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A NEW INVESTIGATION OF THREE FATIGUE MODELS FOR ASSESSING CRACK PROPAGATION IN PIPELINES UNDER BENDING LOADING

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Abstract

This work uses the three-dimensional finite element method to compare three fatigue models (NASGRO, FORMAN, and WALKER) for assessing crack propagation in structures subjected to bending. The impact of several key factors, including material qualities, load ratio (R), and environmental conditions, is investigated. The chance of structural failure is assessed using the Monte Carlo method. Two mathematical functions—a sixth-degree polynomial and a Gaussian function—are analysed to determine the density distribution. This research offers important insights into the fatigue behaviour of cracked structures, enhancing the reliability of failure risk assessments. The study's conclusions emphasise the critical influence of geometric and mechanical parameters on crack propagation, providing a solid foundation for predicting fatigue life in engineering applications. The finite element method results align well with Zahoor's (1988) findings, validating the numerical model with a standard deviation of less than 3%. Environmental conditions significantly influence crack propagation, with ambient conditions enhancing the durability of TP304 compared to humid and dry environments. A higher load ratio (R=0.5) delays crack growth, increasing the number of cycles before failure. TP304 exhibits more excellent crack resistance than TP316, particularly in the NASGRO and FORMAN models, emphasising the importance of selecting an appropriate predictive model. The Gaussian distribution provides an accurate estimate of the mean and a good approximation of the probability density function.

Keywords: Fatigue, bending load, Propagation of crack, Finite element method, Safety, Monte Carlo method, Durability.

1. Introduction

Pipelines play an important role in the transportation of hydrocarbons, ensuring efficient and secure delivery over long distances. However, these infrastructures are continuously exposed to various environmental factors that may affect their durability and performance (Badida et al., 2019; Bastian et al., 2019; Gachlou et al., 2019; Kimiya et al., 2020; Ibrahim et al., 2018). Their integrity can be compromised by multiple forms of degradation, jeopardising their proper functioning and Safety. Among the primary causes of damage are corrosion, mechanical stresses, environmental conditions, and operational errors, each of which can result in structural failures with significant economic, environmental, and safety-related consequences (Serier et al., 2016; Salem et al., 2024; Maachou et al., 2024a; Mechab et al., 2020; Fizazi et al., 2021; Zhou et al., 2025; Maachou et al., 2025).

Corrosion is one of the primary factors contributing to the degradation of pipelines, threatening their integrity and longevity. It results from the interaction of metal with moisture, chemical substances in the soil, water, or transported hydrocarbons. This phenomenon manifests in various forms, from uniform corrosion to localised corrosion and stress corrosion cracking (Ma et al., 2024; Wu et al., 2022; Mechab et al., 2025).

Over time, corrosion causes a gradual thinning of pipeline walls, increasing the risk of leaks, ruptures, and structural failures (Qin & Cheng, 2021; Mechab et al., 2018). These deteriorations lead to significant maintenance and replacement costs while posing severe environmental and Safety risks (Metehri et al., 2024; Chen et al., 2020). Therefore, rigorous management and appropriate preventive measures are essential to mitigate these adverse effects and ensure the reliability of pipeline infrastructure.

Pipeline cracking poses a significant risk to the integrity, Safety, and durability of hydrocarbon and fluid transport infrastructure (Mechab et al., 2011; Mechab et al., 2014). Whether caused by material fatigue, stress corrosion cracking, or mechanical and environmental variations, it can lead to severe failures, ranging from leaks to catastrophic ruptures (Yin et al., 2020; Zhou et al., 2020; Wu et al., 2022). Effective preventative measures, such as routine inspections, applying protective coatings, using resistant materials, and improved monitoring procedures, are crucial to reducing these hazards. By adopting these measures, it is possible to extend the service life of pipelines, reduce maintenance costs, and ensure both the Safety of installations and environmental protection (Salem et al., 2019; Maachou et al., 2016). In addition, recent numerical investigations by Maachou et al. (2024b) analysed the mechanical response of A510AP steel pipe bends subjected to combined internal pressure and bending loads, incorporating the influence of thermal agitation parameters. Using ABAQUS and the extended finite element method (XFEM). This study compares three fatigue models for assessing crack propagation using the three-dimensional finite element method applied to bending-susceptible structures. The environment, the load ratio (R), and material qualities are among the important parameters whose effects are investigated. The chance of structural failure is assessed using the Monte Carlo method. Two mathematical functions—a sixth-degree polynomial and a Gaussian function—are analysed in order to characterise the density distribution. The plastic energy approach has also been employed to predict fatigue crack growth, offering valuable insights into energy dissipation mechanisms during crack propagation.

