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ASSESSMENT OF STRESS CORROSION CRACKING DAMAGE CONSIDERING THE LOAD INTERACTION EFFECT

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Abstract- Pipelines are a highly dependable method of transporting fluids under pressure. These pipelines, like any mechanical structure, can have flaws. The severity of these defects can be exacerbated if the pipeline transports corrosive fluids. The primary objectives of this paper are to compare the various types of cracking defects that can occur in a longitudinally welded metallic pipeline and to investigate the effect of the most influential parameters on corrosion cracking. A non-linear numerical model of damage accumulation that takes into account the interaction effect of loading is presented for this purpose. This model was used in a parametric analysis to assess the harmfulness of the corrosion cracking defects.

Keywords: Fatigue Corrosion, Pipeline, Numerical Model, Damage Accumulation, Internal Pressure, Cyclic, Stress Corrosion Cracking.

1. INTRODUCTION

Gas pipelines are always at risk of being damaged by external or environmental interference when used to transport large amounts of natural gas, water, or any other pressurized fluid [1].

These pipelines are vulnerable to leaks or even ruptures, which are classified as pipeline integrity failures. A pipeline crack or corrosion, no matter how minor, can pose a permanent hazard, resulting in serious employee injury and/or property damage [2]. This is what drives all oil companies to develop solutions to reduce pipeline ruptures, the consequences of which are frequently disastrous [3-6].

The study of the behavior of buried pipelines must be viewed as a physical-chemical phenomenon that considers the material's mechanical properties as well as the metal corrosion mechanism, which is an electrochemical phenomenon linked to a series of considerations leading to complex electrical measurements [7].

All of these mechanical and chemical failures cannot be treated unless the abrasiveness of the soil or the transported fluid is determined. The abrasiveness of the soil is dependent not only on the mineralogical character of the soil but also on its moisture content, which justifies the interest in the conductivity of the soil, its pH, the chemical composition of the soil material, and its impregnation water, but also in the variation of the soil moisture, aeration, and any data that generate significant fluctuations in the characteristics of the aggressive environment [8].

The pipeline transmission line has a relatively protected metal surface from corrosion thanks to a thin oxide film. The flow of fluid in a pipeline can contain solid abrasive particles that can remove the oxide layer and expose the unprotected active metal. Because bare metal oxidizes quickly, electrochemical corrosion may occur. Steel, which is the most common structural material in pipelines, forms a protective iron oxide layer. Because iron oxide is softer than steel, abrasive action of hard particles can easily remove it [9]. The transported fluid can then cause corrosion pitting on the tube's inner surface, leading to cracks and, eventually, leakage or structural failure [10].

In most cases, a coating with a suitable corrosion protection material (passive corrosion protection) and cathodic protection are required to protect pipelines against environmental influences and thus corrosion in order to avoid loss of value and operational downtime, dismantling, and so on [11]. A careful treatment of the corrosion protection material must be ensured. A failure of these protection systems can have a rapid impact on the pipeline's integrity.

However, the most effective tools to avoid structural unavailability or severe accidents that could lead to natural disasters are residual life assessment methods. Indeed, several organizations operating in the field of the transport of pressurized fluid have developed models to estimate the harmfulness of defects that may be present in pipelines, including corrosion defects [12-16]. These methods enable maintenance operations to be planned in advance, ensuring the structure's continued operation in safe working conditions.

According to these organizations, most of pipelines failures are caused by corrosion pitting, stress corrosion cracking and external mechanical aggressions. Some excavation work performed by construction equipment can result in pipe damage or perforation. This impact may cause dents, notches or combinations thereof. Removal of the protective coating after this impact can also initiate corrosion of the pipeline and cause corrosion fatigue.

Crack initiation complications and ruptures caused by stress concentrations account for more than 70% of all ruptures in service [17-18]. The presence of a geometric discontinuity, such as a notch, causes the pipe's resistance to rupture to weaken. It reduces the pipe's cross-section, making it more sensitive to operating pressure and soil movement stresses. The effect of local stress amplification then exponentially increases the defect's harmfulness [10].

The fluid transported by the pipeline is under pressure. This pressure is a source of stress on the pipe wall, especially when it is cyclical. The soil around the pipeline can move and is another source of stress. Pipe manufacturing processes such as welding can introduce residual stresses. These are the reasons why industrialists seek to control the propagation and arresting of a crack, as well as the control of corrosion in a pipeline, in order to achieve a higher level of reliability and performance [19-20].

This paper presents a nonlinear numerical model for assessing damage accumulation in a metal pipe under cyclic loading. The details and validation study for this model were developed by the authors in a previous study published in [21-22]. This paper will only include the most important elements. This numerical model will be adapted to study stress corrosion cracking in this paper by incorporating a fatigue crack growth rate estimation model. This model will be used in a parametric study to investigate the effect of fatigue corrosion on pipeline integrity.

2. STRESS CORROSION CRACKING

2.1. Corrosion Damage

Corrosion damage caused by intergranular attack, pitting and exfoliation, frequently initiates cracks in metallic materials. Such issues are common on aging pipelines that have corroded as a result of environmental exposure. Pitting corrosion, for instance, has been reported as a result of electrochemical attack or the transported fluid on metal surfaces or within the inner and outer surfaces of a pipe [23].

As a result, multiple cracks frequently form at localized corrosion, lowering the residual strengths and fatigue lifetimes of aging pipelines significantly. Because an increasing number of aging pipelines reach, if not exceed, their expected life span, understanding the effect of corrosion on fatigue life is critical. Specifically, for pipeline failure limits and reliability evaluations during the design simulation phase [9].

Many studies have demonstrated that the corrosion environment has a significant negative impact on the properties of metallic materials such as fatigue strength, pit nucleation and extension, crack propagation resistance, and pit-to-crack transition [24-33]. This is due to the fact that fatigue cracks initiate and develop more easily on metal surfaces in a corrosive medium than they do in inert environment.

Mathematical models that allow for a quantitative description of pit-to-crack transition [24, 34] and pit nucleation and extension [24-25], S-N corrosion fatigue properties [28-30], and corrosion crack propagation laws [32, 33, 35] have been presented in a number of studies.

Several studies [24, 35-36] proposed methods for estimating corrosion fatigue lifespan by superimposing the rate of crack growth caused by corrosion on the rate of mechanical fatigue. This last model is generally based on linear elastic fracture mechanics. The same approach is employed in the current paper.

In fact, mechanical fatigue and corrosion effect are frequently present concurrently, and their synergistic interaction has far more detrimental effects on crack growth than either of them acting alone [28, 34]. Furthermore, many ageing metallic pipelines are more prone to variable amplitude loads than constant amplitude loads in a corrosion environment [36-39]. As a result, when evaluating the harmfulness of stress corrosion cracking in internally pressurized pipelines, this phenomenon must be taken into account.

Fatigue lifetimes are also affected by the load interaction [40-41]. As a result, it is critical to fully understand the synergistic effect of corrosion and fatigue loading, as well as the effect of load interaction on fatigue lifespan, in order to ensure the safe operation of metallic structures subjected to internal pressure.

Additionally, it is valuable to have a practical approach for evaluating the previously mentioned effects on structural integrity in order to develop rational maintenance plan. This can be achieved by understanding and assessing corrosion fatigue damage during the exploitation phase for metallic pipelines, which is one purpose of the present study.

