CORRODED GAS PIPELINE REMAINING LIFE UNDER VARIABLE OPERATING PRESSURE

M.H. Belkacemi[1], D. Benzerga[2*], A.Choutier[3], A. Haddi[4]

[1,2,3]LSCMI, Mechanical Department, University of Sciences and Technology of Oran, , B.P. 1505, 31000 Oran, Algeria
[4] University of Artois, EA 4515, Laboratoire de Génie Civil et géo-Environnement, Béthune F-62400, France
*Corresponding's Author Email: djeb_benz@yahoo.fr

Article History: Received 18 January 2022; Revised 18 February 2023; Accepted 06 March 2023

ABSTRACT*: Gas pipelines are subjected to mechanical and chemical stresses which lead to failures of various types such as corrosion, cracking, deformation and rupture. Corrosion damage to pipelines has become a growing concern in the gas industry. Corrosion defects in the form of pitting caused by the corrosion phenomenon cause high concentrations of stresses and plastic strains thus reducing the strength of the pipe by threatening its structural integrity. Indeed, the internal operating pressure is variable and can generate the phenomenon of fatigue, which is dangerous, given its insidious nature, causing damage to the corroded zone for stress levels well below the yield stress of the material. The standards used in the framework of the rehabilitation of corroded pipes allow the determination of their burst pressure but not their remaining life. To address this issue, we have developed a model based upon damage mechanics to predict the remaining life of a pipe in the presence of an external corrosion defect.*

KEYWORDS : *corrosion, gas pipeline, remaining life, variable operating pressure, fatigue, damage mechanics, finite element.*

1.0 INTRODUCTION

Pipeline transportation is of global importance in the oil and gas industries. It is an evolving system around the world representing appropriate solutions for reliable transport. Indeed, over the past 50 years, pipelines have become the cheapest and safest way to transport large amounts of energy and over long distances [1]. Today, under strong economic pressure, the operating life of structures is often extended, under service conditions which can sometimes be more severe than those foreseen in the design. Gas pipelines are exposed to mechanical and chemical stresses leading to failures of various types such as corrosion, cracking, deformation, and rupture. The deterioration of underground pipelines by the phenomenon of corrosion has become a growing concern in the gas and environmental sectors. European Gas Pipeline Incident Group has published that among 1060 cases of rupture in pipelines, 15.3% were caused by the phenomenon corrosion [2]. The losses of metal in the form of pitting caused by the phenomenon of corrosion, cause concentrations of stresses and significant plastic deformations in the vicinity of the corrosion defects thus reducing the strength of the pipe by threatening its structural integrity and causing its rupture [3-5]. The rupture of the corroded pipe also depends on the variation of the service pressure of the gas which causes fatigue of the structure [6-7]. The stress and strain field as well as the burst pressure closely depend on the geometry of the corrosion defect [8]. Burst is assumed to occur when the operating pressure is greater than the pressure predicted by the various standards used for the evaluation of the corroded pipe burst pressure [9-10]. The periodic inspections by intelligent tool not only allow the localization of corrosion defects but also their dimensions, their nature and the severity of their danger [11]. Managers in gas industry are faced with a major problem given the large number of accidents occurring in gas and oil pipeline networks and the huge rehabilitation budgets that result [12]. The pipes affected by corrosion must be renovated by recalculating the maximum allowable operating pressure (MAOP) according to the geometry of the corrosion defect or by replacing the sections affected by corrosion or by installing new lines to meet demand new consumers or to increase the reliability of the pipeline system [13]. Short-term increases in demand and / or reductions in supply may cause variations in operating pressure, especially during winter. These pressure variations may cause a phenomenon of fatigue which can be dangerous in the vicinity of corrosion defects because of its insidious nature. The current assessment procedures used in the gas pipeline industry for the rehabilitation of corroded pipes (B31G, MODIFIED B31G, RESTRENGH, DNV, Shell, PCORR, Fitnet FFS and the approaches of Choi and Cronin) allow the determination of burst pressure [14-15]. However, the disadvantage of these standards is that they can't predict the remaining life of corroded pipe when the operating pressure is variable. The main motivation for this work is to respond to the concern of Algerian gas pipeline industry leaders to determine the remaining life of a corroded pipeline subjected to variable operating pressure. The study and the analysis of the damage in the vicinity of a corrosion defect of an X65 steel pipe, were carried out with the aim to develop a numerical simulation tool allowing the determination of the remaining life of a superficially corroded pipe.