2. Fundamental relations

This study uses the NASGRO, Forman, and Walker models to predict fatigue crack growth under cyclic Loading. Each offers distinct approaches to modelling crack propagation.

The NASGRO model extends the Forman equation by incorporating stress ratio effects, threshold behaviour, and crack closure, making it suitable for various materials and conditions (Equation 1). It accounts for various physical mechanisms affecting crack growth, such as plasticity-induced closure and material-specific parameters.

The Forman model introduces stress ratio dependence to the Paris law, improving predictions near fracture toughness by considering the influence of stress intensity factors and load ratios (Equation 2). This model is beneficial in high-stress fatigue applications where failure is imminent.

The Walker model incorporates an empirical exponent to account for stress ratio effects, making it adaptable to variable amplitude loading conditions (Equation 3). It adjusts for different load ratios by modifying the stress intensity factor range, providing a more flexible approach for complex loading spectrum cases. These models differ in complexity and assumptions, making their selection dependent on material properties, stress conditions, and environmental influences.

$$\frac{da}{dN} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{\max}}{K_{cr}}\right)^q} \tag{1}$$

$$\frac{da}{dN} = C\frac{\left(\Delta K\right)^n}{\left(1-R\right)K_c - \Delta K} \tag{2}$$

$$\frac{da}{dN} = C\left(\Delta K\right)^n\left(1-R\right)^p \tag{3}$$

Where:

$$R = \frac{K_{\min}}{K_{\max}} \tag{4}$$

$$\Delta K = K_{\max} - K_{op} \tag{5}$$

$$K_{\max} = Y\sigma_{\max}\sqrt{\pi a} \tag{6}$$

$$K_{op} = Y\sigma_{\min}\sqrt{\pi a} \tag{7}$$

$$K_{cr} = Y\sigma_{cr}\sqrt{\pi a_{cr}} \tag{8}$$

The function f is:

$$f = \frac{K_{op}}{K_{\max}} \tag{9}$$

$\frac{da}{dN}$: Crack growth rate (*mm/cycle*);

R : stress ratio;

ΔK : Stress intensity factor range;

K_{max} : Maximum stress intensity factor;

K_{op} : The Crack opening stress intensity factor corresponds to the minimum value.

K_{cr} : Critical stress intensity factor.

2.1 Geometrical

This paper employs the three-dimensional finite element method to investigate the fatigue study of crack propagation in axial cracks under bending loads. The ratio (Rm/t) equals 10, and the mean radius (Rm) equals 200 mm. The applied stress is equal to 100MPa. Figure 1 displays the geometrical model used in the study.

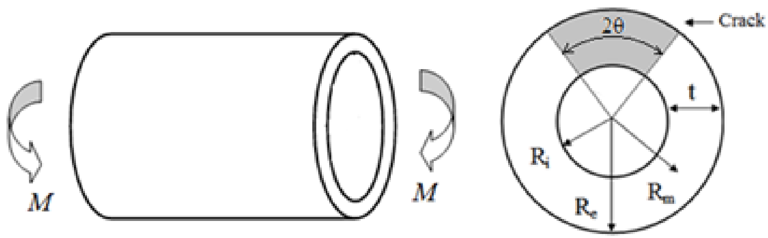

Fig. 1. Geometry of the studied pipe.

2.2 FEM analyses

This work presents a fatigue analysis of crack propagation in cracked structures under bending loads using a three-dimensional finite element approach. A quarter-pipe model was constructed using twenty-node isoparametric quadratic brick elements with reduced integration (C3D20R in ABAQUS). The completed finite element model comprises 20,550 elements, as shown in Fig. 2.

