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DAMAGE-RELIABILITY APPROACH FOR FATIGUE CRACK PROPAGATION IN MDPE GAS PIPE

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Fatigue crack propagation tests are carried out on arc-shaped specimens prepared from MDPE gas pipes. Damage zone characterization is achieved using the diamond wafer sectioning technique from partially propagated and prematurely arrested cracks. Damage ahead of the crack-tip is used to assess a damage parameter and reliability based on statistical laws and subsequent use the PHIMECA Software. It is shown that a length and a width associated with a corresponding change in thickness at the fracture surface satisfactorily describe the damage zone size. The 3-parameter Weibull model gives the best reliability behavior and a critical lifetime of *82*%. When considering separately both the Dugdale model and experimental damage zone measurements, it is possible to establish the evolution of the reliability index as a function of crack length. It is concluded that the reliability index approach based on damage provides a more consistent representation compared to analytical models.

Key words: MDPE gas pipe, fatigue crack propagation, damage zone, limit state function, reliability index.

1. Introduction

At the end of the 1970s, medium-density polyethylene (MDPE) pipes were introduced in the gas distribution systems of numerous Algerian cities to replace existing steel, copper and nodular cast iron sections. In 1990, with the considerable advent of semi-crystalline polymers in the gas industry showing many attractive advantages, i.e., service lifetime exceeding 100 years, increased operating pressure, corrosion-free systems, rapid installation and low maintenance costs, MDPE was substituted with high-density polyethylene (HDPE). Such an important shift vis-à-vis of plastics piping is supported by innovative technical standards and numerous recommendations highlighting its superior performance compared to classical piping materials (Mamoun *et al.* [1]; Nguyen *et al.* [2]; PPI [3]; Zhang *et al.* [4]).

A lot of research work on plastic pipelines discussed various aspects such as fatigue crack propagation (FCP) (Chaoui [5]; Favier *et al.* [6]), damage growth (Frank *et al.* [7]; Gu *et al.* [8]), creep lifetime (Khelif *et al.* [9]), critical damage and lifetime modeling (Majid and Elghorba [10]) and reliability index computation (Alimi *et al.* [11]). On the other hand, studies invoking fatigue loading as an accelerating agent for slow crack growth (SCG), damage characterization and durability of polyethylene pipes are also prevalent (Chudnovsky [12]).

An original testing procedure was developed for MDPE gas pipes [5]. It is based on arc-shaped specimens directly issued from the pipe and subjected to fatigue mode under specific conditions to produce brittle-like fracture at laboratory scale within a shorter period. Damage analysis revealed that the brittle regime is led by a craze zone which becomes diffuse and larger as the crack extends [5-8,12]. Redhead *et al.* [13] employed a cracked round bar to study crack initiation in HDPE pipe grade with an implementation of a lifetime assessment procedure. In addition, they analyzed the crack tip damage zone to uncover the mechanisms of the initiation of SCG. Hence, damage zone dimensions are investigated for a better appreciation

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of SCG mechanisms under both creep and fatigue [5,6,12,13]. However, very few studies are devoted to plastic pipe reliability combined with FCP and damage zone growth. This could be the culminating approach to soundly assess the long-term plastic pipe lifetime from laboratory accelerated fatigue tests.

The objective of this study is to consider accelerated fatigue test data of MDPE pipes and corresponding damage measurements to suggest a method to establish reliability parameters. Such work is necessary as many MDPE pipe networks have reached expected theoretical service life and reliability is the foremost tool to help make safer decision as a function of fraction of life and defect size for older network maintenance and replacement programs.

2. Experimental and modeling approaches

The pipe material considered in this study has been selected as a reference to allow a comparison of results from different studies. Characterization properties are well-established and published in one identified resource for public use (Crissman [14]). The material is an ethylene-hexene copolymer with a density of *0.938 g/cm*^{3}. The pipe is *11 mm* thick and its outside diameter is *115 mm*. Figure 1 shows the arc-shaped specimen geometry which is subjected to a maximum stress of $0.25\,\sigma_y$.