2.0 MODELLING

Manuscript should content a title, list of authors, abstract, body, conclusions, acknowledgement (if necessary) and references. In this work, we consider that the damage is very localized in the vicinity of the corrosion defect where the plastic deformations are important so that the damage of the material occurs only in a small volume. This is due to the high sensitivity of damage to stress concentrations at the macro scale. This allows us to consider that the effect of damage on the state of stress and strain only occurs in very small damaged areas. The coupling between the damage and the strains can be neglected in the whole of the pipe except in the corrosion defect where the damage develops [16-17]. The locally coupled analysis is well suited for fatigue damage cases since the behavior of the corroded pipe remains elastic everywhere except in the vicinity of the corrosion defect [18]. The critical zone where the equivalent stress is maximum (Figure 1) constitutes the bridge between computation by finite elements and the post processor.

$$\sigma^*\left(M^*\right) = Max\left(\sigma^*\left(M^*\right)\right) \rightarrow M^*$$

The elastoplasticity calculation by the *ANSYS* code allows the determination of the strain and stress fields then the local analysis will deal with the elastoplastic constitutive laws coupled with the damage at the level of the critical zone only.

Taking into account the symmetry of the corroded pipe, a quarter of the pipe was modeled using code *ANSYS* [19] with a parabolic defect taking into account its geometry and the boundary conditions. The stress-number of elements curve allows the best meshing choice of the structure [20].

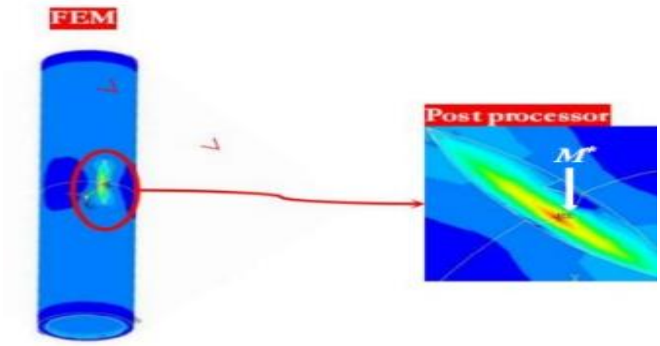


Figure 1: Locally coupled approach of the damage initiation.

A finite element analysis (FEA) was performed using ANSYS simulation software for the determination of the critical zone (*M**) in the vicinity of the corrosion defect where damage of the material develops giving rise to microcracks whose propagation will lead to failure then the bursting of the pipe [21]. A post processor based upon the damage mechanics using coupled damage strain constitutive equations and introducing a variable of continuous isotropic damage [22-23], allows the computation of the conditions of crack initiation from the history of the strain components of the critical zone (*M**) taken as the output of the finite elements.

$$D = \frac{\delta S_D}{\delta S}\ ;\ 0 \le D \le 1 \tag{1}$$

The introduction of the effective stress notion allows to:

$$\tilde{\sigma} = \frac{\sigma}{1 - D} \tag{2}$$

$$\sigma^*(M) = Sup(\sigma^*)$$
$$\text{with}\quad \sigma^* = \sigma_{eq} R_v^{1/2} \tag{3}$$
$$R_V = \frac{2}{3}(1+\nu) + 3(1-2\nu)\left(\frac{\sigma_H}{\sigma_{eq}}\right)^2$$

Rv: is the triaxiality function which depends on the triaxiality coefficient σ_H / σ_{eq}. In the majority of the cases, this criterion is satisfied in the zones with high concentration of stresses with a high value of coefficient of triaxiality σ_H / σ_{eq}.