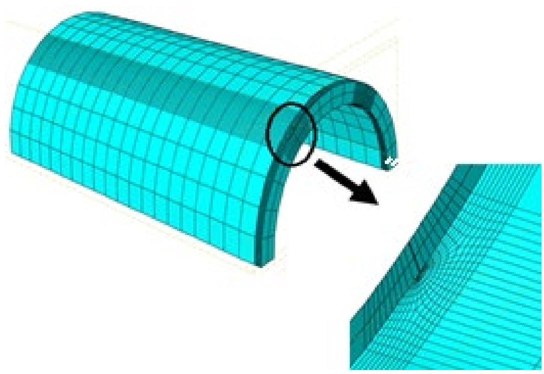

Fig. 2. FE mesh of the cracked pipe.

Finite element analysis (FEA) employs various models and criteria to investigate the initiation and propagation of fatigue cracks. When defining crack initiation in a meshed component using the finite element method (FEM), two critical factors must be considered: the element size and the threshold for crack growth. To improve accuracy, conducting a mesh sensitivity analysis is essential. This involves refining the mesh around potential crack initiation sites in order to capture stress gradients more effectively. If the mesh elements are too large, they may fail to detect localised stress concentrations that can lead to crack formation. For an accurate representation of stress distribution near the crack tip, the element size should be comparable to or smaller than the expected crack length.

2.2.1 Indirect Cyclic Approach

An alternative method, the indirect cyclic approach, is employed for high-cycle fatigue (HCF) analysis, wherein only the crack-driving parameters are extracted using Abaqus. XFEM-based fatigue analysis in Abaqus is limited to Linear Elastic Fracture Mechanics (LEFM) and low-cycle fatigue via the direct cyclic method. Furthermore, performing finite element simulations over many loading cycles requires substantial computational resources. Consequently, there is a need for a more efficient and reliable alternative for XFEM-based fatigue analysis. The underlying concept involves conducting multiple static simulations to evaluate fatigue-driving parameters, such as the *J*-integral, which represents the energy release rate associated with crack propagation.

$$J = \oint \left[U dy - T \left(\frac{\partial u}{\partial x} \right) ds \right] \tag{10}$$

Where, U is strain energy density, T is traction on the contour integral, and u is the displacement field.

2.2.2 XFEM for fatigue simulation

The Extended Finite Element Method (XFEM) builds upon the conventional Finite Element Method (FEM) by applying the partition of unity concept. In XFEM, stress and displacement fields are calculated by introducing enrichment functions into the finite elements intersected by a crack. This method enhances the accuracy of crack modelling without requiring mesh refinement.

Select nodes are assigned additional degrees of freedom (DOF) beyond their standard DOF, enabling a more accurate representation of discontinuities. The displacement field within these enriched elements is approximated using Equation (11) by the standard XFEM formulation (Fries & Belytschko, 2010).

$$u = \sum_{I=1}^{N} N_I(x) \left[u_I + H(x) a_{I^*} + \sum_{a=1}^{4} F_a(x) b_{I^*}^{a} \right] \tag{11}$$

Here, u is the displacement,

$N_I(x)$ is the standard shape function;

u_I is the conventional nodal DOF;

$H(x)$ is the jump function across the crack surface;

a_{I^*} is the associated DOF enriched;

$F_a(x)$ is the elastic asymptotic crack tip function;

$b_{I^*}^{a}$ is the associated nodal DOF enriched;

Only the first two terms associated with the crack surface are used for a propagating crack.

In the indirect cyclic approach for high-cycle fatigue (HCF), the XFEM model in Abaqus is employed for static analysis to compute the J-Integral. This value is subsequently used to estimate the number of cycles required for the crack to advance by a predefined length, typically at least one element length beyond the current crack tip, as specified in Equations (1), (2), and (3). As fatigue-induced crack growth occurs, the crack geometry is continuously updated until it reaches a critical size or the material's fracture toughness limit.

2.3 Materials

The mechanical properties of the pipe model studied are presented in Tables 1 and 2.