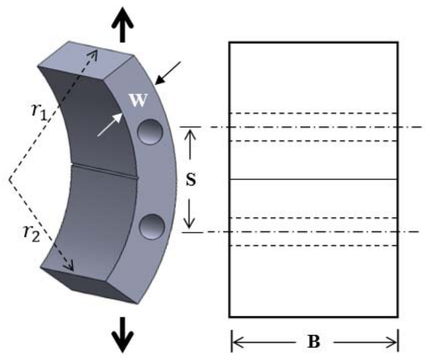

Fig.1. Schematic of arc-specimen machined from PE pipe.

Figure 2 illustrates the procedures for reliability computation using both (*i*) statistical laws and (*ii*) the First Order Reliability Method (FORM). It is important to investigate specimens extracted from the pipe to account for intrinsic property variances imparted by temperature gradients and extrusion process. FCP is followed in the center of the specimen during the test and recorded data is compared with the post-fracture thinning microscopic observations. Damage zone (DZ) dimensions are revealed experimentally from interrupted tests and cutting thin material slices using diamond wafers.

Equations (2.1) and (2.2) are designed to represent the damage parameter based on the damaged volume and the fraction of life, respectively [5,10]:

$$D = \frac{V_{Di}}{V_f} \tag{2.1}$$

$$\alpha = \frac{N_i}{N_f} \tag{2.2}$$

where indices *i* and *f* designate a given position and a final state, respectively. Accordingly, such an approach makes it possible to establish the relationship between the damage function (or damage parameter; *D*) and the fraction of life (α) allowing various reliability functions to be considered based on selected statistical laws (Lyonnet [15]). For the critical position, it is judicious to estimate the critical life fraction (α_c) which can be used for comparison purposes.

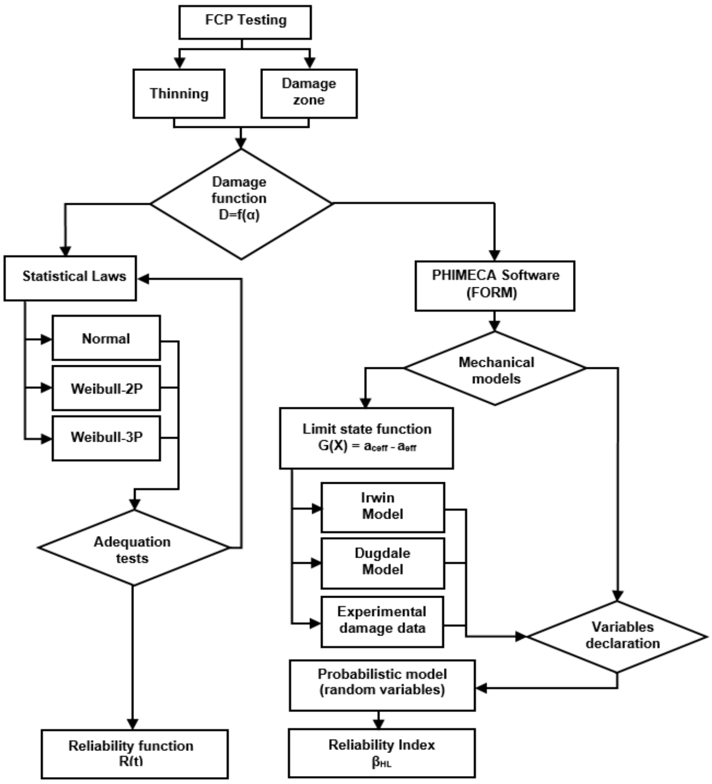

Fig.2. Procedures for reliability computation.

Alternatively, the computation of the reliability index is based on a limit state function designated by $G(X)$ to monitor the system as it evolves from safe towards unsafe domain [9,11,15]. In the case of FCP in MDPE pipes, $G(X)$ is chosen to be expressed in terms of a difference between effective crack lengths at critical and normal conditions:

$$G(X) = a_{ceff} - a_{eff} \tag{2.3}$$

The effective crack lengths in normal and critical conditions are calculated as follows (Dahlberg and Ekberg [16]):

$$a_{eff} = a + r_p \tag{2.4a}$$

$$a_{ceff} = a_c + r_{pc} \tag{2.4b}$$

Analytical damage zone size (r_p) is calculated using the Dugdale model which serves as a basis for subsequent cases of reliability estimations using the PHIMECA Software [17]. Three cases are analyzed involving Irwin and Dugdale analytical models and the experimental damage zone data. In the latter case, a measured DZ length (l_a) and its corresponding critical value (l_{ac}) are deduced experimentally.

