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The Impact of Corrosion Outer Defects on the Reliability of Hydrogen Pipeline Transport Systems

Abdelhakim MAIZIA *[1], Ghania HABBAR [1], Abdelhamid GHOUAOULA [1], Abdelkader LOUZA[1]
Abdelkader HOCINE [1], Abderrezak BEZAZI [2]

[1] Hassiba Benbouali University of Chlef, Science and Technology, Department of Mechanical Engineering, CLTMSM Laboratory, PO. Box 151, Hay Salem, Chlef, Algeria.
[2] University 8 May 1945, Science and Technology, Department of Mechanical Engineering, Laboratory of applied mechanics of new materials (LMANM), BP 401 Guelma 24000, Algeria.

**(a.maizia@univ-chlef.dz) Email of the corresponding author*

***Abstract* –** Corrosion in hydrocarbon pipelines poses a significant threat to the integrity and safety of these critical infrastructure components. This research paper delves into the crucial issue of corrosion defect interaction and its influence on the reliability of pipelines used for the transportation of hydrocarbons. The study investigates the complex interplay between pipeline corrosion, defects, and failure pressure, aiming to provide valuable insights into the mitigation of potential catastrophic failures. The aim of this research is to assess the correlation between corrosion defects and their interaction in pipeline systems. To achieve this goal, a comprehensive numerical analysis is conducted. The present investigation uses the finite element numerical model, which simulates the behavior of corroded pipelines under various loading conditions. This model allows us to rigorously evaluate the extent to which corrosion defect interaction affects the mechanical properties of pipelines, including stress concentrations and deformations, and, consequently, their ability to withstand the operating pressures associated with hydrocarbon transportation. Understanding the dynamics of corrosion defect interaction is vital for pipeline operators and engineers seeking to enhance the safety and longevity of their infrastructure. By quantifying the impact of corrosion defects on failure pressure through our finite element numerical model, this research contributes to the development of more accurate risk assessment models and proactive maintenance strategies. Ultimately, these insights improve the reliability and integrity of hydrocarbon transportation pipelines, with a particular emphasis on addressing the depth and spacing of defects as key determinants of system reliability. The results of our study reveal that the depth of defects and their spacing within the pipeline are two of the most crucial parameters affecting the reliability of pipeline systems. Corrosion defects located at critical depths and with specific spacing patterns can significantly reduce the failure pressure of the pipelines.

Keywords – Corrosion, Hydrogen Pipelines, Reliability, Defect Interaction, Failure Pressure.

I. INTRODUCTION

In the context of combating climate change and transitioning towards a sustainable, low-carbon future, hydrogen has emerged as a key alternative energy carrier. Ensuring the efficient and secure transportation of hydrogen is vital to realizing its potential as a clean energy solution. This paper delves into the complex realm of hydrogen transport pipelines, investigating cutting-edge technologies, materials, and engineering approaches [1], [2]. The study explores the intricate strategies employed to guarantee the smooth transportation of hydrogen from production sites to end-users, addressing crucial aspects of this innovative energy transportation system. In the domain of hydrocarbon transportation, pipelines serve as the essential lifeline, facilitating the extensive movement of vital energy resources.