The resolution of the constitutive equations below in incremental form by the numerical method of Newton, allow the determination of the evolution of the damage of the material in the critical zone within the corrosion defect [24]:

$$\begin{aligned} E_{ij} &= E_{ij}^{e} + E_{ij}^{p} \\ E_{ij}^{e} &= \frac{1+\nu}{E}\frac{\sigma_{ij}}{1-D} - \frac{\upsilon}{E}\frac{\sigma_{kk}}{1-D}\delta_{ij} \\ E_{ij}^{p} &= \frac{3}{2}\frac{\tilde{\sigma}_{ij}^{D}}{\sigma_{eq}}P \quad if \quad f = \dot{f} = 0 \\ D &= \frac{\sigma_{eq}^{2}}{2ES}R_{v}P \quad if \quad p \geq p_{0} \end{aligned} \tag{4}$$

Where $f = \tilde{\sigma}_{eq} - \sigma_s = 0$ is the plastic yield function, σ_s is the threshold of plasticity (the condition $\sigma_{equ} < \sigma_s$ deviates any plastic strain and ensures a pure elastic strain) and P is the accumulated plastic strain.

The method used for solving the above constitutive equations is integration schemes such as the radial return method [25]. It is assumed in a first that all variables of the model are known at the initial time (t_n) and that the behavior is purely elastic.

$$\tilde{\sigma} = \lambda \, tr\varepsilon 1 + 2\mu\left(\varepsilon - \varepsilon_{n}^{p}\right) \tag{5}$$

λ and μ are the Lamé coefficients and 1 is the identity tensor of order 2.

All other "plastic" variables are equal to their values at time (t_n). If this "elastic predictor" satisfies the condition of the load function $f \leq 0$, the assumption is then valid, and the calculation procedure for this time increment is completed. In the contrary case $f > 0$, this elastic state is "corrected" to find the plastic solution.

The method developed above has been implemented in the *ANSYS* commercial code and the post-processor. It will use as data, the parameters of the material and the components of the total deformations. As result, it will give, a function of the internal pressure in the corroded pipe, the damage value, the accumulated plastic strain and the stress components at each step, until initiation of macroscopic cracks in the critical zone. This will permit to determine the remaining life that the corroded pipe can withstand as a function of the variation of inner pressure.

3.0 NUMERICAL RESULTS

The study was carried out on pipes of external diameter of 40'' and a thickness of 12.7 mm in steel X65 whose mechanical properties are given in the Table 1[26].

Table 1: Mechanical properties of X65 steel

Young's modulus	Poisson's ratio	Yield strength	Tensile strength
210.7 (GPa)	0.3	464.5 (MPa)	563.8 (MPa)

For numerical simulation allowing the determination of the remaining life of corroded pipes. Each pipe with its corresponding corrosion defect (extension, width and depth) was subjected to variable operating pressure as function of time. Table 2 below shows the corroded pipes selected for numerical simulation.

Table 2: Various parameters of the corrosion defect (extension, width and depth representing a percentage of the pipe wall thickness)

Defect extension in mm	Defect width in mm				
	C=5	C=10	C=15	C=20	C=25
20	20%	20%	20%	20%	20%
40	30%	30%	30%	30%	30%
60	40%	40%	40%	40%	40%
80	50%	50%	50%	50%	50%
100	60%	60%	60%	60%	60%

The internal pressure of the gas fluctuates as a function of the gas demand (see Figure 2), therefore undergoes variations which cause the phenomenon of fatigue. Fatigue is an insidious phenomenon due to its hidden nature which can cause fractures for stress levels below the yield strength. During service the pipe can be damaged this is explained by the fact that the phenomenon of fatigue is a phenomenon characterized by a strong micro plasticity in the vicinity of micro defects (micro voids, inclusions, precipitates) that are potential sources of damage [15].