3. Results and discussion

The results are examined in three successive steps. The procedures involve (*i*) monitoring the FCP process, (*ii*) investigating the associated damage levels and subsequently, (*iii*) applying the proposed analytical and experimental methods to compute the Hazofer-Lind reliability index (β_{HL}) [17]. The idea is to get hold of the most representative damage data in order to allow performing adequate reliability analysis and to decide about the most reliable case in service.

3.1 Crack propagation

The concept of slow crack growth (SCG) is mostly associated with polyethylene pipes under fatigue or creep loading. The evolution of the crack length as a function of the number of cycles for three identical tests is shown in Fig.3:

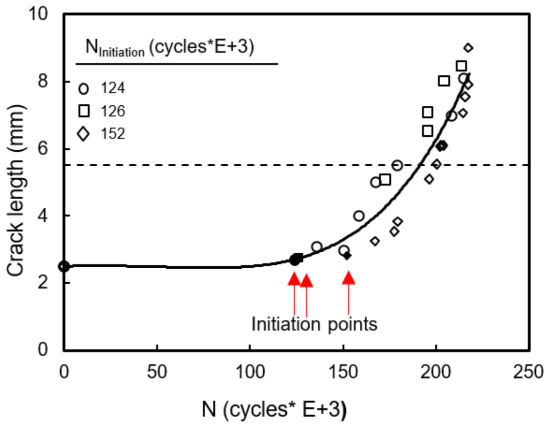

Fig.3. Observed crack length as a function of number of cycles.

The results illustrate a monotonically increasing curve and the dispersion between tests remains relatively low. Such a finding has already been reported in literature implying a good reproducibility of the test [5-7]. The discrepancy in the number of cycles for crack initiation $(N_{initiation})$ can be as high as *28%* between similar tests while the total life (N_f) may reach $2.40\ 10^5$ cycles due to final large-scale drawing and tearing of the material. On an average basis, it is found that the duration for the crack to initiate is approximately *62%* of the total fatigue life. At *~5.5 mm* crack length (horizontal dashed line), the loaded specimen starts to undergo rotation allowing more crack opening and exhibiting elongated fibers being torn at the crack-tip mid-span while general yielding begins at around *8 mm*.

3.2. Damage dissemination

Investigating FCP and damage evolution (crazing and thinning) in such an experimental work is not a straightforward task. To go around difficulties to quantify damage accumulation, a set of crack propagation tests were designed and deliberately stopped at specified numbers of cycles within the total life span. Typical observations from thin slices of cracked material ($t < 0.3$ *mm*) are exhibited in Fig.4. Such a technique is time consuming but it is efficient in reading actual crack length and assessing the shape of the wake and active parts of the damage zone. The horizontal, upward and downward arrows indicate, respectively, crack propagation direction, notch-tip and crack-tip.

In Fig. 4a, the test was stopped at the early stages after crack initiation (downward arrow). The measured crack length from microscopy is *3.89 mm*. The DZ is basically a set of two shear bands (SB) and one principal craze at the tip. At this step, it is usually understood that stresses are concentrated at the crack-tip and the mechanism of fracture is quasi-brittle as deformation accompanying propagation is low. Beyond the *5.5 mm* limit, the DZ evolves towards a new configuration. For instance, at *7.56 mm* (Fig.4b), the DZ shape is rather diffuse and multiple crazes are observed at the crack-tip [5].

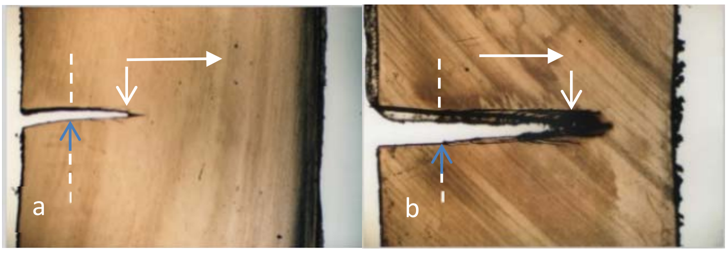

Fig.4. Thin slices of cracked material revealing respective damage zones;
(a) brittle regime and (b) ductile regime $(5X)$.

