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Establishment of a database and a classification of the defects in the metal of pipes according to their severity

M. Bettayeb a*, E. Bouali, N. Abdelbaki, M. Gaceb

*Laboratoire de Fiabilité des Equipements Pétroliers & Matériaux,
FHC, M'Hamed Bougara University, 35000 Boumerdes, Algeria*

Abstract

Given the distances between areas of production and consumption of hydrocarbons, transport by pipeline is the most competitive means. These pipelines made of metal pipes can contain several types of defects of different origins. These defects can lead to pipeline failures that may have serious consequences resulting in ecological or financial disasters. The causes of these failures can be of various kinds. To assess the integrity and study the ageing of hydrocarbons transport pipelines is a current problem in the world which must be solved. The degraded state of thousands of kilometers of pipeline in the world requires the elaboration of rehabilitation by repair or replacement programs of sections in poor condition. If on one hand rehabilitation operations do improve the safety of hydrocarbons transport pipelines and prolong their remaining life, they are very expensive on the other. Therefore they must be carried out according to a previously well established plan, which determines the priority given. This priority must be defined by a multi-criteria evaluation, which also includes the criterion of severity of the defects located in the pipes metal according to the result of previous inspections of the pipelines towards the importance and the integrity of each section of the pipe.In this context the elaboration of a database and a classification of the defects in the metal of the hydrocarbons transportation pipes according to their severity are essential in this study.

Keywords: Fracture mechanics, safety, pipeline, integrity, fatigue, weld defect

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* Corresponding author. Tel.: 00213662481356; fax: 0021324819172.
E-mail address: bettayeb_mourad@yahoo.fr.

1. Introduction

Oil and gas provide over 60% of the world's primary fuel. Therefore, it is not surprising to note that there are over 1 million tons of oil and 250 million m^3 of gas consumed every hour around the world [1].

Most of this oil and gas is transported in pipelines. The larger of these pipelines are called 'transmission' pipelines; the general public will not normally see these lines as they are either under the sea, or buried on land, but they are the main arteries of the oil and gas transportation systems.

They are usually large diameter and operate at high pressures to allow high transportation rates. They are designed, built and operated to well-established standards and laws, because the products they carry can pose a significant hazard to the surrounding population and environment, but the combination of good design, materials and operating practices has ensured that transmission pipelines have a good safety record.

All pipelines must ensure safety, Compliance with Codes and Legislation, security of supply and Cost Effectiveness. These are achieved by ensuring our pipeline is correctly designed and does not experience a structural failure due to burst, puncture, overload, structural collapse, fatigue and fracture.

We do not want our pipeline to become 'unserviceable' due to ovalisation, blockages, distortions, and displacements. Therefore, the structural integrity of pipelines commences with good design and construction practices, which will eliminate most of the above potential failure modes, but as pipelines can operate in hostile environments (underground or subsea) they are constantly threatened by defects and damage that occur in-service. These in-service defects are the major cause of pipeline failures; therefore to understand and control structural integrity, in -service defects must be understood and controlled. The occurrence and behavior of defects in pipelines has been the subject of extensive research and development for over 35 years. In this work we propose to study the life of a pipeline subjected to service pressure in the presence of a longitudinal surface semi-elliptical crack opening into the inner longitudinal weld joint of a pipeline, propagating in its thickness.

Nomenclature

a_c	Critical length of crack
D_e	Pipe's outer diameter
E	Young's elastic modulus
K_I	Stress intensity factor
K_{IC}	Material toughness at the vicinity of defect
ΔK_s	Threshold stress strength
m,c	Paris law parameters
P	Service pressure
P_L	Limit pressure
R_i	Internal radius of pipe
t	Pipe wall thickness

Greek symbols

υ	Poisson's ratio
σ_n	Stress in the ligament ahead of the defect
σ_f	Average flow stress
σ_y	Yield strength
σ_u	Ultimate tensile strength
δ_C	Materiel toughness

2. Approach

A pipeline failure mode can be defined as the manner in which a pipeline could potentially fail to meet the design service intent. Some typical failure modes include, overload (e.g., corrosion thinning, over-pressure), deformation (dents, wrinkles, buckles,etc.), and Cracking (SCC, seam weld anomalies, Hydrogen embrittlement, etc.). The failures modes are further classified by the manner in which they fail (e.g., leak or rupture). Furthermore, a pipeline failure mechanism can be defined as the process or phenomenon behind a failure mode causing a pipeline to leak or rupture. Some of the more common failure mechanisms are corrosion/erosion, plastic deformation, impact, fatigue, environmental cracking, buckling/wrinkling, and creep.