2.2. Stress Corrosion Mechanism

The mechanical strength of a cracked structure is influenced by the stress intensity factor (K_I) assessed in the cracked structure under cyclic loading and in the absence of the aggressive effect of the external environment [31]. The growth of the crack is stable as long as the maximum stress intensity factor (K_{MAX}) measured in the structure is less than the material's fracture toughness (K_{IC}).

Under the presence of the effect of an aggressive external medium, crack growth becomes unstable, and the previous criterion ($K_I<K_{IC}$) is no longer sufficient to ensure resistance in corrosive environments [42].

The crack propagation mechanism observed during cyclic loading of a cracked part exposed to the effect of a corrosive environment is known as Stress Corrosion Cracking (SCC). In these load cases, the state of the cracks becomes unstable, depending primarily on the applied loading, the material, and the nature of the corrosive fluid [35]. Thus, a crack that was initially unable to propagate in an inert environment can propagate under the combined effect of cyclic stress and corrosion, eventually causing the structure to fracture.

The stress corrosion cracking does not affect all materials; the initiation of this mechanism requires the fulfillment of certain conditions that promote the initiation and propagation, and these conditions are related to the material, the environment, and the loading (Figure 1) [43].

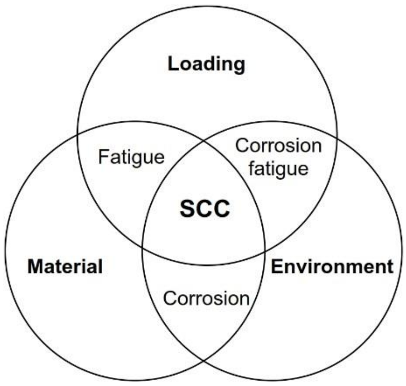

Figure 1. The conditions that must be present in order for stress corrosion to initiate

Previous researchers as in [42-46] investigated cracked specimens in a corrosive environment to determine the time required to observe the onset of the propagation of the crack as a function of the applied stress intensity range. The findings revealed that when the stress intensity is low, the time required to initiate propagation becomes more important. The crack does not propagate if the applied stress intensity K_I is less than the K_{ISCC} limit value (Figure 2).

The threshold stress intensity factor K_{ISCC} was discovered to be the main parameter capable of assessing the mechanical strength of a cracked part in a corrosive environment [45-46]. This parameter is intrinsically linked to the couple (material, environment).

It is worth noting that the stress intensity calculated at the crack is the primary driver for crack propagation in a corrosive environment. The cycle of crack propagation begins with the initiation of propagation as a result of loading and corrosion. Figure 2 summarizes the kinetics of stress corrosion cracking propagation. In this figure, there are three major regions that are easily distinguished.

- *Region 1:* This is the zone where the material is only mildly susceptible to the effects of stress corrosion. This zone is restricted to low loading values and stress intensities less than K_{ISCC}. The stress intensity factor influences the crack growth rate in this region.
- *Region 2 (plateau region):* It is distinguished by the movement to a sufficient level of stress intensity, which results in a sufficient growth rate for crack progression. The stress corrosion cracking begins at this loading level. The initial crack, which has a stress intensity greater than K_{ISCC}, progresses with a constant speed known as plateau speed $(da/dN)_p$, and this speed remains stable despite the increase in the stress intensity factor caused by crack progression.
- *Region 3:* Similar to region 1, this zone exhibits behavior where the (da/dN) parameter is influenced by the stress intensity factor. The limiting value of K_I that gives rise to the start of zone 3 is extremely important. The effect of high values of stress intensity approaching the value of fracture toughness K_{IC} causes an increase in crack growth rate in this zone.

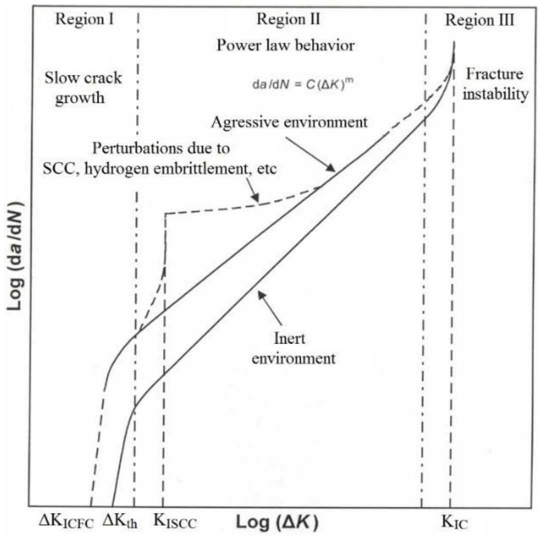

Figure 2. The rate of crack growth in an inert medium versus a corrosive medium [46]

2.3. Stress Corrosion Modeling

When a crack defect is present in a structure subjected to a cyclic stress intensity with a maximum value less than the K_{ISCC} parameter, the stress corrosion effect on crack propagation does not occur [44-46]. In this case, crack propagation is caused by the mechanical effect produced by each loading cycle. The action of the corrosive environment alters the response of the material in terms of crack propagation resistance under these loading conditions, according to experimental work [43].

The curve linking the crack growth rate (da/dN) to the applied stress intensity is modified while maintaining a linear behavior on a logarithmic scale. Thus, the Paris law [47] can be used to estimate crack propagation by taking into account new parameters that have been modified by the effect of corrosion. This mode of fatigue behavior occurs for materials with very high K_{ISCC} values or when the applied loading is low in comparison to this limit.

Crack propagation is governed by time and the applied stress intensity factor in the presence of a corrosive environment and under the action of stress corrosion. The high loading application, which produces the initiation condition, causes the crack to propagate at a rate of $(da/dt)_p$, as determined by the stress corrosion curve (Figure 2).

Knowing the crack growth rate for one second allows one to easily calculate the crack growth rate for each cycle by dividing the speed $(da/dt)_p$ by the frequency f (Equation (1)). It should be noted that this is only true if the applied stress causes the crack to react in the manner shown in region 2 (Figure 2). This case is of particular interest in the current study.

$$\left(\frac{da}{dN}\right) = \frac{1}{f}\left(\frac{da}{dt}\right)_p \quad (1)$$

The first effect of frequency can be seen in this expression, which indicates that if the number of cycles applied per second is large, the propagation of the crack after each loading cycle is low due to the short duration of the cycle applied.

The calculation of corrosion fatigue life necessitates knowledge of the crack propagation law, which is embodied by the evolution curve ($da/dN=f(\Delta K)$). This corrosive environment curve is built on the crack propagation curve obtained in an inert environment [46]. This curve takes into account the stress corrosion parameters ($(da/dt)_p$ and K_{ISCC}) as well as the effect of the solicitation frequency.