Two types of shear-bands are observed: (*i*) short SB initiate at the crack trajectory and most probably indicate a starting point of damage build-up before the next crack jump and (*ii*) longer SB surrounding the main crack and acting as a sink for damage creation are supporting the leading craze. Also, it is noted that at around *4.5 mm*, the number of SB is intensified. This observation is probably related to the beginning of the marked specimen rotation under cycling as the crack length approaches half of the specimen thickness. Such an approach makes it possible to define the length (l_a) and width (w_a) for such DZ where all damage accumulation is taking place. The experimental measurements of DZ size as a function of the crack length are given in Fig.5.

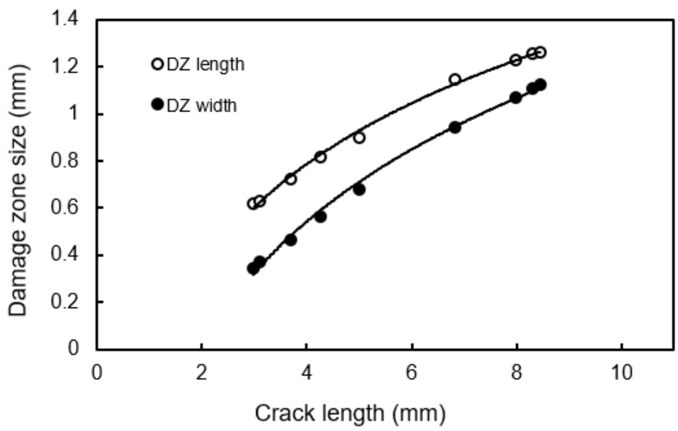

Fig.5. Evolution of damage zone size as a function of crack length.

A monotonic increase of both (l_a) and (w_a) is recorded and the length is higher than the corresponding width. This is a good indication that more energy is spent on crack extension rather than crack expansion. For the sake of modeling; both dimensions are well described by a logarithmic fit in terms of the crack length:

$$l_a = 0.6371 \ln(a) - 0.0965 \; ; \qquad (R^2 = 0.997) \tag{3.1}$$

$$w_a = 0.7559 \ln(a) - 0.5053 \; ; \qquad (R^2 = 0.995) \tag{3.2}$$

During FCP, the material is subjected to thinning (specimen thickness reduction) suggesting that a given volume of transformed material ahead of the crack-tip can be anticipated using (l_a), (w_a) and the thickness at different crack lengths. The values of (t_i) are directly measured from microscopic examination of the fracture surface. The following equation is proposed to estimate such a volume if the crack length is between *2.5 mm* and *8.25 mm*:

$$V_{Damaged} = l_{a_i} \cdot w_{a_i} \cdot t_i \tag{3.3}$$

Hence, using Eqs (2.1) and (3.1) to (3.3), the damage parameter D is directly calculated.

3.3. Mechanical model and reliability analysis

In this section, reliability is approached firstly via statistical laws and subsequently, using the numerical FORM procedure. Reliability analysis has become an essential step for structures subjected to random external effects that can affect mechanical behavior and reduce safe service life. The parameters and factors usually studied concern for instance: service life, damage, intrinsic mechanical resistance, critical stress intensity factor, burst pressure, failure modes, environmental effects and other structural characteristics.

Frequently employed statistical distributions in the case of fatigue testing include normal, Weibull-2 (W-2P) and Weibull-3 (W-3P) parameters for small samples. The numbers of fatigue cycles are converted into time data using testing fatigue test frequency. W-2P and W-3P parameters are graphically obtained using the appropriate distribution function and the mean ranks method [15]. Table 1 summarizes the parameters of the statistical models as verified by Anderson-Darling (AD) and Kolmogorov-Smirnov (KS) adequation tests.

Table 1. Statistical models and calculated corresponding parameters.