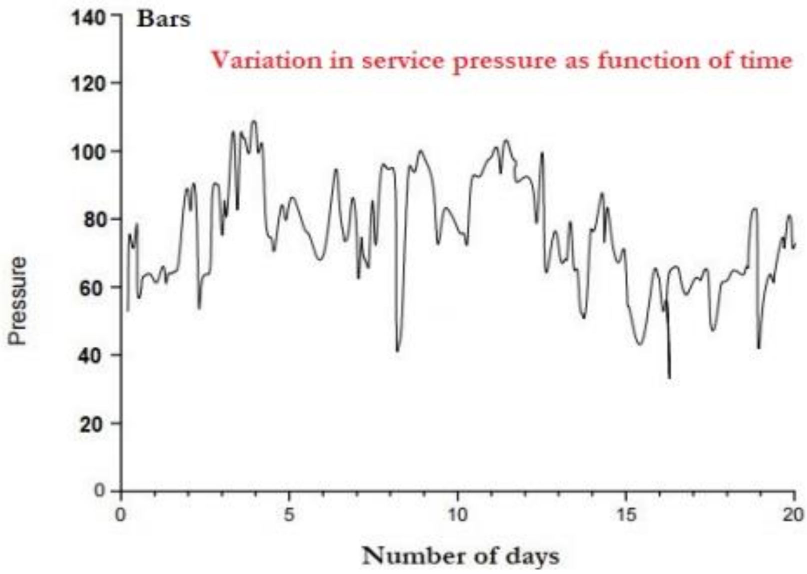


Figure 2: Variation in service pressure as function of time

The method developed above gives as function of the internal operating pressure, the value of the damage, and the accumulated plastic strain and stress components at each instant until a macroscopic crack initiation in the corrosion defect. This allows determining the maximum remaining life that a corroded pipe could support before rupture. The maximum remaining life is the number of years corresponding to the critical value of the damage D_C (corresponding to crack initiation).

In Figure 3, histogram shows the damage as a function of years' number for retained corrosion defects. It is noted that the damage is initiated in the material for a number of years equal to Y_0 (microscopic crack initiation) and the microcrack propagates until a macroscopic crack is obtained for a number of cycles equal to Y_R. Figure 3 also highlights the corrosion defect geometry effect (extension, width and depth) on the corroded pipe remaining life. The calculation of the remaining life of corroded pipes is summarized in the Table 3.

Table 3: The remaining life of corroded pipes in cycles, days and years.

Corrosion defect	Cycles		Days		Years	
width, extension, depth	number of cycles at crack initiation (N_0)	number of cycles at rupture (N_R)	number of days at crack initiation (D_0)	number of days at rupture (D_R)	number of years at crack initiation of (Y_0)	number of days at rupture (Y_R)
Def 1 5 20 20%	1,10E+02	9,30E+02	1,10E+03	9,30E+03	3,01E+00	2,55E+01
Def 2 5 40 30%	9,70E+01	5,59E+02	9,70E+02	5,59E+03	2,66E+00	1,53E+01
Def 3 5 60 40%	8,53E+01	4,98E+02	8,53E+02	4,98E+03	2,34E+00	1,36E+01
Def 4 5 80 50%	8,23E+01	3,61E+02	8,23E+02	3,61E+03	2,25E+00	9,89E+00
Def 5 5 100 60%	5,56E+01	2,67E+02	5,56E+02	2,67E+03	1,52E+00	7,32E+00
Def 6 10 20 20%	1,32E+02	9,12E+02	1,32E+03	9,12E+03	3,62E+00	2,50E+01
Def 7 10 40 30%	1,01E+02	5,41E+02	1,01E+03	5,41E+03	2,77E+00	1,48E+01
Def 8 10 60 40%	7,98E+01	4,89E+02	7,98E+02	4,89E+03	2,19E+00	1,34E+01
Def 9 10 80 50%	7,33E+01	3,76E+02	7,33E+02	3,76E+03	2,01E+00	1,03E+01
Def 10 10 100 60%	6,74E+01	3,21E+02	6,74E+02	3,21E+03	1,85E+00	8,79E+00
Def 11 15 20 20%	1,23E+02	8,95E+02	1,23E+03	8,95E+03	3,37E+00	2,45E+01
Def 12 15 40 30%	1,01E+02	6,32E+02	1,01E+03	6,32E+03	2,77E+00	1,73E+01
Def 13 15 60 40%	8,97E+01	5,29E+02	8,97E+02	5,29E+03	2,46E+00	1,45E+01
Def 14 15 80 50%	7,46E+01	4,16E+02	7,46E+02	4,16E+03	2,04E+00	1,14E+01
Def 15 15 100 60%	6,66E+01	3,49E+02	6,66E+02	3,49E+03	1,82E+00	9,56E+00
Def 16 20 20 20%	9,70E+01	8,14E+02	9,70E+02	8,14E+03	2,66E+00	2,23E+01
Def 17 20 40 30%	8,80E+01	6,45E+02	8,80E+02	6,45E+03	2,41E+00	1,77E+01
Def 18 20 60 40%	7,90E+01	5,75E+02	7,90E+02	5,75E+03	2,16E+00	1,58E+01
Def 19 20 80 50%	7,21E+01	4,68E+02	7,21E+02	4,68E+03	1,98E+00	1,28E+01
Def 20 20 100 60%	6,37E+01	3,65E+02	6,37E+02	3,65E+03	1,75E+00	1,00E+01
Def 21 25 20 20%	8,90E+01	7,97E+02	8,90E+02	7,97E+03	2,44E+00	2,18E+01
Def 22 25 40 30%	7,82E+01	6,25E+02	7,82E+02	6,25E+03	2,14E+00	1,71E+01
Def 23 25 60 40%	6,98E+01	4,85E+02	6,98E+02	4,85E+03	1,91E+00	1,33E+01
Def 24 25 80 50%	6,28E+01	3,55E+02	6,28E+02	3,55E+03	1,72E+00	9,73E+00
Def 25 25 100 60%	5,35E+01	2,98E+02	5,35E+02	2,98E+03	1,47E+00	8,16E+00