Nevertheless, this expansive network encounters formidable challenges, notably in the form of defects and corrosion. The harsh operating conditions, coupled with the corrosive nature of hydrocarbons, render pipelines susceptible to deterioration over time. Defects, ranging from cracks and dents to welding imperfections, can compromise the structural integrity, potentially leading to leaks or ruptures. Simultaneously, corrosion acts as a relentless adversary, gradually weakening the pipeline material and elevating the risk of failure. Effectively addressing these issues is crucial, necessitating meticulous inspection, advanced materials, and innovative corrosion-resistant technologies. Comprehensive understanding and mitigation of these defects and corrosion complexities are imperative to ensure the steadfast reliability and safety of hydrocarbon transportation pipelines, preserving both the environment and the integrity of the energy supply chain. Pipeline defects encompass a range of issues such as cracks, deformations, weld defects, leaks, and corrosion problems, among other quality-related concerns. These defects stem from diverse factors, including design flaws, manufacturing discrepancies, severe environmental conditions, physical impacts, or errors in maintenance practices. These faults within pipelines have the potential to result in gas or oil leaks, posing significant risks to both the environment and human safety, as documented in [3] and [4]. Engineers designing mechanical structures consistently aim to evaluate the reliability and safety of their creations. This imperative arises from the fundamental significance of structural safety and its profound impact within their specific fields of application. The significance of tubular structures in the transport and storage of gas and oil cannot be overstated. Researchers have dedicated substantial efforts to assessing the reliability of pipelines, recognizing the critical role they play in the energy industry. Among the various models utilized, one notable approach is the modified ASME B31G standard method [5]. Additionally, the work conducted by [6] has yielded a significant analytical model, providing reliable outcomes with minimal error. The majority of these numerical and analytical models undergo validation and comparison against experimental research findings, establishing them as dependable references in the field.

In this last study by Choi et al. [6], a comprehensive series of tests was conducted to assess the burst pressure across a range of scenarios, considering various cases and types of corrosion defects.

This study aims to present an overview of key models documented in the literature for estimating burst pressure in both virgin and corroded pipelines. To achieve this goal, a numerical model employing the finite element method was developed in ANSYS Apdl. The present numerical model can be used to evaluate both virgin and corroded pipelines. This model enables the estimation of operational parameters for tubular structures in both conditions, facilitating preliminary optimization studies. Moreover, this finite element model has the capability to simulate the behavior of hydrogen pipelines, accounting for the presence of various internal and external corrosion defects and the interaction of these defects.

II. MATERIALS AND METHOD

A. *Analytical models of corroded pipelines*

Defining the geometric characteristics of a corrosion defect proves challenging due to its irregular shape, compounded by its tendency to expand through corrosion reactions. Flaw assessment methods typically rely on determining the maximum metal loss to estimate the remaining strength of pipelines. In recent years, numerous industry models and codes have been developed to assess the impact of corrosion defects and predict the burst pressure of corroded pipelines. These research studies typically employ standardized defect shapes, including rectangles and ellipses (Fig. 1), [5], [6], [7], [8], and [9].

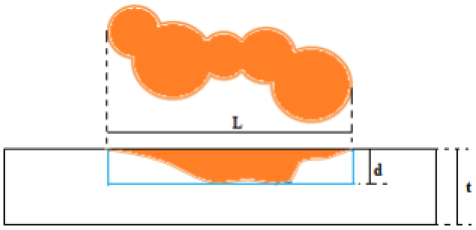

Fig 1. Corrosion defect of a mixed shape (parabolic and rectangular)[5].

In this study, a rectangular-shaped defect was utilized as an approximation approach. The following table presents the analytical models that were used to validate the numerical results of this paper.

Table 1. Analytical burst pressure models of corroded pipelines.

Method	Model
ASME B31G Modified, [03]	$M = \sqrt{[1 + 0.6275\left(\frac{l^2}{Dt}\right) - 0.003375\left(\frac{l^2}{Dt}\right)}$ $P = \frac{2\,t}{D}(1.1\sigma_y)\frac{1 - 0.85\,{}^{d_{max}}/_{t}}{1 - 0.85\,{}^{d_{max}}/_{tM}}$
DNV RP-F101, [02]	$Q = \sqrt{[1 + 0.31\left(\frac{l^2}{Dt}\right)}$ $P = 1.05\frac{2\,t\sigma_y}{D - t}\frac{(1 - {}^{d_{max}}/_{t})}{(1 - {}^{d_{max}}/_{tQ})}$

B. Failure criterion

The Von Mises criterion serves as a method for evaluating the fracture toughness of materials subjected to intricate stress conditions. Widely employed in the design and analysis of metallic structures and other isotropic materials, this criterion ensures the safety assessment of mechanical structures. The Von Mises criterion posits that material failure occurs when a particular zone within the material experiences deformation equivalent to the overall material when it reaches its ultimate tensile strength limit, as indicated in references [10] and [11]. This criterion finds extensive application in ductile materials like steel. The equation number (1) presents the Von Mises criterion [12]:

$$\sigma_e = \left(\frac{1}{\sqrt{2}}\right) \times \sqrt{[(\sigma_{\theta\theta} - \sigma_{rr})^2 + (\sigma_{\theta\theta} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{rr})^2} \quad (1)$$

C. Material studied

The results of this research paper were generated using FEA for steels: API 5L X52, X65, and X80. These material properties are presented in Table 2.