Distribution	Distribution parameters	AD Test	KS Test
Normal	$\mu = 70.10$ $\sigma = 31.04$	*0.55*	*0.18*
Weibull-2P	$\beta = 4.10$ $\eta = 93\ h$	*0.29*	*0.13*
Weibull-3P	$\beta = 4.10$ $\eta = 110\ h$ $\gamma = -0.50$	*0.22*	*0.11*

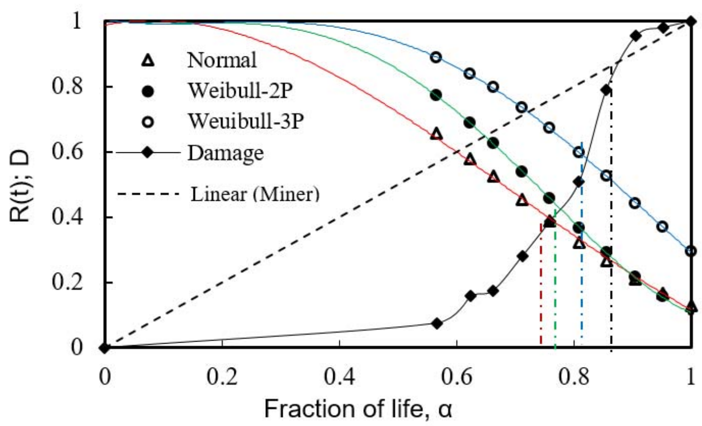

Fig.6. Reliability $R(t)$ and damage (D) parameter evolution as a function of fraction of life.

Since the shape parameter β for both W-2P and W-3P is higher than 3, it means that the failure rate is increasing with time and the distribution is getting closer to the normal one. The negative offset (or position) parameter γ indicates that at the origin of time, some kinds of failure are already present which is the case (i.e. notch) while the η parameter corresponds to the time where failure probability is *63.2%*. The AD and SK tests clearly show that W-3P distribution is the best to describe this case as it appears in Fig.6. The criterion of cumulative damage has given rise to several research studies in the context of the estimation of critical damage. The simplest way to describe it is Miner's law which is based on the assumption of linearity in fatigue.

The damage function *D* is described by Eq. (2.1) and depends on the fraction of life α (Fig.6). It is supposed to vary from *0* to *1* as the material evolves from a damage-free state towards a totally failed situation at the end of total fraction of life.

When relating calculated $R(t)$ to damage, the critical fraction of life (α_c) is found to be *0.82* for the W-3P law (Tab.2).

Table 2. Matching between crack length and critical life fraction for different distributions.

Distribution	*N* (cycles)	a_c (*mm*)	α_c	*D* parameter
Normal	*157434*	*4.39*	*0.76*	*0.40*
Weibull-2P	*160541*	*4.62*	*0.78*	*0.42*
Weibull-3P	*169863*	*5.36*	*0.82*	*0.58*
Miner	*182292*	*6.43*	*0.88*	*0.88*

It should be noted that the corresponding critical crack length for α_c is around the position where the occurrence of specimen rotation has become manifested, i.e., $a_c = 5.36\,mm$ (Table 2). The highest α_c and a_c are logically obtained with the Miner's distribution.

Usually, a structural reliability study is interested in the mechanical-reliability coupling whose uncertain parameters are modeled by random variables (RV) (Fig. 2). One best known method for failure probability $\left(P_f\right)$ approximation is FORM which gives a better contribution when substituting the limit state function by an approximate form. Physically, the Hasofer-Lind reliability index $\left(\beta_{HL}\right)$ is identified as the minimum distance between an origin and a design point where the most probable failure may occur in the space of standard Gaussian variables. Thus, the failure probability function is usually related to β_{HL} as follows:

$$P_f = p_r\left[G(X) \le 0\right] \approx \varnothing(-\beta) \tag{3.4}$$

where p_r is the probability operator and ϕ is the cumulative Gaussian probability function. Irwin or Dugdale analytical expressions for the plastic zone radius which combine stress intensity factor $\left(K_I\right)$ and the yields stress $\left(\sigma_y\right)$ are used by PHIMECA software to compute the reliability index ([16]; Niglia *et al.* [18]):

$$r_{p|\boldsymbol{Irwin}} = \frac{1}{\pi}\left(\frac{K_I}{\sigma_y}\right)^2, \tag{3.5}$$