Failure assessments can be classified as being either Flow Stress dependent, or Fracture Toughness dependent. A flow stress-dependent assessment assumes plastic collapse and hence uses either yield and/or ultimate tensile strength parameters. A fracture toughness-dependent assessment uses either a critical stress intensity factor or correlation with upper shelf Charpy V Notch impact energy [2].

The presence of defects is generally detected by non destructive testing of the finished structure. The industrial problem is to control rupture risks due to the presence of defects in structures. Wherever a defect is detected in structures three attitudes may be considered:

- Conserving the defect as it is while continuing to use the equipment.
- Repairing bearing in mind, however that this may lead to other defects which may be more severe.
- Replacing the defected part or section

In order to make a right decision, there exist various methods of assessment of defect severity. Amongst these we can cite [3]:

- The two criteria or modified R6 method.
- The PD6493 (1991) recommendation or its recent version BS7910 (1999).

According to these two methods, the treatments of defect acceptability, in terms of rupture risks, is based on the failure assessment diagram (FAD).

2.1. Failure Assessment Diagram

This diagram needs the calculation of two parameters corresponding respectively to brittle fracture risk K_r (y-axis) and plastic collapse S_r (x-axis) for each defect. These parameters are calculated by the following expressions [4]:

$$\text{Brittle fracture: } K_r = \frac{K_I}{K_{IC}} \tag{1}$$

$$\text{Plastic collapse: } S_r = \frac{\sigma_n}{\sigma_f} \tag{2}$$

σ_f is equal to $\dfrac{\sigma_y + \sigma_u}{2}$ for $\sigma_f < 1.2\,\sigma_y$ and equal to $1.2\sigma_y$ otherwise.

A boundary envelope is then defined by a relation of the form $K_r = f(S_r)$. The graphical representation of the relation in the referential (K_r, S_r) constitutes the failure assessment diagram (FAD). A defect therefore is acceptable if the calculated pair (K_r, S_r) is located under the curve $K_r = f(S_r)$ in the FAD. According to British Standards, PD6493 recommendation applies to:

- welded martensitic and austenitic aluminium alloy structures,
- volume defects,
- Different failure modes.

Different levels of investigation are proposed. Fig 1. presents three levels (1, 2 and 3).
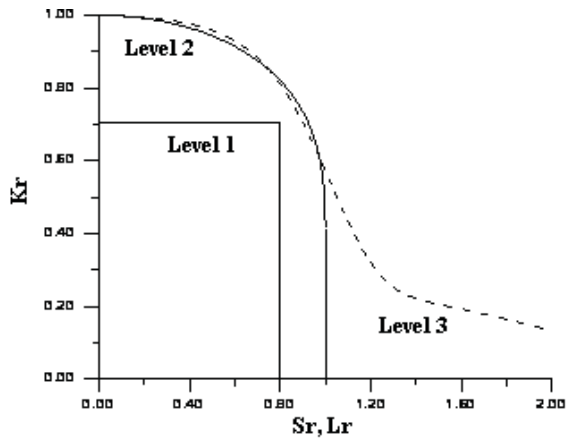

Fig. 1. FAD for three possible investigation levels

Level 1: The most basic, is applicable in the case of brittle fracture (Linear Elastic Fracture Mechanics). Required necessary data on materials is limited and the investigation is rapid.

Level 2: Does not require taking into account the safety factor which is accounted for by the maximizing of the stresses and defect dimensions and by the minimizing of mechanical properties.

Level 3: Can be used when the failure is preceded by strong plastic deformation.

