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Mechanical behavior analysis of corroded pipelines used to transport hydrogen

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Abstract – This paper is dedicated to the implementation of a numerical model of corroded pipelines using the finite element method. This last model was carried out on the commercial software ANSYS Apdl. A numerical model of a pipeline with one defect was made to validate the results of the bursting stress. This results have been compared with data and results from experimental and analytical large-scale pipeline tests. Then, four numerical models were implemented with different types of external defects. Thanks to these models, we carried out a series of numerical tests for the four cases, and from the results obtained, we found that the depth of the defect affects the stress more than the circumferential Sc and longitudinal Sl spacing between the defects. On the other hand, the interaction between the defects clearly manifests when these spacings take small values. In addition, for larger spacings, we noticed the absence of interactions between the defects, and each defect alone affects the equivalent Von Mises stress.

Keywords – Hydrocarbons, Pipes, API 5L Steels, Corrosion, Defects, Finite Elements

I. INTRODUCTION

In the field of transportation of hydrocarbon products and hydrogen, pipelines play a very important role. Pipelines are made of different materials, including steel, polymers and composite materials, but for transportation of fuels steels still lead these materials. Tubular steel structures are widely used in the oil and gas industries due to the material's high strength-to-weight ratio, which reduces the cost of the material. The size of the commonly used pipelines ranges from 100 mm to 1500 mm. Algeria is a major producer and exporter of natural gas, and gas pipelines are an essential part of the country's energy infrastructure. The Algerian gas pipeline network is managed by the national company Sonatrach, which is responsible for the production, transport and marketing of natural gas in Algeria. Transporting natural gas through pipelines is one of the safest and most efficient ways to transport natural gas over long distances. They are designed to withstand high pressures and extreme temperatures.

Pipeline defects can include cracks, deformations, weld defects, leaks, corrosion issues, and other quality issues. These defects can be caused by a variety of factors, including design errors, manufacturing issues, extreme environmental conditions, physical damage, or maintenance errors. Pipeline faults can lead to gas or oil leaks, which can be hazardous to the environment and human safety, [01], [02].

Designers of mechanical structures always seek to assess the reliability and safety of mechanical structures. This need is justified by the importance of structural safety and its impact in their fields of application. Tubular structures play a very important role in the transport and storage of gas and oil. For this, the researchers invested their enormous efforts in order to estimate the state of reliability of the pipelines. Among these models we also find the method of the modified ASME B31G standard [03], on the other hand [05], the work of has developed an important analytical model and gives reliable results with a minimum error rate. The majority of these numerical and analytical models are validated and compared with experimental research work as more reliable reference. Among these experimental works we find the essays of Choi et al, [04]. This last work carried out a series of tests to determine the burst pressure with different cases and types of corrosion defects.

In this context, this research paper aims to provide the reader with the main models that exist in the literature, and which can be used to estimate the burst pressure of virgin and corroded pipelines. Also, a numerical model by means of the finite element method was carried out with virgin and corroded pipelines. This model will allow us to estimate the operating parameters of virgin and corroded tubular structures, on the other hand we can carry out with this model a preliminary optimization study.

II. MATERIALS AND METHOD

A. *Analytical models of corroded pipelines*

It's always difficult to define the geometric characteristics of a corrosion defect due to the irregularity of the defect. In addition, the defect continues to grow by corrosion reaction. According to the flaw assessment method, a maximum metal loss on pipelines is used to estimate the residual strength of pipelines. In recent years, many industry models and codes have been developed to assess the influence of corrosion defects and predict the burst pressure of corroded pipelines. These works propose generally use regular shapes of defects like; rectangular defects, elliptical defects, (Fig 1), [02], [03], [04], [05] and [06]. For this, the present work will use a rectangular shape defect as an approximation approach. The following table presents the analytical models that were used to validate the numerical results of this paper.