$$r_{p|\boldsymbol{Dugdale}} = \frac{\pi}{8}\left(\frac{K_I}{\sigma_y}\right)^2, \tag{3.6}$$

$$K_I = \sigma_a \sqrt{\pi a}\, Y\left(\frac{a}{w}\right), \tag{3.7}$$

$$Y\left(\frac{a}{w}\right) = \frac{2}{3}\left(\frac{a}{w}\right)^{-\frac{1}{2}} \left[1 + \left(1 - \frac{r_1}{r_2}\right) h_1\left(\frac{a}{w}\right)\right] f_1\left(\frac{a}{w}\right) \tag{3.8}$$

where σ_a is the mean applied stress and $Y(a/w)$ together with its related functions $(h_1 \text{ and } f_1)$ are correction factors for the arc-specimen geometry available in literature [18]. By invoking an effective crack length, the limit state is therefore defined as the difference between the critical state (uncontrolled cracking) and the state that is actually taking place. The PHIMECA software is used to calculate β_{HL} which reflects a failure scenario based on the performance function of the structure as described by the system of Eqs (3.1-3.3) and (3.5-3.7). Figure 7 presents calculated reliability index as a function of the crack length for 3 different DZ models: *(i)* Eq. (3.5), (*ii*) Eq. (3.6) or (*iii*) Eq. (3.3).

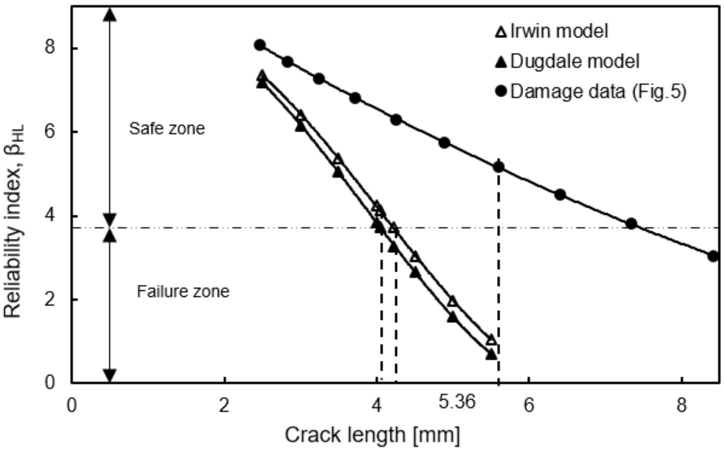

Fig.7. Reliability index based on analytical models and experimental damage data.

The dashed horizontal line is the boundary between safe and failure zones $(\beta_{HL} = 3.7272)$ and represents the recommended lower limit for safety from mechanical construction standards. Both Irwin and Dugdale DZ theoretical models predict structure ruin at *4.22 mm* and 4.05 mm, respectively which do not reflect reality as the fatigue life largely goes beyond such limits. This means that both models are down-estimating the structure lifetime although the Irwin model is suggesting a slightly higher β_{HL} than the Dugdale approach at the same size of the defect represented here by the crack length. If the critical crack length suggested by W-2P statistical distribution (i.e., $\alpha_c = 0.82$) is considered, it is clear that failure has been attained well before the limits suggested by analytical models. On the other hand, the damage data indicates that there is still some room for a safe life up to *7.4 mm* crack length which should be considered with serious awareness based on β_{HL} closer to recommended lower limit of safe operation.

Furthermore, the PHIMECA software allows a supplementary analysis of variables importance for reliability index computation. This is intended to determine the sensitivity of each factor combining the related uncertainties in the calculation process. Table 3 presents the most significant parameters.

Analysis based on analytical models indicates that the most important variables for plastic pipe safety are critical the crack length (~ *62%*) and crack length (~ *36%*). As expected, both analytical models show roughly similar sensitivities although the Irwin model gives always a slightly higher β_{HL} for any given crack length. It is understood that the critical crack length is a particular position for a given set of conditions during service lifetime.

In fracture mechanics, this position refers to the onset of an uncontrolled state reflecting a disequilibrium as material resisting energy is being overturned by failure momentum and damage events. Unfortunately, in real service conditions, the crack length and other failure data in plastic pipes are not easily accessible.