Property	**TP 304**	**TP 316**
Young's Modulus (E) [MPa]	204330	193000
Poisson's Ratio (Nu)	0.3	0.3
Ultimate Tension Strength (UTS) [MPa]	558.50	515
Yield Stress (YS) [MPa]	268.91	205
Effective Fracture Toughness (K1e) [MPa√m]	307.676	307.676
Plane Strain Fracture Toughness (K1c) [MPa√m]	219.769	219.769
Paris Crack Growth Rate Constant (C)	1.1486e-11	1.5315e-11
Paris Exponent (n)	3	3
Exponent in Forman-Newman-de Koning-Henriksen Equation (p)	0.25	0.25
Exponent in Forman-Newman-de Koning-Henriksen Equation (q)	0.25	0.25

Table 1. Mechanical properties of the model studied (AFGROW 2006)

Environment	**C**	**n**
Dry environment	1.0e-10	3.5
Ambient environment	1.1486e-11	3.0
Humid environment	5.0e-9	3.0

Table 2. Equation parameters for TP304 (AFGROW 2006)

3. Analyses and results

3.1 Validation of results

The SIF solution given by Zahoor (1988) has been considered in the present study as follows:

$$K = \sigma_b \sqrt{\pi R_m \theta} F_b \left(\theta/\pi , R_m/t \right) \tag{12}$$

Where:

$$\sigma_b = M / \pi R_m^2 t \tag{13}$$

$$F_b = 1 + A\left[4.5967\left(\theta/\pi\right)^{1.5} + 2.6422\left(\theta/\pi\right)^{4.24} \right] \tag{14}$$

$$\begin{cases} A = \left[0.125\left(R_m/t\right) - 0.25 \right]^{0.25} & for 5 \le \left(R_m/t\right) \le 10 \\ A = \left[0.4\left(R_m/t\right) - 3.0 \right]^{0.25} & for 10 \le \left(R_m/t\right) \le 20 \end{cases} \tag{15}$$

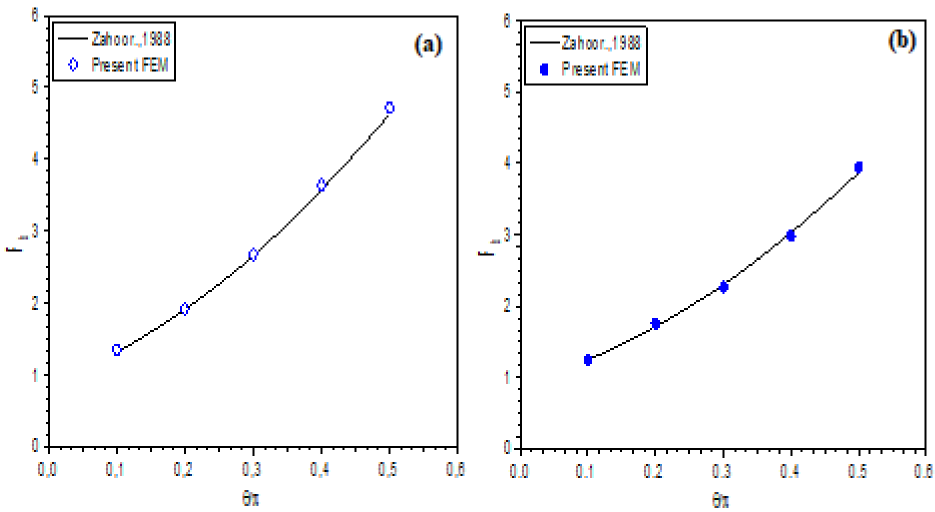

Fig. 3. Presents the numerical results obtained using the finite element method (FEM), compared to those of Zahoor (1988): (a) for Rm/t=10, (b) for Rm/t=5.

Figure 3 presents the numerical results obtained using the finite element method (FEM) compared to those of Zahoor (1988). The results obtained through the finite element method show excellent agreement with those of Zahoor (1988), demonstrating the validity of the numerical model used. The standard deviation does not exceed 3% (see Figure 3).