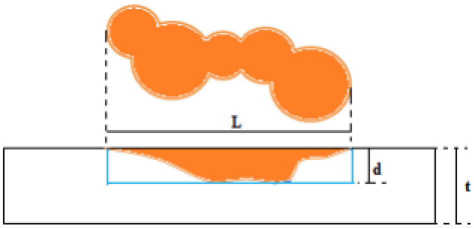

Fig. 1 Corrosion defect of a mixed shape (parabolic + rectangular), [03].

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 is a method used to assess the fracture toughness of materials under complex stresses. The Von Mises criterion is often used in the design and analysis of metallic structures and other isotropic materials to assess the safety of mechanical structures. The Von Mises criterion considers that the failure of a material occurs when a specific zone of this material reaches a level of deformation equivalent to that which occurs on all the material when it reaches its limit of simple tensile strength; [08], [09]. This criterion is often used for ductile materials such as steels. The formula of the Von Mises criterion is expressed by the equation (1), [07]:

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

C. *Material studied*

The calculations for this work were generated using FEA for steels; API 5L X52, X65 and X80. The material properties are shown in Table 2.

Table 2. Material properties of the studied pipelines.

Propriétés	**API 5L X52**	**X65**	**X80**
E (Mpa).	210000		
$\boldsymbol{\upsilon}$	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 calculate the equivalent Von Misses stress, a numerical 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.

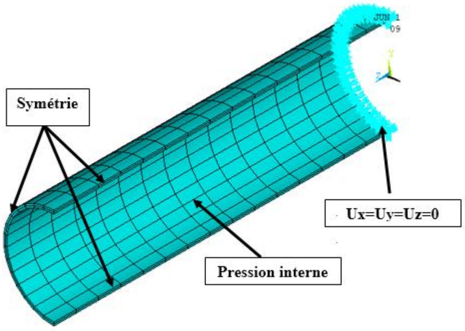

Fig. 2 Mesh and boundary conditions.

Before finalizing this study, a numerical model of a corroded pipeline with one defect was produced. And to ensure the reliability of the numerical results, we followed a comparison approach between our numerical results and the experimental results of Choi et al [04], and other analytical results proposed by; ASME B31 G modified, [02], PRACTICE DNV-RP-F101 [03] and [05]. The following table 3 presents the geometric data of the tubular samples used and the values of the burst pressures obtained in the experiments carried out by [04].

Table 3. Geometries of artificial corrosion defects, [04].

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

The latter carried out 08 burst tests of corroded pipelines manufactured by the API 5L X65 steel grade, having rectangular corrosions of different dimensions obtained artificially by machining. We also note that the indices (DA, DB, DC, LA, LC, CB, CC) are used as references of the samples proposed by [04].

When we analyze the values of the burst pressures Pf, experimental and numerical (FEM) presented in table 4, we can notice that the percentage of maximum error equal to 4.37% and the average of these errors is of the order of 2.55%, therefore the pressures of the present numerical model are reliable and this last one can be used to make a study of reliability of the corroded pipelines. Regarding the analytical results, the error rate is higher, and it reaches the value of 12.36%, this shift can be justified by the absence of the parameter w in the equations of these analytical models. After this validation, this present numerical model (FEM) can be used to complete this investigation.

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

Pipe	***Pf* Exp [04]**	**Pf EFM [03]**	**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

In this part, the numerical results of the mechanical behavior of corroded pipelines under internal pressure are presented.

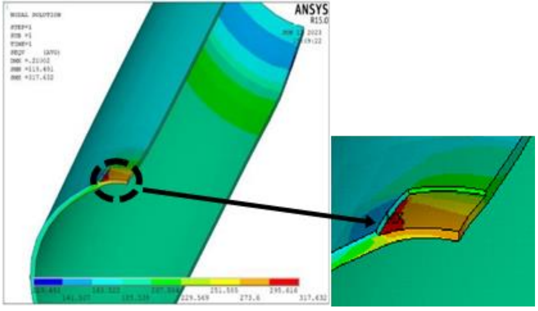

Fig. 3 Variation of the Von Mises stress through the thickness, (d=3mm).