Table 3. Importance of variables as determined by PHIMECA software.

Variable	Sensitivity (%)		
	Dugdale Model (at *4.22 mm*)	Irwin Model (at *4.05 mm*)	Experimental Data (at *5.90 mm*)
a	*35.88*	*35.94*	-
a_c	*61.84*	*61.73*	*62.86*
r_{pc}	*1.36*	*1.36*	-
l_a	-	-	*35.76*
l_{ac}	-	-	*1.38*

Both parameters (a_c and a) are difficult to detect or to follow especially in PE pipes, that is why statistical and reliability methods are used whenever possible to give more assurance for making the best decision about a system life. The sensitivities for experimental damage data give similar importance for a_c (*63*%) but emphasize on the DZ length (l_a: *36*%) which is expressed in the program as a function of w_a (combination of Eqs (3.1) and (3.2). Both r_{pc} and l_{ac} are credited with very low sensitivities (<*1.4*%). The lower reliability index from these analytical models is basically due to the hypotheses of elastic stress fields and limited damage surrounding the propagating crack. However, when considering the real experimental damage data, a much better decision is taken and an important gain of structure life is revealed which can lead to some economic repercussions.

4. Conclusions

1. FCP in MDPE gas pipes is achievable from notched arc specimens. Up to a *5.5 mm* crack length, propagation is relatively slow and is associated with a lessened amount of thinning. Beyond this limit, the process is accelerated and the specimen undergoes an important crack opening resulting in tearing and final fracture.
2. Results of a destructive technique which experimentally appraise the DZ dimensions are presented and discussed. They allowed estimating the damage parameter, critical fraction of life and reliability functions.
3. The Weibull-3P distribution turns out to be the best statistical model to describe reliability under FCP testing of a PE pipe. The critical fraction of life is *82*% at a corresponding crack length of *5.36 mm*.
4. When considering measured damage and FORM approach (PHIMECA software), the reliability index is found to decrease steadily during crack propagation while analytical models undergo a rapid decline towards the unsafe zone $(\beta_{HL} = 3.7272)$.
5. For all crack lengths, β_{HL} index from experimental damage is always higher compared to analytical models and remains in safe zone until *7.4 mm*. This result is in accordance with experimental measurements and indicates that the system can be securely operated up to similar defect sizes. In practice, more conservative measures are usually undertaken well before this circumstance.

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Nomenclature

a	– crack length (mm)
B	– specimen width (mm)
D	– damage parameter
DZ	– damage zone
FCP	– fatigue crack propagation
FORM	– First Order Reliability Method
G(X)	– limit state function
HDPE	– high-density polyethylene
K_I	– stress intensity factor $(MPa\sqrt{m})$
l_a	– damage zone length (mm)
MDPE	– medium-density polyethylene
N	– number of cycles (*cycles*)
PE	– polyethylene
$R(t)$	– reliability function
r_1	– outer pipe radius (mm)
r_2	– inner pipe radius (mm)
r_p	– damage zone radius (mm)
s	– center-to-center distance separating loading holes
SB	– shear bands
SCG	– slow crack growth
t	– thickness (mm)
w	– specimen width (mm)
w_a	– damage zone width (mm)
$Y(a/w)$	– geometric correction factor
α	– fraction of life
β	– Weibull shape parameter
β_{HL}	– Hasofer-Lind reliability index
γ	– Weibull location parameter
η	– Weibull scale parameter (h)
μ	– mean (h)
σ	– standard deviation
σ_a	– applied stress (MPa)
σ_y	– elastic limit stress (MPa)
ϕ	– cumulative Gaussian probability function

Indices:

c	– critical
eff	– effective

References

[1] Mamoun M.M., Manpin J.K. and Miller M.J. (2009): *Plastic pipe failure, risk, and threat analysis*.– Final Report, Gas Technology Institute, 337p.

[2] Nguyen K.Q., Mwiseneza K., Mohamed C., Cousin P., Robert M. and Benmokrane B. (2021): *Long-term testing methods for HDPE pipe: advantages and disadvantages*: *A review*.– Engineering Fracture Mechanics, vol.246, pp.1-13, https://doi.org/10.1016/j.engfracmech.2021.107629

[3] PPI, Plastic Pipe Institute (2008): *Handbook of Polyethylene Pipe*, 2nd Edition, 620p.