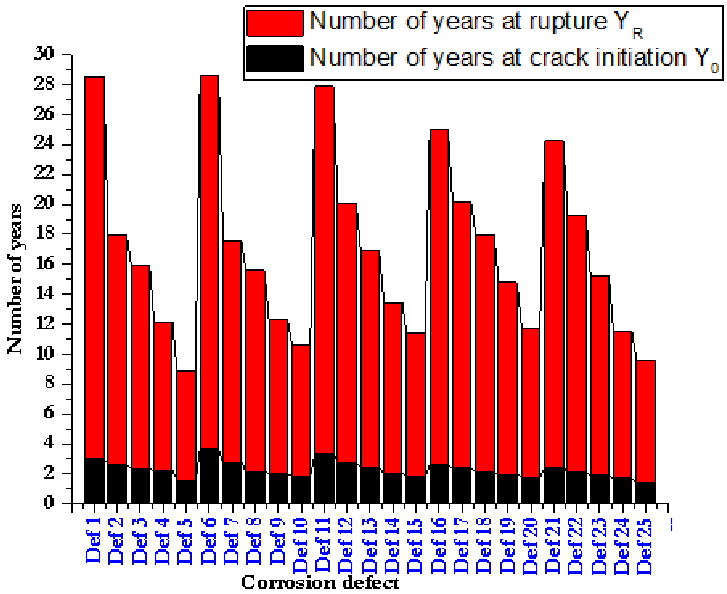
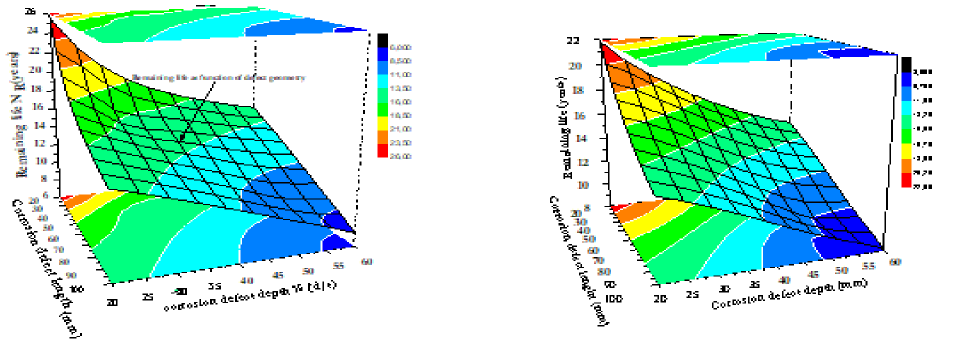


Figure 3: Remaining life as function of corrosion defect geometry

The histogram groups the remaining life results obtained in number of years for each corrosion defect. Investigated pipeline has an initial of years Y0 whose damage appeared (crack initiation). On the other hand, the pipeline considered can go up to a YR number of years (the maximum remaining life) related to the damage causing a rupture. It can be seen that the life Y0 at crack initiation or YR at failure decreases as the extension and the depth of the defect increase while keeping a constant width. It is also noted that the remaining life decrease, when the width of the defect becomes important, this can be explained by the increase in the loss of metal and the increase in the volume of the corrosion defect.