A model for determining the crack propagation curve has been proposed based on experimental observations [48]. This model, which takes into account the superposition of crack propagation caused by the mechanical effect and crack propagation caused by the stress corrosion effect, can be written in the form of Equation (2).

$$\left(\frac{da}{dN}\right)_{SCC}=\left(\frac{da}{dN}\right)_S+\left(\frac{da}{dN}\right)_C \tag{2}$$

The stress corrosion curve is used to derive the expression for the cracking rate $(da/dN)_C$ shown in Equation (2). During the interval where the stress intensity factor is superior to K_{ISCC}, this parameter is considered constant. As a result, the expression for the propagation rate due to corrosion effect can be deduced. The expression can be displayed in the simplified form shown in Equation (3). It should be noted that this equation takes into account the general case in which the load ratio is asymmetrical ($K_{MAX}\neq -K_{MIN}$).

$$\left(\frac{da}{dN}\right)_C=\frac{\alpha}{f}\left(\frac{da}{dt}\right)_P \tag{3}$$

where,

$$\alpha=\frac{1}{2}-\frac{1}{\pi}\arcsin\left(\frac{K_{ISCC}-K_{MOY}}{K_{MAX}-K_{MOY}}\right) \tag{4}$$

$$K_{MOY}=\frac{K_{MAX}+K_{MIN}}{2} \tag{5}$$

The Paris law as described in Equation (6) can be used to express the fatigue progression component shown in Equation (2).

$$\left(\frac{da}{dN}\right)_S=C\left(\Delta K\right)^m \tag{6}$$

The phenomenon of crack closure was discovered during experimental testing on specimens subjected to cyclical loading [49]. Due to the contact between the crack surfaces, it was uncovered that the crack begins to close before reaching K_{MIN} which represents the minimum value of the applied load's stress intensity factor. It appears that the crack stops closing at the stress intensity (K_{OP}) value at which it opens.

Due to the closing effect, Elber [49] assumes that the part of the cycle below K_{OP} does not contribute to fatigue crack propagation and defines an effective stress intensity range (ΔK_{eff}), as shown in Equation (7).

$$\left(\frac{da}{dN}\right)_S=C\left(\Delta K_{eff}\right)^m \tag{7}$$

2.4. Stress Intensity Factor

The modified Paris model (Equation 7) is used in this study to compute the number of cycles to fatigue of a pipe submitted to stress corrosion cracking. After accounting for the effect of crack closure and some rearrangement, the effective stress intensity range can be written in the form of Equation (8).

$$\Delta K_{eff}=0.25K_{MAX}+0.5K_{MIN}+0.25\frac{K_{MIN}^{\ 2}}{K_{MAX}} \tag{8}$$

It should be noted that the crack propagation rate caused by the effect of stress corrosion remains constant throughout the crack propagation cycles. Meanwhile, the crack growth rate caused by the mechanical effect of cyclic loading increases with the stress intensity factor, which depends on the crack size.

After several loading cycles, the stress intensity factor becomes more significant, so the propagation rate caused by the applied loading increases and becomes more dominant than the propagation rate caused by the stress corrosion effect, which remains stable. In the vicinity of high K_I values, the sum of these two growth rates approaches the one produced by cyclic loading, and the crack propagation curve approaches the initial one due to mechanical effect (Figure 2).

Newman's approach [52] was found to provide the best engineering prediction of the stress intensity factor for a plate part-through crack by several authors [50-51]. To take into consideration the finite thickness of the structure surface and the plasticity due to cracking, several authors incorporated correction factors for both the surface sides of the structure and the plastic zone in the vicinity of the crack tip [51, 53].

A modified form of this model that has been adapted for thin-walled shells with cracks of dimension $(a/c)\leq 1$ is given in Equation (9). It should be noted that a correction factor (f_1+a^{f2}) was introduced in [54] to account for the position of the crack (internal or external) and improve results for high pressures.

Authors [54] adjust the factors f_1 and f_2 to achieve the best possible agreement with numerical results from a developed and validated finite element model. The value of f_1 for internal cracks, which is the focus of this study, is 0.0447, and the value of f_2 is 0.00188.

$$K_I=\left(f_1+a^{f2}\right)\cdot k_1\,p\sqrt{a}\,M_{TM}\left(1+k_2\,a^s\right) \tag{9}$$

where,

$$M_{TM}=\frac{1}{1-\frac{a}{t}}\left(1-\frac{\frac{a}{t}}{\sqrt{1+\frac{6.4\,c^2}{\left(D_I+D_O\right)\times t}}}\right) \tag{10}$$

$$k_1=\frac{\sqrt{\pi}\,k_3D_I}{2\times t} \tag{11}$$

$$k_2 = \frac{t^{-s}}{k_3} \times \sqrt{\frac{c}{a}} - 1 \quad (12)$$

$$k_3 = \frac{1.13 - 0.1 \times \frac{a}{c}}{1 + 1.464 \left(\frac{a}{c}\right)^{1.65}} \quad (13)$$

$$s = 2 + 8\left(\frac{a}{c}\right)^3 \quad (14)$$

It has been demonstrated in [54] that the calibrated analytical model (Equation (9)) produces results that are similar to those of the numerical model, and can thus be put to use in order to calculate the stress intensity factor and estimate the fatigue life of a cracked pipe. In the current study, this model is used in a numerical model of damage accumulation to analyze the severity of stress corrosion cracking in pipelines subjected to variable amplitude loading.

3. DAMAGE ACCUMULATION MODEL

The main objective of the present paper is to compare the harmfulness of various types of corrosion defects present in a longitudinally welded metal tube. This is made possible by using a nonlinear numerical model that allows for the estimation of the fatigue damage accumulation *D*. The fracture mechanics parameters are used in this model.

The load interaction effect is taken into account in this numerical model. This model's algorithm employs a modified model to account for the effect of stress corrosion cracking. This accumulation damage model is detailed in greater depth below.

To estimate fatigue lifespan of mechanical structures under random spectrum loading, certain accumulation damage methods, such as the Palmgren-Miner and modified Miner models, have been suggested in the literature [8, 40, 55-57].

Despite its simplicity, the linear cumulative Palmgren–Miner model [56] appears to be useful in predicting fatigue life. This model is described in Equation (15). The integral form of Equation (15) for the *i*th stress cycle in a block of real random spectrum representing load history is Equation (16).

$$D = n / N \quad (15)$$

$$N_{b\_Block} \times \sum_{i=1}^{k} \Delta D_i = N_{b\_Block} \times \sum_{i=1}^{k} \frac{1}{N_i} = 1 \quad (16)$$

Several studies [8, 40] discovered that, despite surpassing the Palmgren-Miner model in prediction accuracy, the modified Miner models [55-57] require a significant set of experimental datasets to identify the damage buildup in a structure. The difficulty and complexity of distinguishing fatigue crack formation and propagation is one of these models' drawbacks.

It has been proven that the load interaction has a considerable impact on fatigue failure of a structure under random spectrum loading [8]. The inadequacy of the abovementioned accumulation damage methods to account for load interaction in fatigue analysis under arbitrary spectrum loading is their one shortcoming.

The current study presents a nonlinear model for estimating cumulative damage that is derived from the research of Thun et al. [35]. More details concerning the validation of this model are available in [22].

The damage accumulation is estimated using an analytical model in the study led by Thun et al. Figure 3 depicts the approach used in the current research, which is based on a numerical estimation of the cumulative damage. The pressure peak p_i is used for $n_i = 1$ cycle in this figure. This algorithm, written in *C*, estimates the cumulative damage after applying N_{b_Block} cycles. A total of *k* pressure peaks are present in each cycle. The algorithm's pressure peaks correspond to variations in the internal pressure of the pipe.