3.2 Effect of environmental conditions

Figure 4 illustrates the evolution of crack growth as a function of the number of cycles for three different models (NASGRO, FORMAN, and WALKER) under three environmental conditions: dry, ambient, and humid. The NASGRO (a) and FORMAN (b) models display similar behaviour, with a steady increase in crack growth followed by a sudden acceleration. In contrast, the WALKER model (c) exhibits a more gradual initial phase, culminating in an even sharper final acceleration. Generally, crack growth progresses slowly in the early cycles before rapidly increasing beyond a critical threshold. Compared to dry and humid conditions, the ambient environment enhances the durability of TP304 material and delays its failure. These results underscore the significant impact of environmental factors on crack growth and highlight the importance of selecting an appropriate model to accurately predict the service life of the studied material (TP304, R=0.5).

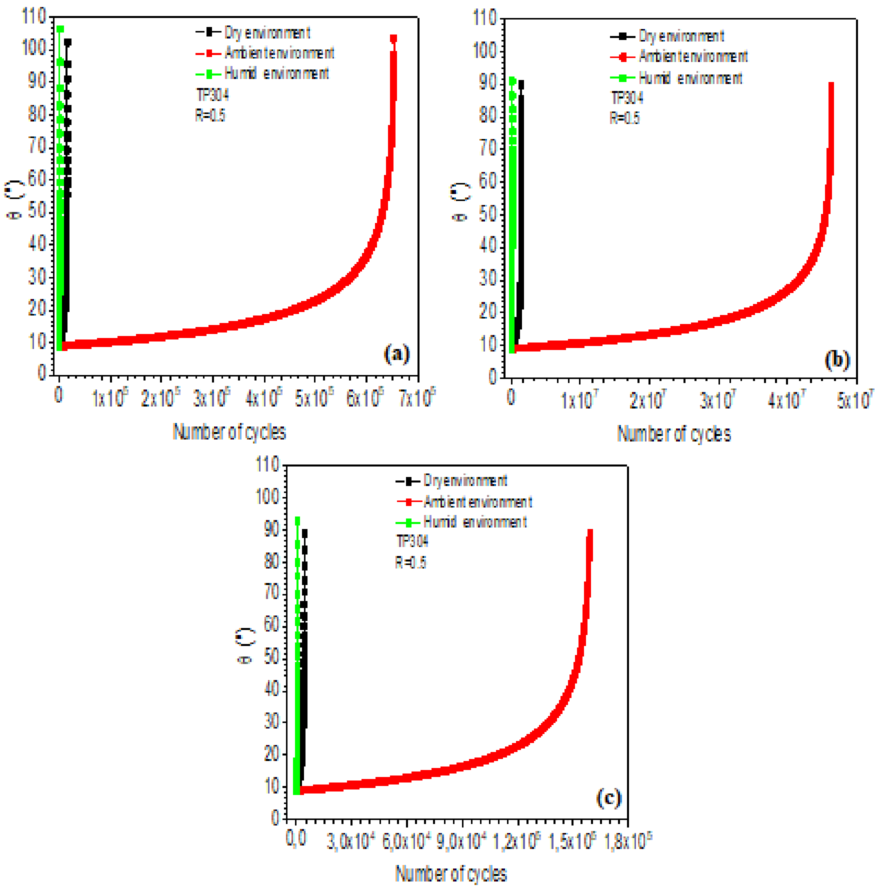

Fig. 4. Illustrates the evolution of crack growth as a function of the number of cycles for three different models: (a) NASGRO, (b) FORMAN, and (c) WALKER, under three environmental conditions: dry, ambient, and humid, Rm/t=10

3.3 Effect of load ratio R

Figure 5 illustrates the evolution of crack growth as a function of the number of cycles for three models (NASGRO, FORMAN, and WALKER) in an ambient environment, for different load ratio values (R = 0, 0.1, 0.3, 0.5). The NASGRO and FORMAN models display comparable patterns, characterised by a sharp increase in crack growth beyond a certain threshold, with FORMAN suggesting a slightly extended lifespan. In contrast, the WALKER model exhibits a steadier initial progression, followed by an abrupt acceleration, which is especially noticeable at lower (R) values. In general, an increase in the load ratio (R) delays crack propagation: the higher the (R) value (R=0.5), the greater the number of cycles required to reach a critical crack size. Conversely, for R=0, crack growth occurs more rapidly, indicating increased vulnerability of the material under fully compressive Loading or minimal crack opening. These findings confirm that the load ratio (R) plays a crucial role in crack propagation, with higher values contributing to an extended fatigue life of the material (TP304). Furthermore, the differences between the models highlight the significant impact of equation selection on crack growth predictions, a crucial factor in assessing the durability of materials subjected to fatigue conditions.