Table 2. Material properties of the studied pipelines.

Proprieties	API 5L X52	X65	X80
E (MPa).	210000		
$\boldsymbol{v}$	0.3		
$\boldsymbol{\sigma y}$ **(MPa).**	359	464	534.1
$\boldsymbol{\sigma uts}$ **(MPa).**	612	629	718.2

D. Finite element model

In order to determine the stress field and the equivalent Von Misses stress in the pipeline-corroded structure, a finite element model was implemented using the commercial software ANSYS APDL. For the mesh, we used Solid186 20-node volume elements. Figure (2) illustrates all the boundary conditions used in this study.

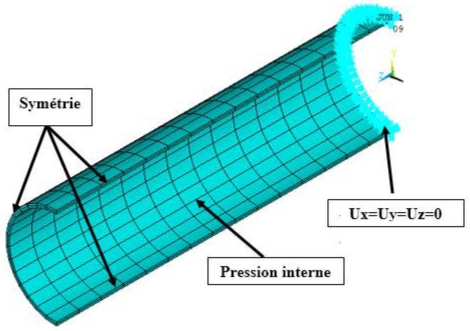

Fig 2. Mesh and boundary conditions.

Prior to concluding this study, a numerical model of a corroded pipeline featuring a single defect was developed. To validate the accuracy of our numerical outcomes, we adopted a comparative approach, contrasting our results with the experimental data from Choi et al. [6], as well as analytical findings proposed by ASME B31 G modified [4], PRACTICE DNV-RP-F101 [7], and [8]. Table 3 below provides the geometric details of the tubular samples used, along with the burst pressure values obtained from the experiments conducted by [6].

Table 3. Geometries of artificial corrosion defects [6].

Pipe	l (mm)	w (mm)	d (mm)	P_f (Mpa)
DA	200	50	4.4	24.11
DB	200	50	8.8	21.76
DC	200	50	13.1	17.15
LA	100	50	8.8	24.30
LC	300	50	8.8	19.80
CB	200	100	8.8	23.42
CC	200	200	8.8	22.64

In the experimental study [6], eight burst tests were conducted on corroded pipelines made from API 5L X65 steel grade. These pipelines featured rectangular corrosion of varying dimensions, created artificially through machining. The samples were identified using specific indices (DA, DB, DC, LA, LC, CB, CC) as referenced in the study by [6].

Table 4 provides validation of our current numerical results. Upon analysing the burst pressure values Pf, both experimental and numerical (FEM) data in this table, we observe that the maximum error percentage is 4.37%, with an average error of approximately 2.55%. This confirms the reliability of the burst pressures generated by the present numerical model, making it a suitable tool for conducting a study on the reliability of corroded pipelines. In contrast, the analytical results exhibit a higher error rate, reaching 12.36%, which can be attributed to the absence of the parameter 'w' in the equations of these analytical models. Following this validation, the current numerical model (FEM) can be confidently employed to further advance this investigation.

Table 4. Comparison of FEM results with experimental and analytical results.