The fatigue damage accumulation process can be used to model fatigue life using Equations (2), (3), (7), (8), (9), (17), crack and pipe geometries and material properties, as well as actual random spectrum load history, as shown in Figure 3.

$$\Delta D_i = n_i / N_i \quad (17)$$

From Equation (17), the fatigue damage increment ΔD_1 and the damage D_1 for the first stress cycle in a block of actual random spectra can be calculated. Likewise, using the same equation, $N_{2,equ}$ can be calculated from the current damage accumulation D_1 and the second stress cycle. The fatigue damage increment ΔD_2 due to the second cycle of pressure and the current damage D_2 can be obtained by substituting ($n_2+N_{2,equ}$) into Equation (17).

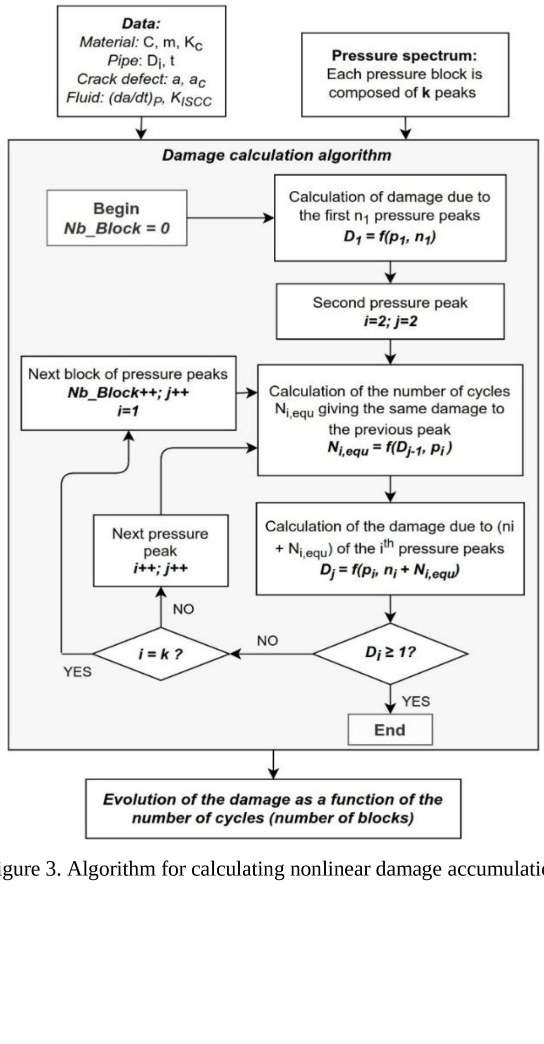

Figure 3. Algorithm for calculating nonlinear damage accumulation

The fatigue damage increase referring to each consecutive neighboring loading case in actual arbitrary spectra loading data may be evaluated using this cycle-by-cycle cumulative damage computation. Furthermore, the cumulative fatigue damage throughout the whole loading history may be calculated.

The Palmgren-Miner rule states that the fatigue accumulation damage computation is halted when the damage magnitude exceeds the threshold damage value (or roughly the value of unity). The accumulative number of stress cycles relating to final failure is then calculated.

The cumulative damage method proposed in this paper can then be used to investigate the impact of load interaction on the fatigue behavior of a structure under internal pressurization.

Relevantly, the model's parameters and fatigue accumulative damage can be determined quickly and easily to assist industrialists in making maintenance planning decisions for defected pipelines.

4. PARAMETRIC ANALYSIS

The main purpose of this analysis is to look into the impact of the main parameters on the harmfulness of corrosion defects in metallic pipelines subjected to varying magnitudes of stress.

To accomplish this, a parametric study is carried out on a pipe made of X52 steel, the mechanical properties of which are shown in Table 1 and the dimensions of which are shown in Figure 4. The Young modulus of this material is 200 GPa, the Poisson's ratio is 0.3, the yield strength is 410 MPa and the ultimate tensile strength is 498 MPa.

It should be noted that this tube is welded longitudinally and thus has three different areas whose mechanical properties vary: the base metal, the weld bead, and the HAZ.

Table 1. Mechanical properties of three pipe zones

Material	Parameters of Paris law		Critical fracture toughness
	C	m	K_{IC} (MPa.m$^{0.5}$)
Base metal	3.3×10^{-09}	2.74	53.36
HAZ	1.13×10^{-09}	3.25	53.36
Weld metal	1.04×10^{-09}	3.28	61.02

Figure 4. Pipe dimensions

Stress corrosion affects X52 steel, which is primarily used in piping. Table 2 displays corrosion data from two different environments, which were used in this study to examine the effect of stress corrosion cracking parameters.

Table 2. Corrosion parameters of the two studied fluids

Environment	K_{ISCC} (MPa.m$^{0.5}$)	$(da/dt)_p$ (mm/s)
Ethanol	33	9×10^{-9}
Carbonate-Bicarbonate	21	5×10^{-9}

The pressures used to transport fluids in pipelines are determined by the elastic limit of the pipe's material as well as its dimensions. In this paper, we attempt to simulate the behavior of a structure in the presence of cracking or corrosion cracking after it has been pressurized.

Figure 5 depicts a pressure spectrum with variable amplitude ranging from 28 MPa to 56 MPa for this purpose. The reason for selecting these two pressure values is that 28 MPa represents a medium pressure and 56 MPa represents a high pressure in relation to the pipe under consideration.

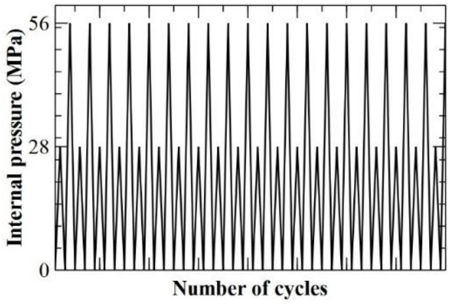

Figure 5. The pipe's internal pressure spectrum

One hundred and eight cases are examined in order to assess the impact of the stress corrosion cracking due to different fluids on the structural integrity of a steel pipe. Furthermore, eighteen cases involving a pipe with a cracking defect with no corrosion will be analyzed to allow a comparison of these two types of defects and a better understanding of the effect of corrosion on pipelines.

The proposed non-linear damage accumulation model (Figure 3) uses the pressure spectrum presented in Figure 5 as input for the simulation of a pipe transporting ethanol and bicarbonate. The effect of the corrosion frequency parameter is also investigated, with values of 0.05, 0.1, and 1Hz considered.

The values considered for the a/c which represent the crack depth to with ratio parameter are 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9. The cracks are all surface cracks present in the inner surface of the tube. The effect of the localization of the crack (base metal, weld metal or HAZ) is also analyzed. To permit the comparison, all cases

To allow for a comparative study, all of the cases investigated assume an initial semi-elliptical crack of 1mm depth. This value ensures that the crack propagation originates in region 2 (Figure 2), and thus that the modified Paris model used in the calculation algorithm is appropriate.

5. RESULTS AND DISCUSSION

The presence of several types of crack defect in a metal pipe is analyzed using the validated damage accumulation model. This model allows for the consideration of the history and the loads interaction effects in order to investigation the effect on corrosion defects on the integrity of the transmission pipeline.

The obtained results are depicted in the form of figures. Figures 6 shows the evolution of the accumulation of damage for a cracked pipe of several dimensions subjected to variable amplitude loading. This figure is used as a basis of comparison to evaluate the effect of corrosion caused by the transported fluid on the harmfulness of a crack present in a pipeline.