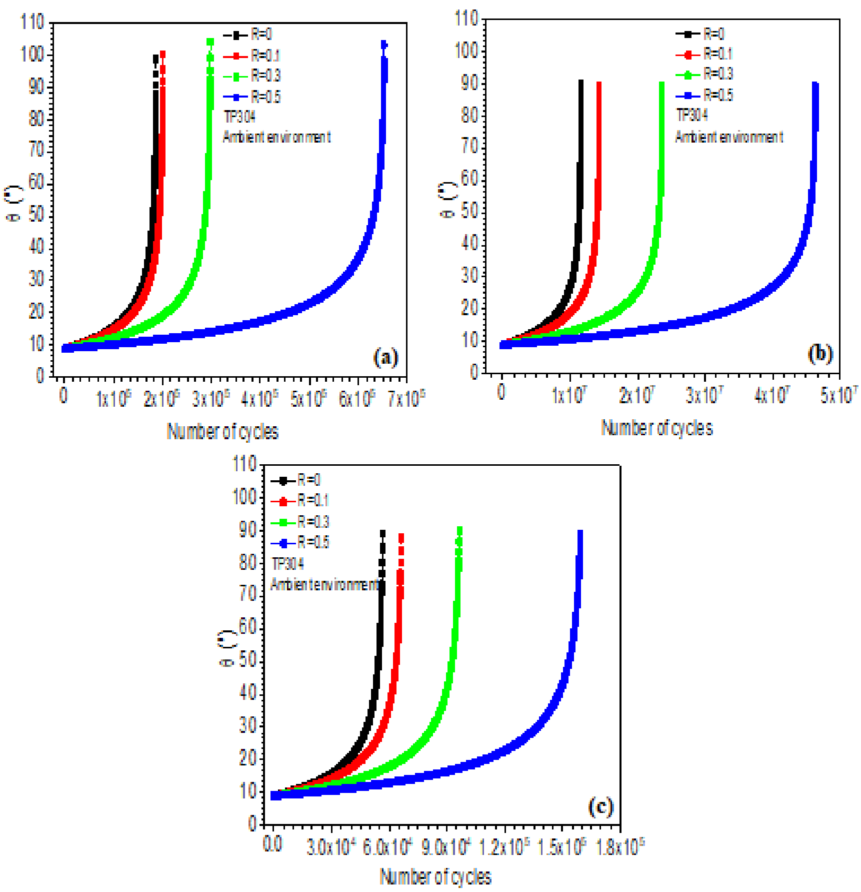

Fig. 5. Illustrates the evolution of crack growth as a function of the number of cycles for three models: (a) NASGRO, (b) FORMAN, and (c) WALKER, in an ambient environment and for different load ratio values R (0, 0.1, 0.3, 0.5), Rm/t=10.

3.4 Effect of property

Figure 6 illustrates the crack growth evolution as a function of the number of cycles for two materials, TP304 and TP316, under ambient conditions with a load ratio of R = 0.5, using three different models: NASGRO, FORMAN, and WALKER. In all cases, crack propagation begins gradually before accelerating sharply once it reaches a critical threshold. The results indicate that TP316 experiences faster crack growth than TP304, suggesting lower fatigue resistance for TP316. The NASGRO and FORMAN models exhibit similar behaviours, showing an initial slow crack growth phase followed by sudden acceleration. According to these models, TP316 has a shorter fatigue life than TP304. Conversely, the WALKER model shows a more progressive crack growth at the beginning and a more pronounced acceleration at the later stages. Unlike the other models, the crack growth curves for TP304 and TP316 in the WALKER model are more similar, indicating a minor difference in crack resistance between the two materials. Overall, the findings suggest that TP304 exhibits higher resistance to crack propagation compared to TP316, primarily based on the NASGRO and FORMAN models. Additionally, the choice of predictive model plays a crucial role in estimating material lifespan, emphasising the importance of selecting an appropriate model for fatigue analysis.