The equations defining the acceptability envelope for each level are given by the following expressions:

Level 1 $K_r < 0.707$ for $S_r < 0.8$ and $K_r = 0$ for $S_r > 0.8$ (3)

Level 2 $$K_r = S_r * \left[\frac{8}{\pi^2} * \ln\left(\frac{1}{\cos\left(\frac{\pi}{2} * S_r\right)} \right) \right]^{-0.5}$$ (4)

Level 3 $$K_r = \left[\frac{E * \ln(1+\varepsilon)}{\sigma * (1+\varepsilon)} + \frac{\sigma^3 * (1+\varepsilon)^3}{2\sigma_y^2 E \ln(1+\varepsilon)} \right]^{-0.5}$$ (5)

It should be noted that a rational tensile curve of the material in which the defect exists is necessary. This curve allows to establish a relationship $\sigma = f(\varepsilon)$ used in level 3. In the case of investigation levels 1

and 2 only data such as σ_y and σ_u are necessary. The S_r parameter is replaced by

$$L_r = \frac{\sigma(1+\varepsilon)}{\sigma_y} = \frac{\sigma_{ref}}{\sigma_y}$$ to characterize rupture by generalized plasticity where $L_{rmax} = \frac{\sigma_f}{\sigma_y}$.

We also give K_r, for level 3 by the relationship:

$$K_r = \left[1 - 0.14L_r^2\right] * \left[0.3 + 0.7 * \exp\left(-0.65L_r^6\right)\right] \qquad (6)$$

2.2. Calculation of stress intensity factor K_I with K_r and L_r parameters

The modeling of the propagation of the semi-elliptical surface crack (a, c) in the seam weld is based on the use of the Paris law [5, 6].Several solutions have been found to evaluate the stress intensity factor; these solutions are exact or empirical, we will only consider here the expressions used in the present study. By comparing the analytical calculation to the calculation made by 3D FE method, we see that these estimates of stress intensity factor are satisfactory, especially as regards the crack front, which justifies the use of these estimates to calculate stress intensity factors along the direction of the crack front and one of two directions along the free edge [7]. At the deepest point on the crack front the factor K_I, is then written:

$$K_I = F_e.F_s.F_t.\sigma\sqrt{\pi a} \qquad (7)$$

Where, F_e, F_s, F_t are given by:

$$F_e = \frac{1}{E(k)}, \text{ Where } E(k) = \int_0^{\pi/2} \sqrt{1 - k^2 \sin^2 \phi} \, d\phi \qquad (8)$$

$$F_s = 1 + 0.12(1 - \frac{a}{c}) \qquad (9)$$

$$F_t = \sqrt{\frac{2t}{\pi a} \tan \frac{\pi a}{2t}}, \qquad (10)$$

A long the free edge and at the ends of the crack, the factor K_I is then written:

$$K_I = g_e g_s \sigma \sqrt{\frac{\pi}{c} a} \qquad (11)$$

With,

$$g_e = F_e \quad \text{and} \quad g_s = 1 + 0.211\left(\frac{a}{c}\right) \tag{12}$$

The parameters $\mathbf{K_r}$ and $\mathbf{L_r}$ are calculated by expression [8]:

$$K_r = \frac{K_I}{K_{IC}} = \frac{K_I}{\sqrt{E' \cdot \delta_C \cdot \sigma_y}} \tag{13}$$

With: $E' = E$ for plain stress and $E' = E/(1 - v^2)$ for plain strain

$$L_r = \frac{P}{P_L} = P \Big/ \sigma_y \left[\frac{a}{M \cdot R_i} + Ln\left(\frac{R_i + t}{R_i + a}\right)\right] \tag{14}$$

With:

$$M = \sqrt{\left[1 + \frac{1,61 \cdot C^2}{R_i \cdot a}\right]} \tag{15}$$

3. Case study

We assume the existence of a detected longitudinal semi-elliptical surface crack taking the original dimensions a_0=2.3mm and c_0= 230mm, opening into the inner longitudinal weld joint of a steel pipeline (X52), with an outer diameter D_e =377mm and a thickness t=6mm, subjected to a service cyclic pressure varies between,
P_{max}=7 MPa and P_{min}=5MPa.
The mechanical properties of the joint are given in the table 1 below:

