[p.\left[\left((255.12 - 0.83d(t) + 0.34d^2(t) + \alpha.\sigma_{RS1}\right)\right)\right]\right],$$

where δ represents the model error coefficient, and α is the residual stress variation factor. It should be noted that errors occur frequently in structure degradation modeling. Therefore, the error coefficient δ in this model can be interpreted as a measure of these errors.

The FORM method is applied to perform reliability analysis, and the corroded pipeline's failure probability is given by (Zhou 2011):

$f(t) = P[G(x_i, t) \le 0] = \Phi(-\beta(t))$, where Φ is the standard normal cumulated probability, and β the reliability index denoted as follows:

$$\beta = \frac{\mu_G}{\sigma_G} = \frac{\mu_y - \mu_v}{\sqrt{\sigma_y^2 + \sigma_v^2}},$$

where μ_G and σ_G stand for the mean and standard deviation of $G(t)$, limit state function.

Numerical application

In this part, we use a numerical case to illustrate the above methodology. A pipeline that is taken from the Algerian petroleum industry, with outer diameter D and nominal wall thickness e_0, is subjected to internal pressure p. The pipeline's steel is of *X70* quality with nominal yield strength σ_y, and the input data are provided in Table 2, in which the random variables are considered as normally distributed.

Results and discussion

The effect of corrosion with high, moderate and low rates on failure probability as a function of pipeline's lifetime is shown in Fig. 3. Not unexpectedly, it is seen that the failure probability decreases abnormally when the pipeline age goes from 0 up to 9 years in the case of high corrosion rate and after this period, a rapid increase in time is notable which is quite significant. However, in moderate and low corrosion rate cases, the failure probability seems to be an almost a linear evolution in time, with a slightly lower deference. This is clearly explained by the reliability indexes illustrated in the three deferent curves in Fig. 4. A main observation regarding the effect of applying a high corrosion rate is that it gives very low reliability levels. It is also observed that the effect of having low and moderate corrosion rates appears almost to be the same.

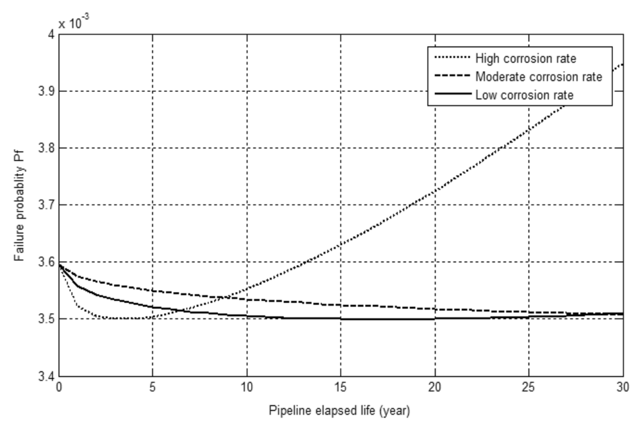

Fig. 3 Probability of failure vs. pipeline's elapsed lifetime with residual stress

Table 2 The pipeline model's input data (case of determining pipeline's characteristics)

Variable	Symbol	Corrosion rate	Mean value	Coefficient of variation
Diameter	D (mm)		508	–
Wall thickness	e_0 (mm)		9.5	–
Yield strength	σ (MPa)		485	0.07
Internal pressure	P (MPa)		4	0.25
Corrosion rate	K	Low	0.16	0.016
		Moderate	0.37	0.037
		High	0.67	0.067
Corrosion parameters	N		0.53	–
Model error	δ		1	0.15
Residual stress variation factor	α		1	0.20

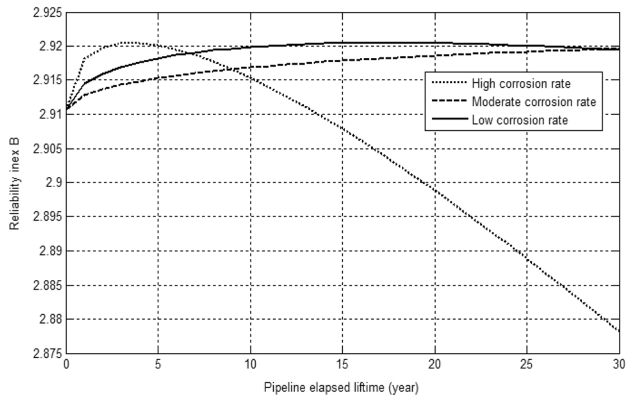

Fig. 4 Reliability index evolution vs. pipeline's elapsed lifetime with residual stress