The remaining life of a corroded pipe as a function of the geometry of the corrosion defect represents a three-dimensional surface, Figure 4. The maximum life that a pipe with a certain geometry of the corrosion defect could withstand is located in the zone safety limited by the 3D surface corresponding to the rupture of the corroded zone. The three-dimensional surface can be interpreted differently by determining, for a given residual life, the size of the critical defect. The zone located under the three-dimensional surface is the range of variation of the remaining life not to be exceeded for a critical size of the defect. Indeed, for a corrosion defect of width c, depth t and extension l, the life of which is below the curve, this defect does not cause the rupture of the pipe. In Figure 4, we have represented only the two cases where the width of the defect has the smallest value c = 5 mm and the largest value c = 25 mm to highlight the effect of the width on the remaining service life.



Remaining life in years for width c = 5mm   Remaining life in years for width c = 25mm

Figure 4: Three-dimensional representation of the remaining

4.0 CONCLUSION

In this study, an approach for predicting the remaining life and assessing the integrity of corroded gas pipelines subjected to cyclic pressure was investigated. Cyclic pressure has a greater influence on the life of corroded gas pipelines. The proposed approach uses locally coupled analysis which is most appropriate for fatigue failure cases when the structure remains elastic everywhere except in the critical point. The determination of the critical point is the bridge between computation FEM and the post processor. This method is much simpler and saves a lot of computer time compared to the fully coupled analysis which takes into account the coupling between damage and strain in the whole structure. The variation in the corrosion defect geometry was considered to calculate the cyclic damage at the critical point. Due to the presence of non-linearity in the formulas, an iterative method was used to calculate the remaining life. The described method provides a basis for determining the priority of inspecting corroded pipelines and, ultimately, for developing a renewal strategy. It is a real decision-making tool for those in charge who manage the transport of gas by pipelines.

REFERENCES

[1] A. G. Rafael, S.S. Mauricio, B. A. Emilio, S. Franck, and M. Felipe, "Reliability assessments of corroded pipelines based on internal pressure", *Engineering Failure Analysis*, vol. 98, pp. 190-214, 2009.

[2] Zhao, Y., Mingliang, L., Min S. and Kingie, J. "Research on Leakage Detection and Analysis of Leakage Point in the Gas Pipeline System", *Open Journal of Safety Science and Technology* ,vol.11, no.3, 2011.

[3] Zhong-ying H., Xiao-guang H, ''Stress corrosion behavior of X80 pipeline steel in the natural seawater with different dissolved oxygen contents'', *Frattura ed Integrità Strutturale* vol. 50, pp. 21-28, 2019.

[4] Ankang C., Nian-Zhong C. "Corrosion fatigue crack growth modelling for subsea pipeline steels", *Ocean Engineering*, vol. 142, pp.10–19, 2017.

[5] Dmytrakh I.M., Leshchak R.L., Syrotyuk A.M. "Influence of sodium nitrite concentration in aqueous corrosion solution on fatigue crack growth in carbon pipeline steel", *International Journal of Fatigue,* 128, 105192, 2019.

[6] Chinedu I. O., Brian B., Ian J. D. "Pipeline failures in corrosive environments – A conceptual analysis of trends and effects", *Engineering Failure Analysis,* vol. 53, pp.36–58, 2015.

[7] Mansor N.I.I., Abdullah S., Ariffin A.K., Syarif J. "A review of the fatigue failure mechanism of metallic materials under a corroded environment", *Engineering Failure Analysis,* vol. 42, pp. 353–365, 2014.

[8] Xu, L.Y., Cheng. Y.F. "Reliability and failure pressure prediction of various grades of pipeline steel in the presence of corrosion defects and pre-strain", *International Journal of Pressure Vessels and Piping*, vol. 89, pp. 75-84, 2012.