Table 1. Mechanical characteristics of the weld joint

E(MPa)	σ_e(MPa)	σ_u(MPa)	ΔK_s(MPa$^{1/2}$)	δ_C(mm)	C	m
206000	450	620	3	0.016	1.8e-8	3.63

4. Results and discussion

The calculation of the fatigue life is through a program we developed. We obtain the lifetime of the pipeline and the stress intensity factors at all steps of calculation and changes in the geometry of the crack (every N cycles of loading) [7]. To take into account the concentrations of stress due to the weld joint and comparing our results with those found by [9], we introduced a factor K_t = 1.195 in the calculations to correct the value of applied stress.

The calculation results are displayed as four curves in Fig 2. The first represent the evolution of the size of the crack along the direction of the crack tip in terms of the number of cycles, and the second gives the fatigue life as a function of initial size. Where, the third and the fourth curves represent the Stress intensity factor and pressure limit in terms of the number of cycles respectively.
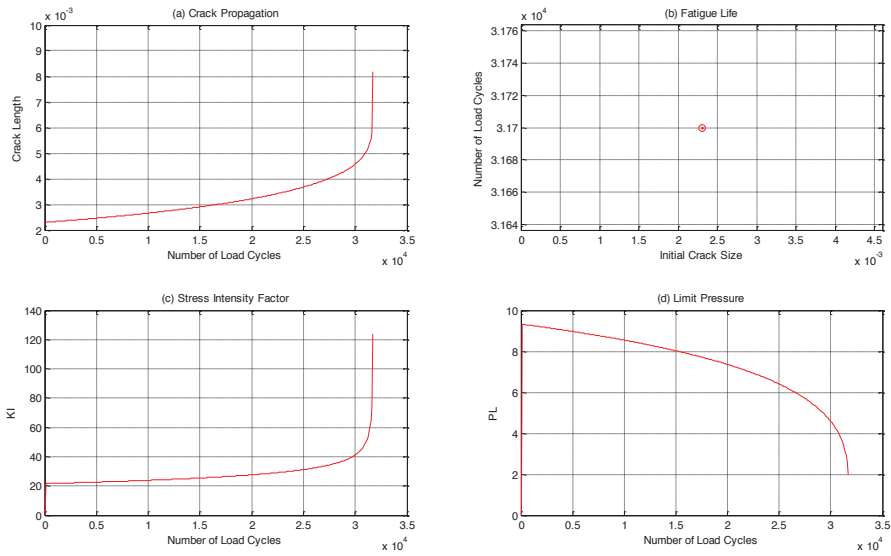
Fig. 2. Crack propagation with K_I and P_L variation

In Fig 3., the results are displayed as three curves, in the first and the second curves represent the brittle fracture and plastic collapse parameters in terms of the number of cycles respectively. Finally the third curve gives the brittle fracture parameter in terms of plastic collapse parameter necessary for FAD diagram.
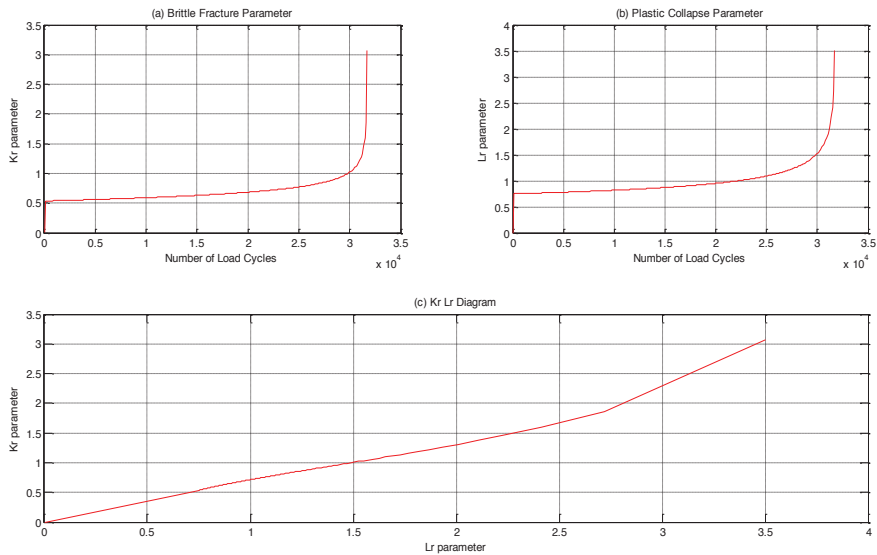