[4] Zhang Y.Z., Ben Jar P.Y, Shifeng X. and Li L. (2019): *Quantification of strain-induced damage in semi-crystalline polymers: A review*.– Journal of Materials Science, vol.54, pp.62-82, https://doi.org/10.1016/j.engfracmech.2019.05.008

[5] Chaoui K. (1989): *A Theory for Accelerated Slow Crack Growth in Medium Density Polyethylene Fuel Gas Pipes*.– PhD Thesis, Case Western Reserve University, Cleveland, Ohio, 179p. (DOE, OSTI 5875509).

[6] Favier V., Giroud T., Hiver J.M., G'Sell C., Hellinckx S. and Goldberg A. (2002): *Slow crack propagation under fatigue at controlled stress intensity*.– Polymer, vol.43, pp.1375-1382, https://doi.org/10.1016/S0032-3861(01)00701-7

[7] Frank A., Pinter G. and Lang R.W. (2009): *Prediction of the remaining lifetime of polyethylene pipes after up to 30 years in use*.– Polymer Testing, vol.28, pp.737-745, https://doi.org/10.1016/j.polymertesting.2009.06.004

[8] G., Xia Y., Lin C., Lin S., Meng Y. and Zhou Q. (2013): *Experimental study on characterizing damage behavior of thermoplastics*.– Material Design, vol.44, pp.199-207, https://doi.org/10.1016/j.matdes.2012.07.062

[9] Khelif R., Chateauneuf A. and Chaoui K. (2007): *Reliability-based assessment of polyethylene pipe creep lifetime*.– Int. J. Pressure Vessels and Piping, vol.84, pp.697-707, https://doi.org/10.1016/j.ijpvp.2007.08.006

[10] Majid F. and Elghorba M. (2019): *Critical lifetime of HDPE pipes through damage and reliability models*.– J. Mechanical Engineering Science, vol.13, No.3, pp.5228-5241, https://doi.org/10.15282/jmes.13.3.2019.02.0428

[11] Alimi L., Chaoui K., Amirat A. and Azzouz S. (2018): *Study of reliability index for HDPE based on pipe SDR and fracture toughness limits*.– Int. J. Advanced Manufacturing Technology, vol.96, pp.123-136, https://doi.org/10.1007/s00170-017-1564-7

[12] Chudnovsky A. (2014): *Slow crack growth, its modeling and crack-layer approach: A review*.– Int. J. Engineering Science, vol.83, pp.6-41, https://doi.org/10.1016/j.ijengsci.2014.05.015

[13] Redhead A., Frank A. and Pinter G. (2013): *Investigation of slow crack growth initiation in polyethylene pipe grades with accelerated cyclic tests*.– Engineering Fracture Mechanics, vol.101, pp.2-9, https://doi.org/10.1016/j.engfracmech.2012.09.022

[14] Crissman J.M., Wang F.W., Guttman G.M., Mauray J.R., Fanconi B.M., and Vanderhart D.L. (1987): *Reference Standard Polyethylene Resins and Piping Materials*.– GRI, Final Report # 86/0070, National Bureau of Standards, Gaithersburg, MD, USA, 96p.

[15] Lyonnet P. (1992): *La Maintenance Mathématiques et Méthodes*.– 3rd Ed., Lavoisier TEC & DOC, Paris, 363p.

[16] PHIMECA Engineering (1992): *PHIMECA-Reliability-based design and analysis*.– User's Manual, Ver.1.6, Aubière, France.

[17] Dahlberg T. and Ekberg A. (2022): *Failure and Fracture Fatigue-An Introduction*.– Publisher Studentlitteratur, Lund, Sweden, 356p.

[18] Niglia A., Cisilino R., Seltzer R. and Frontini P. (2002): Determination of impact fracture toughness of polyethylene using arc-shaped specimens.– Engineering Fracture Mechanics, vol.69, pp.1391-1399, https://doi.org/10.1016/S0013-7944(02)00008-5

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