Reliability Estimation of Cracked API 5L X70 Pipeline Steel

O. Ghelloudj\textsuperscript{1,2}, D. Zelmati\textsuperscript{1,2}, D. Berdjane\textsuperscript{1}, A. Gharbi\textsuperscript{1}, S. Achouri\textsuperscript{1}, C. E. Ramoul\textsuperscript{1}, and K. Bouhamla\textsuperscript{1}

\textsuperscript{1}Research Center in Industrial Technologies (CRTI), P. O. Box 64, Cheraga, Algiers 16014, Algeria
\textsuperscript{2}LRTAPM: Research Laboratory of Advanced Technology in Mechanical Production, Department of Mechanical Engineering, Faculty of Engineering Science, Badji Mokhtar University Annaba, BP 12, 23000 Annaba, Algeria

E-mail: ghelloudj23@gmail.com, o.ghelloudj@crti.dz

Abstract. The aim of this paper is to estimate the reliability of cracked pipeline steel grade API 5L X70 used for hydrocarbon transportation, by coupling a developed mechanical model, based in one hand on the simulation of cracked specimen, and an experimental result of tensile and charpy test, and in the other hand, based on a reliability model by using a first order reliability method (FORM). These pipes are produced by the Algerian company of manufacture of welded pipes (ALFAPIPE Annaba). The experimental task such as resilience and tensile test were carried out on specimens taken from a pipe in the longitudinal and the transversal directions. The resilience tests are carried out at different temperatures in order to estimate the fracture toughness of the material, basing on a global correlation. Besides, tensile tests are performed to bring out the mechanical characteristics of the material. After, the stress intensity factor is assessed using the analytical model of IRWIN. In the reliability analysis, the limit state function is attributed to the moment when the stress intensity factor estimated by Irwin mechanical model, is equal to the fracture toughness of the steel pipe. The basic random variables within the limit state function are assumed to follow a normal distribution in order to simplify the assessment. Then, the evaluation of the reliability index and the parameters sensitivities of the cracked pipelines steel are assessed.

1. Introduction

Steel pipeline are made of many tubes manufactured with low alloy steels of high strength, designed for the transport and distribution of hydrocarbons. During exploitation, pipelines are subjected to high stresses due to the internal pressure of the fluid, external traffic and environmental attacks, and the soil of the covering, that can lead to their damage. Stresses resulting from the internal pressure such as the hoop stress, longitudinal stress, and radial stress, are the most important load that lead to the failure of the pipeline. In fact, the radial stress is neglected, and the design is reduced to the ultimate induced stress represented by the hoop stress resulting in the circumferential direction.

It is important to know that pipelines are the most economic mean of transporting hydrocarbon over long distances. During the period of exploitation, pipelines are exposed to different hazard due to the corrosion and crack defects which they are the most common causes of damage. Combined with the applied loads, it constitutes a vast subject of research to understand and analyzing the phenomenon of damage [1-8]. Several methods are used to improve the mechanical properties of steels by either heat...
treatments or by adding alloying elements [9]. The modeling of the mechanical behavior of a material is a pledge of a use rational on the economic plan and safe. This study is based on extensive experimental test, and analytical modeling based on the Irwin engineering model, in order to determine the tensile curve of the material, Charpy energy, and bring out the average values, and standard deviation. In the reliability analysis, the probability density function of the basic random variable within the limit state function is assumed to be normal distribution in order to simplify the assessment.

2. Experimental procedure

2.1. Material

The material used in this study is an API 5L X70 PSL 2 steel grade produced by Arcelor company and used for the construction of tubes for pipelines by the ALFAPIPE Algerian company; in the complex EL Hadjar, annaba, Algeria. This grade is a High-strength low-alloy steel (HSLA) used for hydrocarbon transportation. Table 1 shows the chemical composition of the material according to the specification API 5L.

| Elements | C    | Si   | Mn | P    | S    | Cr | Ni | Mo | Al  | Cu  | Nb  | Ti  | V   | Sn |
|----------|------|------|----|------|------|----|----|----|-----|-----|-----|-----|-----|----|
| [\%]     | 0.067| 0.262| 1.74| 0.016| 0.004| 0.024| 0.004| 0.028| 0.017| 0.065| 0.011| 0.039| 0.01|

2.2. Mechanical properties

The tensile tests were performed at room temperature on specimens prepared from a pipe of 48-inch external diameter, and 14.3 mm wall thickness according to API 5L. The specimens have been prepared in the longitudinal direction of the base metal for determined the mechanical properties of the material. Figure 1 shows the dog bone specimens used to the tensile test according to API 5L standard.

Resilience specimen were cut from the axial and circumferential direction of the tube, on the level of the base metal, Figure 2, of a welded pipeline, with V notch 10×10×55mm dimensional were prepared according to NF A 03-508 standard. The aim is to show that the rolling and manufacturing heterogeneities present in the structure explain the differences Charpy fracture energy.

Figure 1. Specimen Tensile test according to API 5L standard.