Fig. 3. Kr and Lr variation

According to Fig 2., we note that the stress intensity factor and crack size increases with increase in number of cycles. This increase of K_I factor is even more significant for larger defect sizes. This is of course logical since the more the pipe wall section is reduced by the crack, the more sensitive to service pressure it becomes which leads to a stress amplification effect which increases the stress intensity factor up to a critical value $K_I=K_{IC}$, (risk of brittle fracture).

On the other hand, the limit pressure decreases with increase in the crack size until the critical pressure $P_L=P_{max}$, (risk of plastic collapse).

According to Fig 3., we have $L_r >1$ (risk of plastic collapse) for N=22300cycles. Assuming that the pressure changes three cycles per day, the residual life of pipeline is 20.36 years, what corresponds to critical crack length a_c=3.4mm= (0.56) t. On the other hand, there is risk of brittle fracture, if $K_r>1$ for N=33000cycles=27.39 years, where a_c=4.5mm= (0.75) t. Thus, the pipeline tends to damage by plastic collapse before brittle fracture.

To take into account the combination of risk of brittle fracture and plastic collapse, a FAD diagram for case study is drawn in Fig 4. and a point of limiting condition B is calculated. We can say that the pipeline requires a repair before the crack reaches his critical length a_c=3.4mm, what leads to residual life of 20 years.
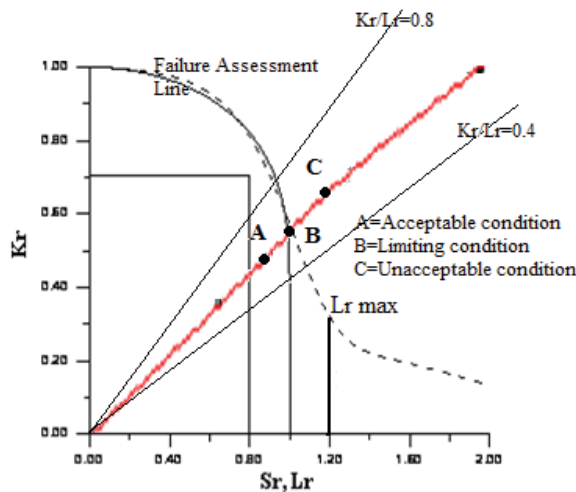

Fig. 4. Failure Assessment diagram for case study

5. Conclusions

Given the distances between areas of production and consumption of hydrocarbons, transport by pipeline is the most competitive means. These pipelines made of steel tubes can contain several types of defects of different origins, which may initiate cracks and cause their rupture. These pipeline failures can have serious consequences resulting in ecological or financial disasters. The causes of these failures can be of various kinds. They can occur either by a rupture or a leak. Most of them are caused by pitting corrosion or by stress corrosion cracking, but there are also failures related to weld defects.

A model for calculating the fatigue life of a pipeline under pressure was used. The possibility of its use has been shown in studying the propagation of an internal semi-elliptical surface crack in a longitudinal seam weld, making a good estimate of the stress intensity factors and residual life of pipeline. This allows us to determine its degree of harmfulness. A FAD diagram was establishes, based on the calculations of fatigue life of the weld joint according to the evolution of the crack length. We have been able to decide rapidly, about acceptability of a type of defect in pipeline and thus seek maximum security. This program combined with FAD diagram can be used as a tool for decision making about repairing or not of the damaged pipelines section. It makes it possible therefore to minimize pipelines exploitation costs.

But it still remains to push the analysis further using other crack growth models which take into account the influence of residual stresses due to welding process, and using the probabilistic fracture mechanics approach in the assessment of pipeline because of uncertainty and scatter of materiel properties, operating stress and defect size, in order to increase the reliability, service life and safety of the pipeline.

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