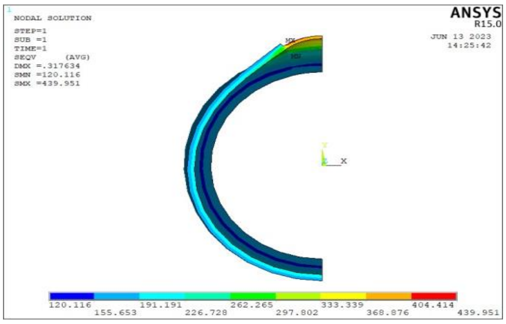

Fig. 4 Variation of the Von Mises stress through the thickness, (d=5mm).

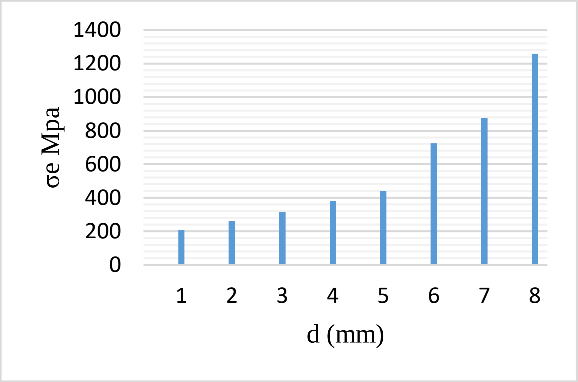

Fig. 5 Von Mises stress as a function of defect depth.

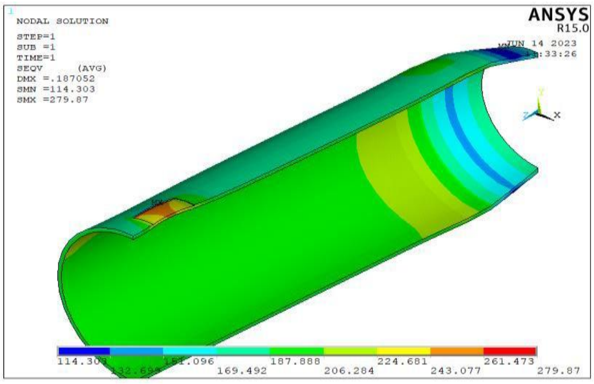

Fig. 5 Variation of Von Mises stress through depth, for two circumferential defects (2DC), (d=2mm)

IV. DISCUSSION

The figure 5 presents the influence of the depth of two defects (circumferential and longitudinal). The depth of the defects varied from 1 mm to 8 mm (from 10 % to 80 % of the thickness). The variation of the equivalent stress of Von Mises was presented, with a constant internal pressure p=15 Mpa and a thickness of 10 mm , where the maximum value is 1176.98 Mpa and the lowest value is 230.536 Mpa. From the analysis of these results, we conclude that the depth controls the Von Mises value, and that when the depth increases, the Von Mises pressure increases, which will say the presence of danger on the reliability of the pipe studied.

V. CONCLUSION

In this paper, a numerical model by the finite element method under the commercial software ANSYS Apdl was implemented. This model allowed us to study a pipeline with an outside diameter equal to 300 mm, a wall thickness of 10 mm and a length L=2000 mm. The results obtained are compared with the results of the analytical model of virgin pipes. After the confrontation and the good agreement between the two results, with a maximum error of about 4.2%. It can be concluded that the most influential parameters on the reliability of the tubular structures are; Internal pressure, pipeline thickness, internal radius and pipe material.

Then, we realized two numerical models with different types of defects (1DL, and 2 DL). Using these models, we performed a series of numerical tests for the four cases, and from the results obtained, we found that the depth of the defect affects the stress more than the spacing Sc and Sl between the defects. On the other hand, the interaction between the defects clearly manifests when these spacings take small values. And for larger spacings we noticed the absence of interactions between the defects, and each defect alone affects the equivalent stress.

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