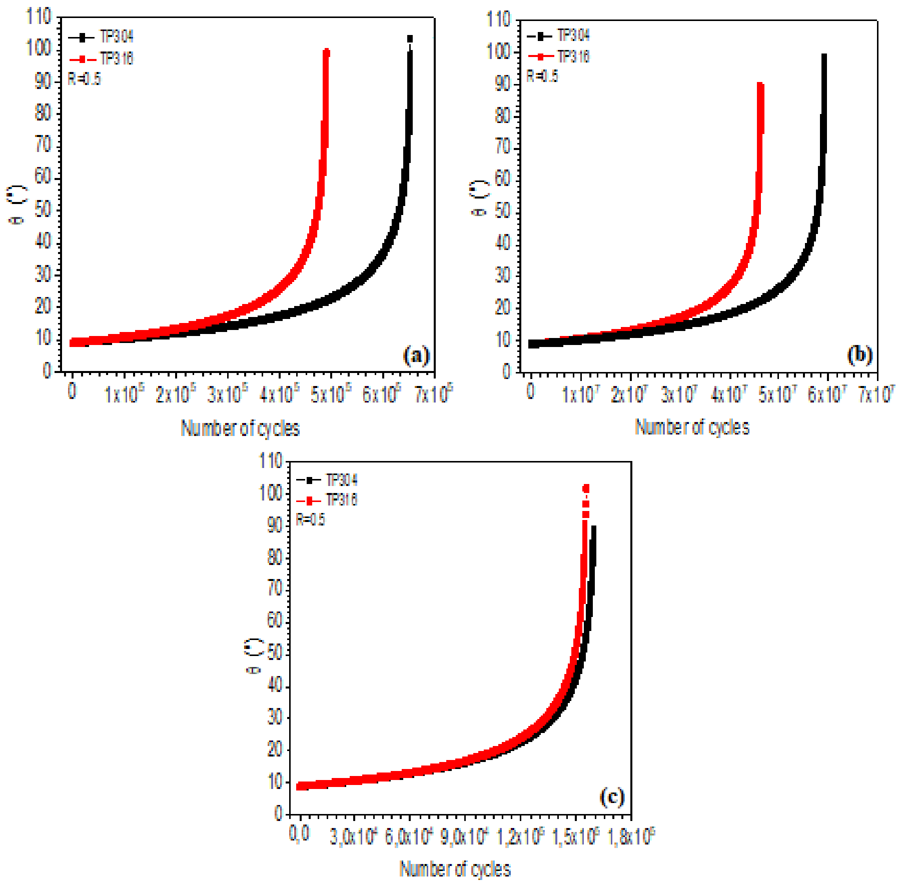

Fig. 6. Illustrates the crack growth evolution as a function of the number of cycles for two materials, TP304 and TP316, under ambient conditions (Rm/t = 10), for three models: (a) NASGRO, (b) FORMAN, and (c) WALKER,

3.5 Analytical Prediction

The Monte Carlo method is a probabilistic technique for estimating numerical values through repeated random simulations. It is particularly valuable for tackling complex problems with difficult or impossible analytical solutions. This approach relies on generating random numbers and applying statistical sampling techniques. In general, increasing the number of simulations enhances the accuracy of the estimation. Key parameters such as geometric factors (a, c, t, Rm), load conditions, bending, and material properties (E, ν) are treated as random variables. Any or all of these factors can be modelled probabilistically. Consequently, any relevant fracture response, such as N(X), should be assessed in probability. To apply this method, Monte Carlo simulations were performed using a FORTRAN program. 10^5 Simulations were conducted to ensure the accuracy of the results. Figure 7 shows the density function obtained by fitting the histogram. Two mathematical functions—a sixth-degree polynomial and a Gaussian function—are analysed to determine the density distribution.