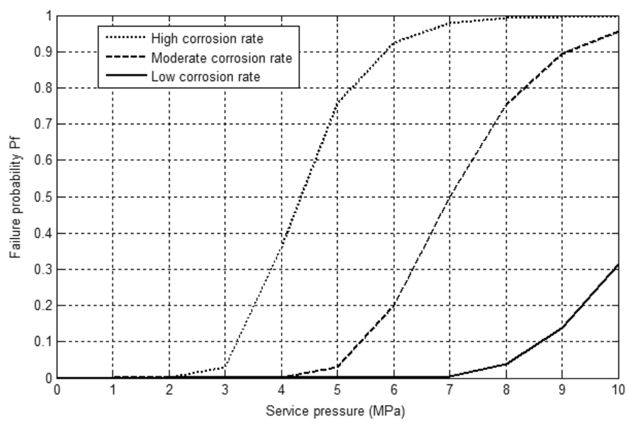

Fig. 5 Probability of failure vs. pipeline service pressure with residual stress

The effect of varying the service pressure on the failure probability of pipeline is observed in Fig. 5, and it is seen that the failure probability curves seems to have the same form in high and moderate cases which implies that there is significant sensitivity when varying the pressure service instead of pipeline's lifetime which is relatively less significant. The reliability indices curves are illustrated in Fig. 6, and it is observed that the reliability levels decrease quite rapidly in high and moderate corrosion rates cases but decrease very slowly in low corrosion rate case.

The case without residual stress is also considered, different observations of the relevant probability of failure are shown in Fig. 7. For the present case, it seems that there was a quite rapid increase of failure probability for high corrosion rate, and the structure (pipeline) showed more resistance to corrosion phenomena in moderate corrosion rate. Although, there was a very slow increase of failure probability in low corrosion rate. Also, the reliability indexes without residual stress are investigated in this study and the

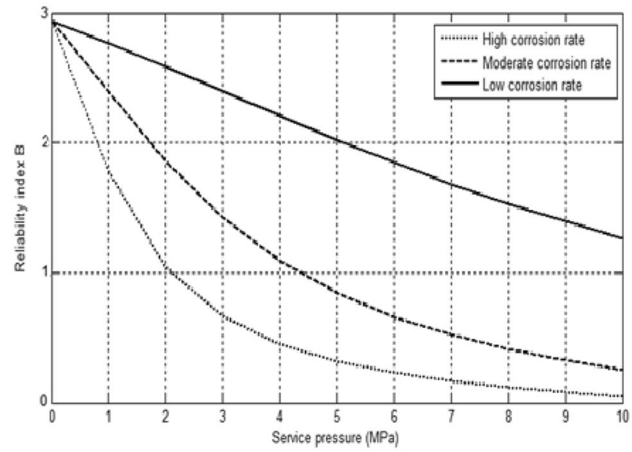

Fig. 6 Reliability index evolution vs. pipeline service pressure with residual stress

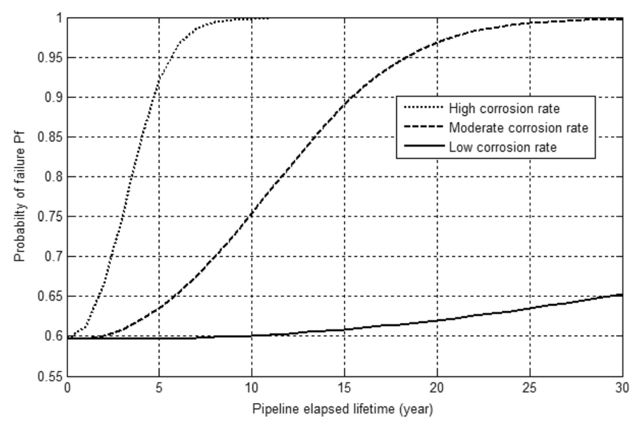

Fig. 7 Probability of failure vs. pipeline elapsed lifetime without residual stress