Figure 2. Geometric configuration of the cracked pipe.
2.3. Observation of microstructure
The micrograph of the X70 steel reveals a bi-phase structure, composed of two principal constituents: ferrite and pearlite. These is the characteristic microstructure of ferritic-pearlitic steel [10, 11]. The volume fraction of ferrite is 73% with a grain size of 14.5 and the volume fraction of perlite is 27% with a grain size of 12.6 according to ASTM E1382-97. Figure 3 shows the metallographic structure of X70 steel.

![Micrograph of X70 steel](image)

**Figure 3.** Ferritic-pearlitic microstructure of API 5L X70 steel.

3. Results and discussion
The results of the resilience of 100 tests were bring out at the temperature -10°C as recommended by the standard NF A 03-508, and the histogram of the Charpy energy in the axial direction and the transverse direction of the pipe are illustrated in Figure 4a and 4b respectively. It is obvious that the fracture energies of specimens cut in the longitudinal direction are greater than those of the transverse direction, due to the mechanical properties of interest in the rolling direction. It is interesting to study the worst case in order to optimize the fracture toughness of the API X70 steel pipe, and avoid all overestimate of the reliability and the security factor of the pipeline transporting oil and gaz. That’s to say in the fracture toughness analysis, the assessment will be based on the Charpy fracture energy in the transverse direction.
Figure 4. Histogram of Charpy fracture energy: (a) axial direction (b) transverse direction.

According to API 1104 standard, the nominal load-displacement curve is illustrated in Figure 5. The industrial challenge common to the field of fracture mechanics is to increase the reliability of the structures. To do this, it is necessary to study the mechanisms of damage of the materials by placing under stress conditions closest to the operating conditions. In order to achieve this objective, it is worth recalling that several models can be used which, despite the difference in their approaches, are complementary and essential [12].

Most of the proposed models well established in the literature are valid only within a restricted temperature range and for particular materials. Rolfe and Barsom proposed for the ductile part.

In the fragile part of the transition curve (Fig. 4), relation (1):
\[
\left( \frac{K_{IC}}{\sigma_e} \right)^2 = 0.646 \frac{KV}{\sigma_e} - 6.35 \times 10^{-3}
\]  
(1)

Sailors and Corten proposed the relation (2):

\[K_{IC}^2 = \alpha E(KV)\]  
(2)

where:

- \(K_{IC}\): Critical stress intensity factor
- \(\sigma_e\): Yield strength
- \(KV\): Fracture energy
- \(E\): Young modulus

In expressions (1) and (2), \(K_{IC}\) is expressed by \(MPa\sqrt{m}\), \(\sigma_e\) in \(MPa\), \(E\) in \(MPa\) and \(KV\) in joules. The coefficient \(\alpha\) varies between \(0.65 \times 10^{-3}\) and \(10^{-3}\) depending on the nature of the metal [13].

Figure 6 illustrates histogram of the critical stress intensity factor established in the transverse direction of the pipe, which corresponds to the maximum instability force. This characteristic value of the fracture toughness of the material translates the ruin by sudden cracking [12-14]. The associated failure criterion corresponds to a critical distribution of the stresses in the vicinity of the crack: the fracture will take place for a value of the stress intensity factor \(K_i\) greater than the critical value \(K_{IC}\).

**Figure 5.** Load-displacement curve for API 5L X70 steel pipe.
3.1. Reliability analysis

Once the fracture toughness of the API 5L X70 steel pipe is determined, the mechanical engineering model utilized is based on the Irwin model [13-16] in order to estimate its probability of failure. A statistical analysis is performed, in order to assess average values and standards deviation of the basic random variables within the limit state function.

The stress intensity factor in a rolled sheet used for the production of a spiral tube and containing a defect of length \( L \) and depth \( a \) and subjected to a tensile stress can be calculated using equation (3):

\[
K_I = 1.12 \sigma \sqrt{\frac{a}{Q} M_k}
\]  

\( K_I \): Stress Intensity Factor in Mode I  
\( \sigma \): Hoop stress  
\( M_k \): Surface correction factor  
\( Q \): Crack shape parameter is given in Eq. (4)

\[
Q = \Phi - \frac{2}{3 \pi} \left( \frac{\sigma}{\sigma_y} \right)^2
\]

\( \sigma_y \): Yield stress  
\( \Phi \): 2\textsuperscript{nd} order elliptic integral

\[
M_k = 1 + 1.2 \left( \frac{a}{t} - 0.5 \right) \quad \text{Pour} \quad a/t \geq 0.5
\]

Basing on the Irwin engineering model, the limit state function \( G(x) \) corresponds to the difference between the critical stress intensity factor of the material and the calculated stress intensity factor, as expressed in Eq. (6)

\[
G(x) = K_{IC} - K_I
\]

Once the mechanical model is developed (Eq. 6), the next step is to assign a probabilistic model for the random parameters contributing in the model. Table 3 shows the basic random variables of the mechanical model as well as the corresponding parameters. In the reliability analysis, PHIMECA
software [17] is used to assess the reliability index $\beta$ as the minimum distance between the origin and the failure zone in the standard space of random variables. This index is estimated by solving the constrained optimization problem as expressed by (Eq. 7) [1-4, 18, 19].