Figures 7, 8, and 9 show the results of the evolution of damage accumulation for a pipe with corrosion cracking caused by the presence of ethanol inside the pipe. Figures 10, 11, and 12 depict the progression of damage accumulation in a bicarbonate-transporting pipe.

This data will be used to assess the impact of crack dimensions and location, solicitation frequency, and transported fluid on the evolution of accumulation damage until the structure collapses. The model predicts the structure's failure if the damage accumulation is equal to unity.

A quick examination of Figures 6 to 12 reveals that the damage caused to the pipeline by the first pressure cycle is equal to 0.07 and is caused by the presence of the previously mentioned crack with an initial depth of 1mm. This damage value is calculated by dividing the initial crack depth by the pipe thickness, which is 13.7mm.

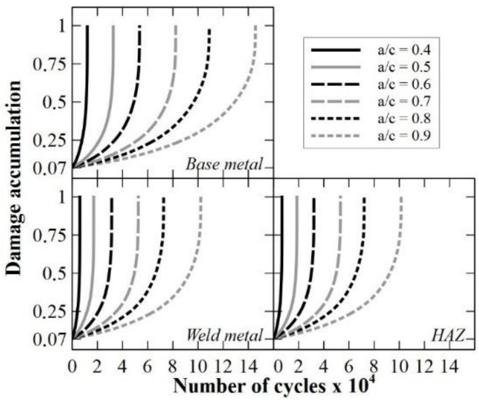

Figure 6. The evolution of damage accumulation in a cracked pipe

Figure 6 shows that a fatigue life of the structure of 11885, 32539, 53503, 82315, 108890, and 145660 can be obtained for cracks with dimensions *a*/*c* of 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9 in the case of a semi-elliptical crack located in the base metal at the inner surface of the tube away from the weld bead. These values are equivalent to a damage accumulation value of one.

If these values are used as references for calculating the deviations, the results for the cracks located in the weld bead with dimensions of 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9 show a deviation of -49.26, -47.62, -41.35, -36.15, -33.27, and -29.9%, respectively. There is also a deviation of -43.99, -42.95, -40.04, -35.4, -33.78, and -30.38% for the cracks *a*/*c* of 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 between the results obtained for the cracks in the HAZ and those obtained for the cracks in the base material.

This demonstrates that a crack is less dangerous when it is located in the base metal and more harmful when it is located in the weld bead. This explains why the weld seam is the most common point of failure in pipelines.

It should be noted that the difference in harmfulness between weld bead cracks and those in the HAZ is very small for cracks with a significant *a*/*c* parameter. Remember that the closer the *a*/*c* parameter is to unity, the more similar the crack shape is to a semi-circle.

Let us now analyses the Figures 7-9, which show results obtained for cracked pipelines exposed to the corrosive environment imposed by ethanol.

To investigate the effect of solicitation frequency, the results for cracks with dimensions *a*/*c*=0.9 are compared. For cracks of these dimensions located in the base material, there is a relative difference of 12.42 and 33.79% between the results obtained for frequencies of 0.1 Hz and 0.05Hz and for frequencies of 1Hz and 0.1Hz, respectively. Similarly, for cracks *a*/*c*=0.9 located in the weld bead, one can observe a relative deviation of 12.42 and 33.78%, whereas for cracks located in the HAZ, the relative deviation is 12.41 and 33.76%.

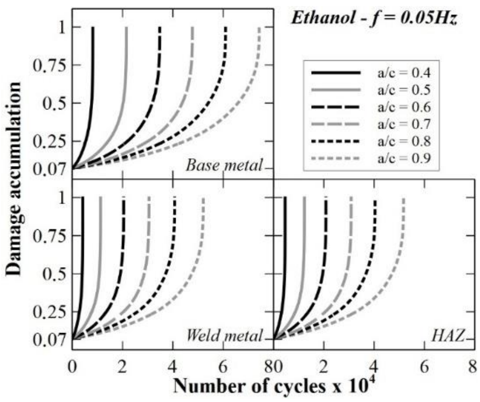

Figure 7. The evolution of damage accumulation in an ethanol-transporting pipe subjected to stress corrosion cracking at a solicitation frequency of 0.05Hz

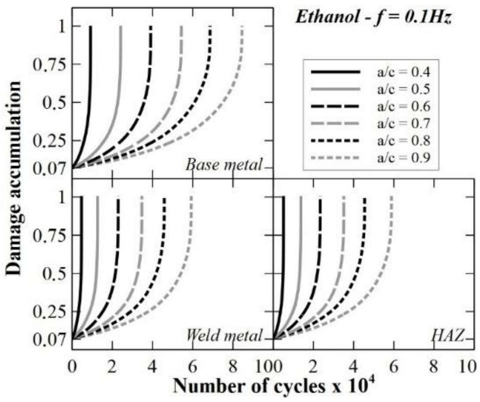

Figure 8. The evolution of damage accumulation in an ethanol-transporting pipe subjected to stress corrosion cracking at a solicitation frequency of 0.1Hz

Based on these differences, it is clear that the effect of solicitation frequency '*f*' on the harmfulness of the corrosion crack defect is the same regardless of where the crack is located. This observation holds true regardless of the crack's size and the transported fluid. Analyzing the Equation (3) used in the numerical model reveals that these deviations are completely logical, as the crack propagation parameter is linearly related to the solicitation frequency. The slight differences in these deviations are due to the calculation algorithm rounding values of number of cycles to the nearest whole number.

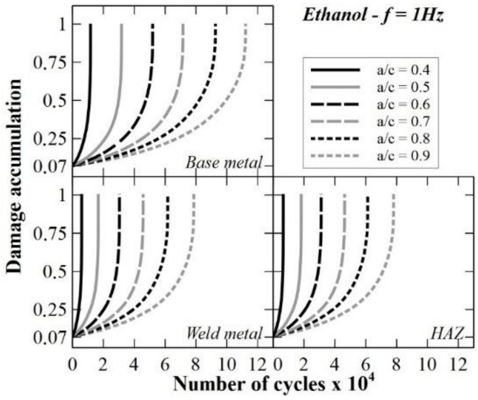

Figure 9. The evolution of damage accumulation in an ethanol-transporting pipe subjected to stress corrosion cracking at a solicitation frequency of 1Hz

These differences also indicate that the greater the frequency of solicitation, the less harmful the corrosion cracking defect is to the structural integrity.

To investigate the effect of crack location on the harmfulness of a corrosion cracking defect, only the results obtained for solicitation frequencies of 0.05Hz are retained. Let us consider the results obtained for the case of cracks located in the base material of an ethanol-transporting pipeline as a reference for calculating the deviations. From Figure 7, the results for the cracks located in the weld bead with dimensions of 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 show a deviation of -46.79, -45.24, -39.29, -34.34, -31.61, and -28.4%, respectively. There is also a deviation of -41.35, -40.37, -37.64, -33.28, -31.75, and -28.56% for the cracks *a*/*c* of 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 between the results obtained for the cracks in the HAZ and those obtained for cracks in the base material.