[9] Ehsan A., Rouzbeh A., Vikram G., Jonathan B., Christopher C., Nima K., Genserik R. "Developing a dynamic model for pitting and corrosion-fatigue damage of subsea pipelines", *Ocean Engineering,* vol. 150, pp. 391–396, 2018.

[10] Mechab B., Medjahdi M., Salem M., Serier B. "Probabilistic elastic-plastic fracture mechanics analysis of propagation of cracks in pipes under internal pressure", *Frattura ed Integrità Strutturale*, vol. 54, pp. 202-210, 2020.

[11] Budhe S., Banea M.D., de Barros S. "Prediction of the burst pressure for defective pipelines using different semi-empirical models", *Frattura ed Integrità Strutturale,* vol. 52, pp. 137-147, 2020.

[12] Zelmati, D., Bouledrouab, O., Hafsid, Z., Djukice, M. B. "Probabilistic analysis of corroded pipeline under localized corrosion defects based on the intelligent inspection tool", *Engineering Failure Analysis*, vol. 115, 2020.

[13] Tee, K. F., Wordu, A. H. "Burst strength analysis of pressurized steel pipelines with corrosion and gouge defects", *Engineering Failure Analysis*, vol. 108, 2020.

[14] Zelmati, D., Ghelloudj, O., Amirat, A. "Reliability estimation of pressurized API 5L X70 pipeline steel under longitudinal elliptical corrosion defect", *The International Journal of Advanced Manufacturing Technology,* vol. 90, pp. 2777–2783, 2017.

[15] Berrekia, H., Benzerga, D., Haddi, A. "Behavior and damage of a pipe in the presence of a corrosion defect depth of 10% of its thickness and highlighting the weaknesses of the ASME/B31G", *Frattura ed Integrità Strutturale*, vol. 49, pp. 643-654, 2019.

[16] Lemaitre, J., Benallal, A., Marquis, D. "Lifetime prediction of structures in anisothermal viscoplasticity coupled to damage", *Nuclear Engineering and Design* , vol. 133, no. 3, pp. 345-360, 1992.

[17] Lemaitre, J. Micro-mechanics of crack initiation. In: Knauss W.G., Rosakis A.J. (eds) *Non-Linear Fracture. Springer*, Dordrech, 1990.

[18] Lemaitre, J. A Course on Damage Mechanics. Berlin; New York: *Springer, 1996.*

[19] Regard, A., Berrekia, H., Benzerga, D., Haddi, A. "Repair and rehabilitation of corroded HDPE100 pipe using a new hybrid composite", *Frattura ed Integrità Strutturale*, vol. 56, pp. 115-122, 2021.

[20] Benzerga, D. Burst pressure estimation of corroded pipeline using damage mechanics. [2015] *Mmssd, ISBN* 978-3- 319-14531-0. doi: 10. 1007/978-3-319-14532-7 springer.

[21] Chouiter, A., Benzerga, D., Haddi, A. and Tamine, T. "Prediction of cycle life of expansion bellows for fixed tube sheet heat exchanger", *Frattura ed Integrità Strutturale*, vol. 47, pp.30-38, 2019.

[22] Lemaitre, J., and Chaboche, J. L., Mécanique des Matériaux Solides. *Dunod*, Paris, 1985.

[23] Benzerga, D., Haddi, A., Lavie, A. "Effect of non-polluting and renewable load on delamination of a composite biomechanical material", *Journal of Mechanical Engineering and Technology*, vol. 6, no. 1, 2014.

[24] Benallal, A., Billardon, R., and Doghri, I. "An integration algorithm and the corresponding consistent tangent operator for fully coupled elastoplastic and damage equations", *International Journal for Numerical Methods in Biomedical Engineering* (E4), pp. 731–740, 1998.

[25] Silva, M., Taylor, W. "Análise elastoplastica de estruturas metálicas utilizando algorítmos de retorno radial", *Revista internacional de métodos numéricos para cálculo y diseño en ingeniería*, vol. 20, no.3, 2004.

[26] António.A. F, Abílio M. P., Renato N.J. "Monotonic and ultra-low-cycle fatigue behaviour of pipeline steels experimental and numerical approaches", pp. 36-120, 2018.