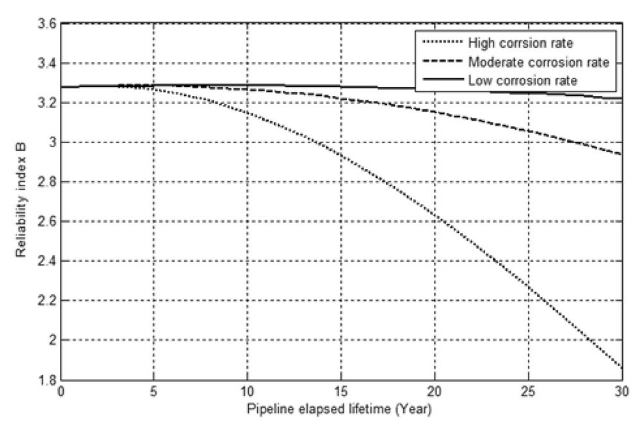

Fig. 8 Reliability index evolution vs. pipeline's elapsed lifetime without residual stress

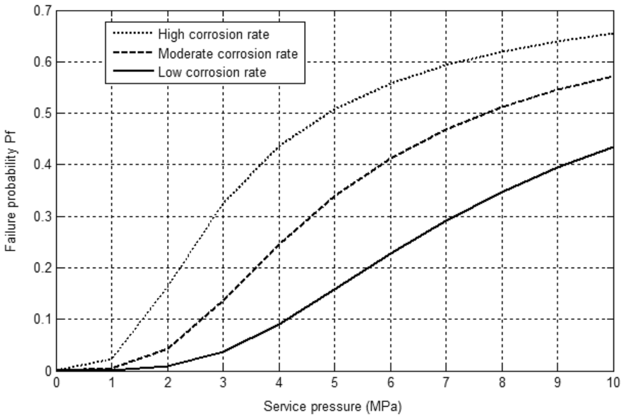

Fig. 9 Probability of failure vs. pipeline service pressure without residual stress

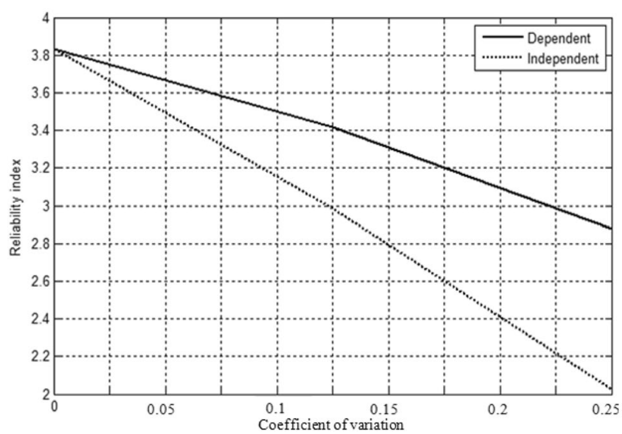

Fig. 10 Reliability index vs. coefficient of variation

different results are shown in Fig. 8. The influence of different corrosion rates without residual stress is therefore less significant on the studied structure. For the pipeline age from 0 to 25 years, it is seen that reliability indexes take the values varying between 2.4 and 3.3 which are shown to be relatively accepting levels.

Instead of varying pipeline's lifetime in Fig. 9 the service pressure was varied to view the failure probability evolution without residual stress. It seems that the three corrosion rates have the same curve form with a slightly lower deference. It is remarkable that in the high corrosion rate the pressure effect appears when the pressure service increases. But, the same effect is not displayed in moderate and low corrosion rates.

The coefficient of variation for reliability indexes was studied with the dependent and independent cases. It has been observed that the dependent correlation is less important compared with the independent correlation in the proposed probabilistic model (Fig. 10).

Conclusion

The present paper deals with a methodology that has been developed for estimating the time-dependent reliability of a corroding pipeline over its lifetime. First, an empirical mechanical behavior model of a corroded pipeline is proposed, according to the finite element modulation of corrosion defect depth. After that, a probabilistic model was also developed and coupled with the mechanical proposed model. The reliability and probability of failure of the studied structure are analyzed under three corrosion rates effects (high, moderate and low rates). The different results are then treated and discussed. The impact of applying both the effect of corrosion and residual stress is shown which appears as a significant failure probability of the studied pipeline. The reliability index decreases when taking into account the residual stress for the various corrosion rates. So, for better managing the pipeline's life, more attention must be provided considering its structure.

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