Let us use the same approach to cracks solicited at a frequency of 0.05 Hz in a bicarbonate-transporting tube. Figure 10 shows a deviation between the results obtained for the cracks located in the weld bead with dimensions of 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 of -46.05, -44.52, -38.67, -33.8, -31.11, and -27.95%, respectively when using the results of cracks in the base material as a reference for calculation. There is also a deviation of -41.13, -40.16, -37.44, -33.1, -31.98, and -28.4% for the cracks *a*/*c* of 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 between the results obtained for the cracks in the HAZ and those obtained for the cracks in the base material.

Based on these findings, it is clear that increasing the crack dimension parameter *a*/*c* and changing the crack location (base metal, weld metal, heat-affected-zone) have nearly identical effects in the inert medium as they do in the corrosive medium. This observation is true regardless of solicitation frequency of corrosion medium.

The results from figures 6, 7, and 10 are used to analyze the effect of fluid with a solicitation frequency of 0.05 Hz on the harmfulness of a corrosion cracking defect in a metallic pipeline subjected to variable amplitude stresses. Only the results pertaining to the cracks in the welding material are taken into account in these figures. Using the results obtained for cracks in an inert medium (Figure 6) as a reference for calculating relative deviations, a deviation of -31.02, -33.96, -35.13, -41.61, -43.62, and -48.76% can be reported for cracks with dimensions *a*/*c* of 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9, respectively, present in an ethanol-filled tube. For cracks with *a*/*c* of 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9, respectively, for the tubes carrying bicarbonate, a deviation of -24.08, -27.75, -29.01, -36.26, -38.52 and -44.1% can be observed.

Similarly, let us examine the effect of a fluid with a loading frequency of 0.1 Hz on the harmfulness of a corrosion cracking defect located in the weld material of a pipe using the results of Figures 6, 8, and 11. Using the results of figure 6 as a reference, one can calculate a deviation of -23.09, -25.92, -27.92, -34.39, -36.67, and -42.39% for cracks with *a*/*c* of 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9, respectively, present in an ethanol-filled tube. For cracks with *a*/*c* dimensions of 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9, respectively, for the tubes carrying bicarbonate, a deviation of -14.11, -16.06, -17.18, -25.29, -27.82 and -34.31% can be reported.

For the cases of corrosion cracking in the weld bead with a solicitation frequency of 1Hz and by using the Figure 6, 9 and 12, a relative deviation of -2.91, -3.85, -6.23, -12.49, -15.37 and 22.92% for cracks with *a*/*c* of 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9, respectively, are observed between results for ethanol-transporting pipe and those of a pipe in an inert environment. A deviation of -2.59, -3.52, -5.84, -11.33, -14.17 and -21.78 for cracks with *a*/*c* of 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9, respectively, are observed between results for bicarbonate-transporting pipe and those of a pipe in an inert environment.

These findings demonstrate the significant impact that corrosion can have on the harmfulness of a crack defect. It is therefore not advisable to disregard the effect of corrosion when conducting a study to evaluate the residual life of a pipeline if the fluid being transported has corrosive effects on the internal surface of the pipe.

It should be noted that, of the fluids studied, ethanol is the one that causes the crack to be the most harmful, owing to the fact that it has the highest plateau velocity value $(da/dt)_p$.

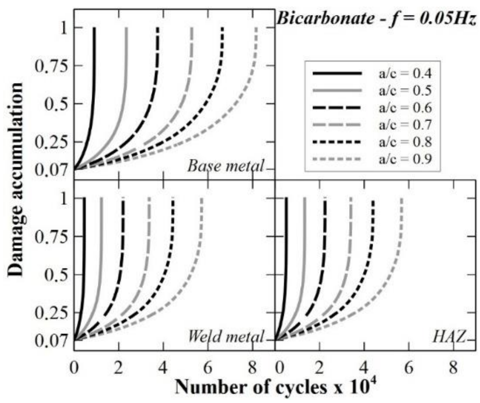

Figure 10. The evolution of damage accumulation in a bicarbonate-transporting pipe subjected to stress corrosion cracking at a solicitation frequency of 0.05Hz

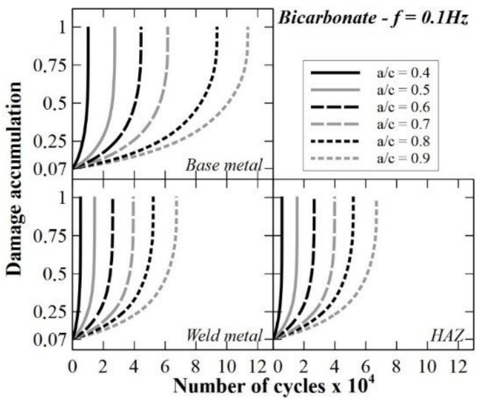

Figure 11. The evolution of damage accumulation in a bicarbonate-transporting pipe subjected to stress corrosion cracking at a solicitation frequency of 0.1Hz

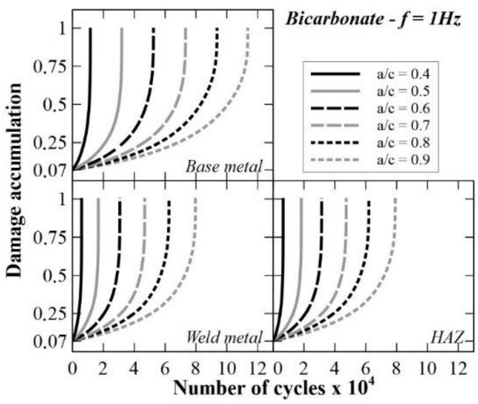

Figure 12. The evolution of damage accumulation in a bicarbonate-transporting pipe subjected to stress corrosion cracking at a solicitation frequency of 1Hz

The differences between the results of crack a/c=0.4 with a corrosion frequency of 1Hz and the same crack in an inert medium are negligible. This implies that for cracks of small dimension a/c and high frequency of solicitation, the component induced by the mechanical effect takes precedence over the component induced by the corrosion (Equation (2)), and thus the effect of corrosion on crack propagation can be ignored.

All of these results indicate that increasing the a/c parameter causes a quasi-linear increase in the fatigue life of the cracked pipe. This observation is useful regardless of the crack localization, the transported fluid, or the solicitation frequency of the corrosion effect.

6. CONCLUSIONS

A numerical model was used to analyze the impact of corrosion on the fatigue cracking process in the case of a metal tube subjected to variable amplitude loading. This non-linear model for estimating damage accumulation allows for the effect of the loading interaction to be considered.

This analysis provided a better understanding of the main parameters influencing the severity of corrosion cracking as well as the ability to numerically quantify the effect of corrosion on the fatigue life of a cracked pipeline. A parametric analysis using the damage accumulation model revealed that:

- Corrosion has a significant impact on the harmfulness of a crack defect. It is therefore not advisable to ignore it when conducting a pipeline study if the fluid being transported has high corrosive properties;
- The effect of corrosion on crack propagation can only be ignored when studying small dimension a/c cracks with a high frequency of solicitation;
- The higher the frequency of solicitation, the less damaging the corrosion cracking defect is to structural integrity;
- A crack in the base material is less dangerous than one in the weld bead of the same size;
- Increasing the depth-to-width ratio of a crack causes a quasi-linear increase in the fatigue life of the cracked pipe;
- In the inert medium, increasing the depth-to-width ratio of a crack and changing the crack location have nearly identical effects as in the corrosive medium;
- Because it has the highest plateau velocity parameter of the fluids studied, ethanol causes the crack to be the most harmful.