$$\beta = \min \left(\sqrt{\{U\}^T\{U\}}\right) \quad \text{Under constrain of } H(U_i)\geq0$$  \hspace{1cm} (7)

**Figure 7.** Evolution of the reliability as a function of the crack depth and crack length.

Figure 7 illustrates the results of the reliability analysis, using the IRWIN model as a mechanical model. In this investigation, different ratios $d/t$ of crack defect to wall thickness ratio were chosen equal to 30%, 40%, 50%, 60% and 80%. It is obvious as illustrated in Figure 8 that the reliability index $\beta$ decrease with the increase of the crack length independently of the depth of the defect. It is interesting to know that the larger defect to thickness ratios are more sensitive to the length of defects than the low ratios [2-5]. Based on the experimental design, the behavior could be used to provide accurate information about critical defects and can be considered as a decision tool for repairing or replacing damaged pipeline potions (Figure 8). For a defect ratio of 80%, the pipeline is no longer reliable and a maintenance plan should be provided, which is confirmed by the ASME B31G standard for corrosion defects.

For a defect of crack depth to wall thickness ratio of 60%, the pipeline is reliable up to a critical length equal to 50mm, of which it is very interesting to know the sensitivity of the basic variables of the mechanical model at this point (point of intersection of curve (for $d/t = 60\%$) with the horizontal line $\beta = 3.72$ as shown in Figure 8.
4. Conclusions

Depending on the heterogeneities and the morphological variances resulting from the manufacturing modes and processes, the Charpy fracture energy, and the stress intensity factor are lower in the transverse direction than the longitudinal direction. This is in agreement with the direction of the rolling which is characterized by elongated grains.

The failure scenario is attributed to the moment when the stress intensity factor estimated by Irwin mechanical model, is greater than the fracture toughness of the steel pipe. The developed mechanical model coupled with the probabilistic approach is used to optimize the investigation of the presence of a crack on the remaining strength of pipelines. The mechanical model used for the evaluation of defects is based on the IRWIN model, and a developed diagram could be used as a decision tool for repairing or replacing portions of damaged pipelines. The sensitivity of the basic variables for the defect depth to wall thickness ratio of 60% for the thickness, diameter and the pressure are the same and the dominant parameter is the fracture toughness, and the control of the pressure fluctuations of gas must be strict.

References

[1] Amirat A, Mohamed-Chateauneuf A and Chaoui K 2006 *Int. J. Pres. Ves. Pip.*, **83**(2) 107-117
[2] Zelmati D, Ghelloudj O and Amirat A. 2017 *Int. J. Adv. Manuf. Technol.*, **90** 2777-2783
[3] Ghelloudj O, Zelmati D, Gharbi A, Berdjane D, Ramoul C E and Chouchane T 2017 *Acta Phys. Pol. A* **131**(3) 420-422
[4] Zelmati D, Ghelloudj O and Amirat A. 2017 *Eng. Fail. Anal.* **79** 171-185
[5] Ahammed M and Melchers R E 1997 *Eng. Struct.* **19**(12) 988-994
[6] Ahammed M and Melchers R E 1996 *Int J Press Ves & Pip* **69**(3) 267-272
[7] Zelmati D, Bouledroua O, Hafi Z and Dukic M B 2020 *Engineering Failure Analysis* **115** 104683
[8] Zelmati D, Ghelloudj O, Hassani M and Amirat A 2019 *In Computational Methods and Experimental Testing In Mechanical Engineering, Springer, Cham.* 145-152
[9] Bouhamla K, Gharbi A, Ghelloudj O, Hadji A, Maouche H, Remili S and Chettouh S 2021 *Defect Diffus. Forum, Trans Tech Publications Ltd.* **406** 334-347
[10] Ghelloudj O, Gharbi A, Zelmati D, Bouhamla K, Ramoul C E and Berdjane D 2021 Defect Diffus. Forum, Trans Tech Publications Ltd. 406 448-456
[11] Gharbi A, Bouhamla K, Ghelloudj O, Ramoul C E, Berdjane D, Chettouh S and Remili S 2021 Defect Diffus. Forum, Trans Tech Publications Ltd. 406 419-429
[12] Shin S W, Hwang B, Kim S, Lee S. 2006 Mater. Sci Eng A 429 196-204
[13] Barthelemy B. 1980, Notion pratique de la mécanique de rupture (Paris: EYROLLES)
[14] Jayadevan KR, Berg E, Thaulow C, Østby E, Skallerud B 2006 Int. J. Solids Struct. 43 2378-2397
[15] Irwin G R 1962 J. Appl. Mech. 29(4) 651-654
[16] Rolfe S T and Barsom J M 1977 Fracture and fatigue control in structures: Applications of fracture mechanics, ASTM International
[17] PHIMECA Engineering 2002 PHIMECA—reliability-based design and analysis. User's manual, version 1.6, (Aubière, France)
[18] Lemaire M. 2013 Structural reliability (John Wiley & Sons)
[19] Ditlevsen O and Madsen H O 1996 Structural reliability methods, 178 (New York: Wiley)