Pipe	***Pf* Exp [04]**	***Pf* EFM**	**ASME B31G**	**Exp-FEM %**	**FEM – ASME %**
DA	24,11	24,5	26,71	1,62	8,27
DB	21,76	21	20,85	3,49	0,72
DC	17,15	16,4	14,25	4,37	11,12
LA	24,3	23,5	20,91	3,29	12,36
LC	19,8	20	20,75	1,01	3,60
CB	23,42	23	20,85	1,79	10,31
CC	22,64	22	20,85	2,83	5,52

III. RESULTS

A. *Influence of the depth of two defects*

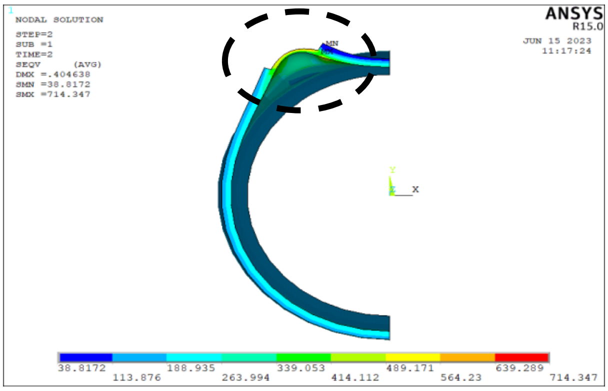

Fig 3. Variation of the Von Mises stress across the thickness, for 2DC (d=6mm).

DISCUSSION

The results presented in both figures 3 and 4 illustrate the variation of Von Mises stress across the thickness of the pipeline for different depths of defects. Two cases were studied: the first involving a pipeline with two circumferential defects (2DC), and the second involving a pipeline with two longitudinal defects (2DL). According to the two figures, we can definitely say that the bursting zone is found in the center of failure for both types of defects.

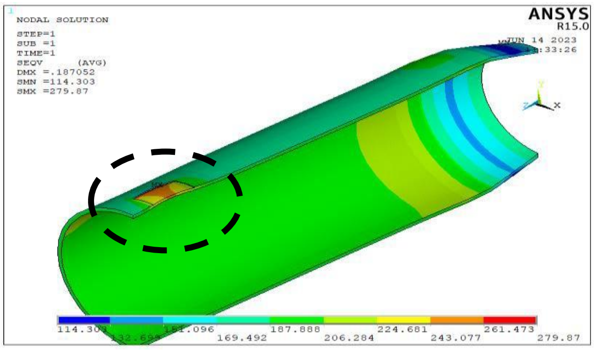

Fig 4. Variation of the Von Mises stress across the thickness, for 2DL (d=2mm).

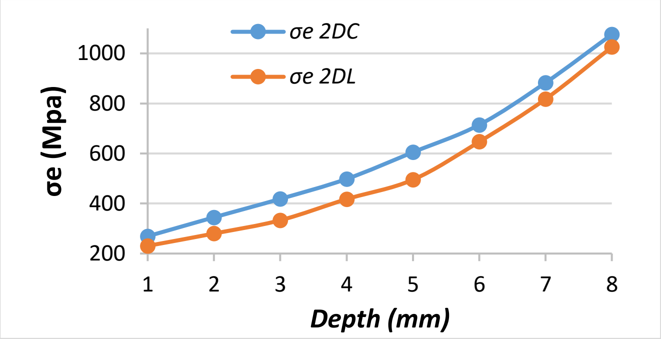

Fig 5. Comparison of the influence of defect depth for 2DC and 2DL.

A comparison between the two cases studied was carried out in order to define the most unfavorable case (Fig. 5). Both graphs show a dominant increase in the maximum Von Mises stress in the case of two circumferential defects (2DC). This increase takes an average percentage equal to 13%. This means that in the presence of circumferential and longitudinal defects, it is necessary to first repair the circumferential defects.

CONCLUSION

In conclusion, the analysis illustrates the Von Mises stress distribution across the pipeline thickness for different depths of defects. The study encompassed two cases: pipelines with two circumferential defects (2DC) and pipelines with two longitudinal defects (2DL). The findings unequivocally indicate that the burst zone is centralized in the middle of the defect for both defect types. Further comparison between these cases distinctly reveals a substantial increase in the maximum Von Mises stress for pipelines with two circumferential defects. This increase averages around 13%. Consequently, when dealing with a combination of circumferential and longitudinal defects, addressing the circumferential defects first is imperative to ensure the structural integrity and safety of the pipeline.

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