It should be noted that, this model can be extended to other types of defects or different types of loading by using the same approach used in the development of the numerical damage accumulation model and making changes to the equations used by its algorithm to estimate the fatigue life.

NOMENCLATURES

1. Acronyms

HAZ Heat affected zone
SCC Stress Corrosion Cracking

2. Symbols / Parameters

a : Crack depth
c : Crack width
C : Paris law constant depending on the material
D : Fatigue accumulation damage
D_I : Inner diameter of the pipe
D_O : Outer diameter of the pipe
E : Young's Modulus
f : Solicitation frequency
k : Number of stress cycles in a random spectrum load history block
K_I : Stress intensity factor
K_{IC} : Material's fracture toughness
K_{ISCC} : Threshold stress intensity factor for stress corrosion crack growth
K_{MAX} : Maximum value of the stress intensity factor
K_{MIN} : Minimum value of the stress intensity factor
K_{MOY} : Average value of the stress intensity factor
m : Paris law constant depending on the material
n : Number of applied cycles
N : Number of cycles to fatigue failure
N_i : Estimated fatigue life due to the ith stress cycle in a

block of random spectrum load history

N_{b_Block} : Block number of random spectrum load history

t : Pipe thickness

UTS : Ultimate tensile strength

ΔD_i : Fatigue damage increment related to the ith stress cycle in a block of random spectrum load history

ΔK : Stress intensity factor range

ΔK_{th} : Threshold stress intensity factor

(da/dN) : Crack growth rate as a function of number of cycles

(da/dt) : Crack growth rate as a function of time

υ : Poisson's ratio

REFERENCES

[1] MMI Engineering, Oil and Gas Pipelines, United States Geological Survey Open File Report 2008-1150, California Geological Survey Preliminary Report 25 version 1.0, 2008.

[2] L. Zahiri, Z. Mighouar, H. Khatib, K. Mansouri, B. Salhi, "Fatigue life analysis of dented pipes subjected to internal pressure", International Review of Mechanical Engineering, Vol. 11, No. 8, pp. 587-596, 2017.

[3] M. Hereth, B. Selig, K. Leewis, J. Zurcher, "Develop a compendium of best practices to prevent mechanical damage to gas and liquids pipelines", GRI Report 05/0136, PRCI Catalogue No. 850LN1B, 2005.

[4] M. Fuglem, "Damage management for operating pipelines - gap analysis", PRCI Catalogue No. L52246, 2007.

[5] C.E. Jaske, B.O. Hart, W.A. Bruce, "Updated pipeline repair manual", PRCI Catalogue No. L52047, 2006.

[6] D. Warman, "Management of pipeline dents and mechanical damage in gas pipelines", ASME 6th International Pipeline Conference, Calgary, 2006.

[7] A. Zrhaiba, S. Yadir, A. Balouki, A. Elhassnaoui, "Internal Corrosion in Pipes, Inspection and Analysis by Pulsed Thermography Using the Finite Element Method", International Review on Modelling and Simulations, Vol. 13, No. 3, pp. 207-213, 2020.

[8] M.D. Liu, J.J. Xiong, C.Q. Wang, "A modified accumulation damage algorithm for predicting corrosion fatigue life by considering load interaction for aluminum alloys", International Journal of Damage Mechanics; Vol. 28, No. 2, pp. 270-290, 2019.

[9] J. Mora Mendoza, M. Hernandez Gayosso, D. Morales Serrat, O. Roque Oms, D. Angel, G. Zavala Olivares, "Evaluation of Stress Corrosion Cracking Damage to an API 5L X52 Pipeline Transporting Ammonia: A Case Study", Materials Sciences and Applications, Vol. 7, pp. 610-622, 2016.

[10] Q. Yang, J. Shuai, S. Zuo, "Research actuality of pipelines with dents", Oil Gas Storage Transport, Vol. 28, No. 6, pp. 10-15, 2009.

[11] A. Amara Zenati, "Study of the behavior of API 5L X60 steels solicited by mechanical stresses and Simulated Algerian soil environment", Thesis in University Abou Bekr Belkaid - Tlemcen Faculty of Technology, 2014.

[12] B.N. Leis, P. Hopkins, "Review and Gap Analysis of Remaining Issues Concerning Mechanical Damage", PRCI - L52013, 2003.

[13] MSL, "Appraisal and Development of Pipeline Defect Assessment Methodologies", Report CH109R001 for U.S. Minerals Management Service, 2000.

[14] P. Roovers, R. Bood, M. Galli, U. Marewski, M. Steiner, M. Zarea, "EPRG Methods for assessing the tolerance and resistance of pipelines to external damage", Proceedings of the 3rd International Pipeline Technology Conference, Brugge, Belgium, pp. 405-425, 2000.

[15] Anonymous, "Public awareness programs for pipeline operators", American Petroleum Institute Recommended Practice 1162 (First Ed), 2003.

[16] M.J. Rosenfeld, J.W. Pepper, K. Leewis, "Basis of the new criteria in ASME B31.8 for prioritization and repair of mechanical damage", ASME 4th International Pipeline Conference, Calgary, 2002.

[17] Anonymous, "10th Report of the European Gas Pipeline Incident Data Group (period 1970-2016)", Doc. number VA 17.R.0395, 2018.

[18] Anonymous, "Pipeline performance", Alberta Energy Regulator New Reports, 2020.

[19] T. Vilkys, V. Rudzinskas, O. Prentkovskis, J. Tretjakovas, N. Visniakov, P. Maruschak, "Evaluation of Failure Pressure for Gas Pipelines with Combined Defects", Metals, Vol. 8, No. 5, pp. 346, 2018.

[20] I. Zhuravska, D. Lernatovych, O. Burenko, "Detection the Places of the Heat Energy Leak on the Underground Thermal Pipelines Using the Computer System", Advances in Science, Technology and Engineering Systems Journal, Vol. 4, No. 3, pp. 01-09, 2019.

[21] Z. Mighouar, H. Khatib, L. Zahiri, K. Mansouri, "Damage Accumulation Model of a Dented Pipeline Subject to Water Hammer Waves", International Review of Mechanical Engineering, Vol. 14. No. 12, pp. 730-742, 2020.

[22] Z. Mighouar, L. Zahiri, H. Khatib, K. Mansouri, "Damage accumulation model for cracked pipes subjected to water hammer", Advances in Science, Technology and Engineering Systems Journal, Vol. 5, pp. 523-530, 2020.

[23] S. Peng, Z. Zeng, "An experimental study on the internal corrosion of a subsea multiphase pipeline", Petroleum, Vol. 1, No. 1, pp. 75-81, 2015.

[24] X. He, Y. Wei, L. Hou, Z. Yan, C. Guo, "High-frequency corrosion fatigue behavior of AZ31 magnesium alloy in different environments", Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Vol. 228, No. 10, pp. 1645-1657, 2014.

[25] R. Amaya Gomez, M. Sanchez Silva, E. Bastidas-Arteaga, F. Schoefs, F. Munoz, "Reliability assessments of corroded pipelines based on internal pressure - A review", Engineering Failure Analysis, Vol. 98, pp. 190-214, 2019.