The Gaussian distribution gives an excellent estimate of the mean value and a good approximation to the probability density function N(x). Figure 8 illustrates the probability density of N(x) failure for three environments (dry, ambient, and humid) applied to the TP304 material, with a coefficient R=0.5. In an ambient environment, failure occurs later, with higher N(x) values. The more spread-out curve indicates better resistance of the material under these conditions. In contrast, failure occurs earlier in a humid environment than in an ambient environment but later in a dry environment. The broader curve suggests a more excellent dispersion of failure cycles, indicating increased variability in the material's lifespan. The ambient environment delays failure and enhances the durability of the TP304 material compared to conditions in humid and dry environments.

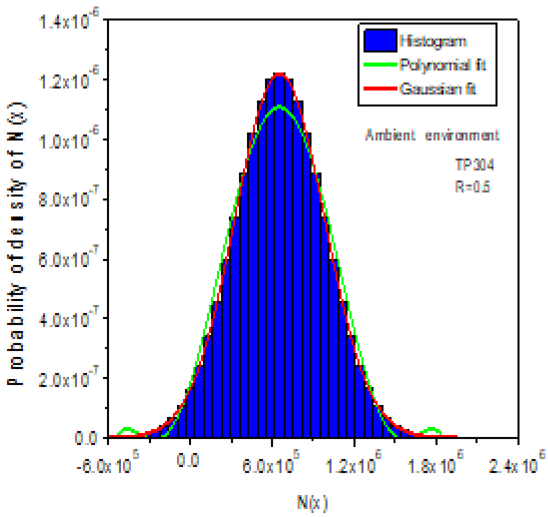

Fig. 7. Histogram and the probability distribution of the number of cycles N(x).

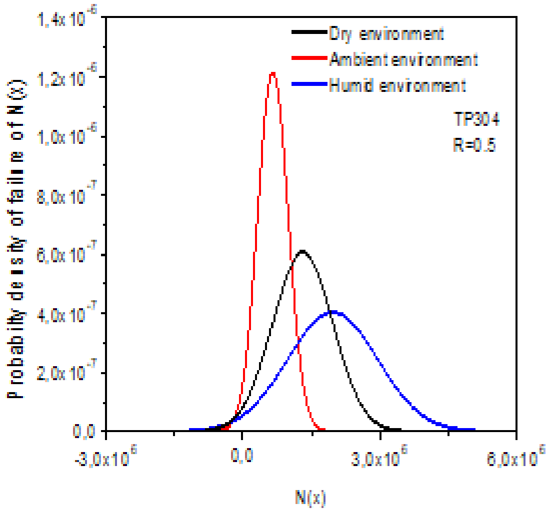

Fig. 8. The probability of failure of N(x) for three different environments**.**

4. Conclusions

This study presents a comparative analysis of three fatigue models for evaluating crack propagation using the three-dimensional finite element method applied to structures subjected to bending. The influence of several key parameters is examined, including the environment, the load ratio (R), and material properties. Using the Monte Carlo approach, the probability of structural failure is assessed. The density distribution is characterised by analysing two mathematical functions: Gaussian and a sixth-degree polynomial. The findings of this study lead to the following conclusions:

- The results obtained through the finite element method show excellent agreement with those of Zahoor (1988), demonstrating the validity of the numerical model used. The standard deviation does not exceed 3%.
- The ambient environment enhances the durability of TP304 material and delays failure compared to dry and humid conditions. These results underscore the significant impact of environmental factors on crack growth and highlight the importance of selecting an appropriate model to accurately predict the service life of the studied material (TP304, R=0.5).
- In general, an increase in the load ratio (R) delays crack propagation: the higher the R value (R=0.5), the greater the number of cycles required to reach an important crack size.
- TP304 demonstrates higher crack propagation resistance than TP316, mainly according to the NASGRO and FORMAN models. Additionally, the choice of predictive model plays a crucial role in estimating material lifespan, emphasising the importance of selecting an appropriate model for fatigue analysis.
- The Gaussian distribution gives an excellent estimate of the mean value and a good approximation to the probability density function N(x).
- Failure occurs earlier in a humid environment than in an ambient environment, but later in a dry environment.

- The ambient environment delays failure and enhances the durability of the TP304 material compared to conditions in humid and dry environments.

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