[26] K. Van der Walde, B.M. Hillberry, "Initiation and shape development of corrosion-nucleated fatigue

cracking", International Journal of Fatigue, Vol. 29, pp. 1269-1281, 2007.
[27] W. Zhao, Y. Wang, T. Zhang, Y. Wang, "Study on the mechanism of high-cycle corrosion fatigue crack initiation in X80 steel", Corrosion Science, Vol. 57, pp. 99-103, 2012.
[28] S.D. Vijaya Kumar, S. Karuppanan, M. Ovinis, "Failure Pressure Prediction of High Toughness Pipeline with a Single Corrosion Defect Subjected to Combined Loadings Using Artificial Neural Network (ANN)", Metals, Vol. 11, pp. 373. 2021.
[29] Y. Fu, J.J. Xiong, R.A. Shenoi, "New models for depicting corrosion fatigue behaviour and calendar life of metallic structural component", Proceedings of the Institution of Mechanical Engineers Part C: Journal of Mechanical Engineering Science, Vol. 231, No. 2, 2017.
[30] M.E. May, T. Palin Luc, N. Saintier, O. Devos, "Effect of corrosion on the high cycle fatigue strength of martensitic stainless steel X12CrNiMoV12-3", International Journal of Fatigue, Vol. 47, pp. 330-339, 2013.
[31] R. Perez Mora, T. Palin Luc, C. Bathias, P.C. Paris, "Very high cycle fatigue of a high strength steel under sea water corrosion: A strong corrosion and mechanical damage coupling", International Journal of Fatigue, Vol. 74, pp. 156-165, 2015.
[32] R. Wang, "A fracture model of corrosion fatigue crack propagation of aluminum alloys based on the material elements fracture ahead of a crack tip", International Journal of Fatigue, Vol. 30, pp. 1376-1386, 2008.
[33] L. Weng, J.X. Zhang, S. Kalnaus, M. Feng, Y. Jiang, "Corrosion fatigue crack growth of AISI 4340 steel", International Journal of Fatigue, Vol. 48, pp. 156-164, 2013.
[34] M.R. Sriaman, R.M. Pidapati, "Crack initiation life of materials under combined pitting corrosion and cyclic loading", Journal of Materials Engineering and Performance, Vol. 19, pp. 7-12, 2010.
[35] L. Zahiri, "Modeling and numerical analysis of the harmfulness of defects on the integrity of pipes containing pressurized liquids", Ph.D. Thesis, Hassan II University of Casablanca, Morocco, 2018.
[36] Y. Xiang, Y. Liu, "EIFS-based crack growth fatigue life prediction of pitting-corroded test specimens", Engineering Fracture Mechanics, Vol. 77, pp. 1314-1324, 2010.
[37] K. Kurmoiartseva, P. Trusov, "Multilevel description of damage accumulation in titanium and titanium alloys", AIP Conference Proceedings, 2018.
[38] H. Dirik, T. Yalcinkaya, "Fatigue Crack Growth under Variable Amplitude Loading through XFEM", Procedia Structural Integrity, Vol. 2, pp. 3073-3080, 2016.
[39] L. Muys, J. Zhang, N. Micone, W. De Waele, S. Hertele, "Cycle-by-cycle simulation of variable amplitude fatigue crack propagation", International Journal Sustainable Construction & Design, Vol. 8, No. 1, 2017.
[40] F.J. Zuo, H.Z. Huang, S.P. Zhu, Z. Lv, H. Gao, "Fatigue life prediction under variable amplitude loading using a non-linear damage accumulation model", International Journal of Damage Mechanics, Vol. 24, pp. 767-784, 2015.
[41] Z. Peng, H.Z. Huang, H.K. Wang, S.P. Zhu, Z. Lv, "A new approach to the investigation of load interaction effects and its application in residual fatigue life prediction", International Journal of Damage Mechanics Vol. 25, pp. 672-690, 2016.
[42] G. Bourse, "Contribution to the study of fatigue and corrosion cracking rates in E36 steel", Ph.D. Thesis, University of Science and Technology of Lille, 1979.
[43] O.I. Zvirko, S.F. Savula, V.M. Tsependa, G. Gabetta, H.M. Nykyforchyn, "Stress corrosion cracking of gas pipeline steels of different strength", Procedia Structural Integrity, Vol. 2, pp. 509-516, 2016,
[44] K. Sadananda, I. Adlakha, K.N. Solanki, A.K. Vasudevan, "Analysis of the Crack Initiation and Growth in Crystalline Materials Using Discrete Dislocations and the Modified Kitagawa-Takahashi Diagram", Crystals, Vol. 10, No. 5, pp. 358, 2020.
[45] B.F. Brown, C.D. Beachem, "A Study of the Stress Factor in Corrosion Cracking by Use of the Pre-Cracked Cantilever Beam Specimen", Corrosion Science, pp. 745-748, 1965.
[46] D.O. Sprowls, "Evaluation of corrosion fatigue", ASM Handbook, Corrosion, 9th ed., ASM International: Materials Park, Vol. 13, pp. 291-302, 1998.
[47] P.C. Paris, M.P. Gomez, W.E. Anderson, "A rational analytic theory of fatigue", The Trend in Engineering, Vol. 13, pp. 9-14, 1961.
[48] R.P. Wei, J.D. Landes, "Correlation between sustained load and fatigue crack growth in high strength steels", Materials Research and Standards, 1969.
[49] W. Elber, "Fatigue crack closure under cyclic tension," Engineering Fracture Mechanics, Vol. 2, No. 1, pp. 37-45, 1970.
[50] L. Gajdos, M. Sperl, "Application of a Fracture-Mechanics Approach to Gas Pipelines", International Journal of Mechanical and Mechatronics Engineering, Vol. 5, No. 1, pp. 67-74, 2011.
[51] M. El Sayed, A. El Domiaty, A.H.I. Mourad, "Fracture Assessment of Axial Crack in Steel Pipe under Internal Pressure", Procedia Engineering, Vol. 130, pp. 1273-1287, 2015.
[52] J.C. Newman, "Fracture analysis of surface- and through-cracked sheets and plates", Engineering Fracture Mechanics, Vol. 5, No. 3, pp. 667-689, 1973.
[53] P. Dai, Z. Li, "A plasticity-corrected stress intensity factor for fatigue crack growth in ductile materials", Acta Materialia, Vol. 61, No. 16, pp. 5988-5995, 2013.
[54] Z. Mighouar, L. Zahiri, H. Khatib, K. Mansouri, Z. El Majid, "Effect of Water Hammer on Pipes Containing a Crack Defect", International Journal of Mechanical & Mechatronics Engineering, Vol. 18, No. 3, pp. 25-31, 2018.
[55] A. Buch, "Fatigue Strength Calculation", Brookfield: Trans Tech Publications Brookfield Publishing Company, 1988.

[56] M.A. Miner, "Cumulative damage in fatigue", Journal of Applied Mechanics, Vol. 67, pp. 59-64, 1945.
[57] D.G. Shang, W.X. Yao, "A nonlinear damage cumulative model for uniaxial fatigue", International Journal of Fatigue, Vol. 21, pp. 187-194, 1999.
[58] J. Willenborg, R.M. Engle, H.A. Wood, "A crack growth retardation model using an effective stress intensity concept", AFFDL, TM-71-1-FBR, 1971.
[59] J.B. Chang, M. Szamossi, K.W. Liu, "Random spectrum fatigue crack life predictions with or without considering load interactions", American Society for Testing and Materials, pp. 115-132, 1981.

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