RELIABILITY INDEX COMPUTATION FOR HDPE PIPE USING CRITICAL STRESS INTENSITY FACTOR

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Résumé :

Cette étude porte sur le calcul de l'indice de fiabilité en utilisant le logiciel PHIMECA pour le cas d'un tube en polyéthylène haute densité (HDPE) soumis à une pression interne. Le facteur critique d'intensité de contrainte (K_{IC}) est adopté comme critère pour l'état limite. L'indice de fiabilité β est obtenu en utilisant un modèle mécanique basé sur la mécanique de la rupture. On constate qu'à des valeurs faibles de K_{IC}, il n'existe pas de domaine sécurisé pour les pressions réelles de service tandis que pour les valeurs modérées et supérieures de K_{IC} (>3,5 MPa.√m), l'indice de conception β est atteint. En ce qui concerne l'augmentation de la longueur de fissure, β a diminué systématiquement pour tous les cas de K_{IC} considérés, soutenant l'idée que la fiabilité et le facteur d'intensité de contraintes critique renvoient à des propriétés similaires pour l'estimation de la durée de vie ou de la résistance du matériau à la fissuration. À K_{IC}=5 MPa.√m, le tube est dans une zone sécurisée lorsque la longueur de fissure est inférieure à 370 µm. Enfin, il est démontré que le ratio de dimension spécifique (SDR) est une approche de conception raisonnable et prudente pour les réseaux en plastique.

Abstract :

This study is concerned with reliability index computation using the PHIMECA Software for the case of a high density polyethylene (HDPE) pipe subjected to internal pressure. The critical stress intensity factor (K_{IC}) is adopted as a criterion to the maximum limit state of a numerically calculated K_I. The reliability index β is obtained using a mechanical model based on fracture mechanics. It is found that at lower K_{IC} values, no safe domain existed for actual service pressures while for moderate and higher values of K_{IC} (above 3.5 MPa.√m), the β design index is reached. In terms of increasing crack length, β decreased systematically for all considered toughness cases supporting the idea that reliability and fracture toughness designate similar properties for service life estimation or material resistance to cracking. At K_{IC}=5 MPa.√m, the pipe is in secured zone when crack length is below 370 µm. Finally, it is shown that the specific dimension ratio (SDR) is a reasonable and conservative design approach for plastic pipes.

Mots clefs: HDPE Pipe, Critical Toughness, Reliability Index, SDR.

1 Introduction

Today, thermoplastic pipes made out of High Density Polyethylene (HDPE) are recommended for major industrial and urban piping applications (drinkable water distribution systems, sewage collectors and gas networks) [1-3]. New resins of HDPE are resistant materials that facilitate handling and construction operations for underground transmission systems. In such cases, guaranteed lifespan is above 50 years on the basis of bursting tests carried out in laboratory and used to build regression curves correlating stress level and failure times for specific temperature conditions [2]. Lifetime management of underground pipelines is mandatory for safety and the use of HDPE pipes subjected to internal pressure, external loading and environmental stress cracking agents, requires a reliability study in order to define the service limits and the optimal operating conditions.

In service, time-dependent phenomena especially creep, lead to significant strength reduction. In a previous work, a reliability-based study of pipe lifetime model was carried out to propose a probabilistic methodology for lifetime model selection and to determine pipe safety levels as well as parameters for pipeline reliability [3]. Approaches coupling mechanical and engineering reliability must then incorporate progressively complex mechanical modeling (nonlinear behavior, fatigue, degradation processes…) to make reliability studies real and usable [4]. There is no general algorithm available to estimate the reliability of a buried pipeline system. The pipeline reliability is usually given by an integral over a high dimensional uncertain parameter space. Methods of reliability analysis such as first order reliability method (FORM), second-order reliability method (SORM), point estimate method (PEM), Monte Carlo simulation (MCS), gamma process, probability density evolution method (PDEM) were cited in several works [4-6]. M. Ahammed and R. E. Melchers presented a methodology for the reliability analysis of metallic pipelines subjected to localized corrosion. It was found that both defect depth and fluid pressure have important influences on pipeline reliability. The reliability index β and probability of failure Pf were found to be 4.5×10^{-6} and 3.3×10^{-6}, respectively [7].

In this work, the aim is to obtain the reliability index for a HDPE distribution pipe under the effect of internal pressure. The critical stress intensity factor (K_{IC}) is adopted as a criterion for the maximum limit of K_I values.

2 Mechanical model

Plastic pipes are exposed to stresses generated by external soil load and by internal fluid pressure. In this work, only the fluid pressure is taken into account. Internal pressure yields a uniform circumferential strain across the wall if the thickness is relatively small as accepted in the current situation. Under the assumption of the thin tube (t/r<<1) with t the thickness and r the radius, it is considered a state of uniaxial stress, for one component nonzero $\sigma_{\theta\theta}$. The tensile stress $\sigma_{\theta\theta}$ (or σ_{hoop}) as a function of fluid pressure P is given by [7,8]:

$$\sigma_{hoop} = \frac{p \cdot r}{t} \tag{1}$$

where σ_{hoop} is the stress due to internal pressure (MPa); P is the internal pressure (MPa); r is the tube radius (mm); and t is pipe wall thickness (mm). It should be noted that if the applied stress becomes too important, degradation (failure) by the plasticization occurs when $\sigma_{max}=\sigma_e$, and subsequently the brutal failure will take place at σ_{max} (given by the limit: $K_C/(\pi a)^{0.5}$). In real service life, polyethylene pipes may experience very catastrophic failures especially in the condition of low temperatures. In Figure 1, four cases of critical tube fracture are shown. In normal conditions, brittle failure is expected to occur after years of use as the resin is affected by external loads and environmental aggressors such as temperature, chemicals, humidity, cases and after a long period of service, the cracks appear in the longitudinal direction since they are driven by the circumferential stresses generated by operating pressure. This is a typical brittle failure in MDPE and HDPE pipes after a decade of service (Fig. 1a). In the following cases, brittle failure is occurring under specific temperature and pressure conditions involving higher crack propagation velocities (Figs. 1b, 1c and 1d). Ductile failure (short term crack) is generally well controlled as deformation and damage evolution can be monitored [9].

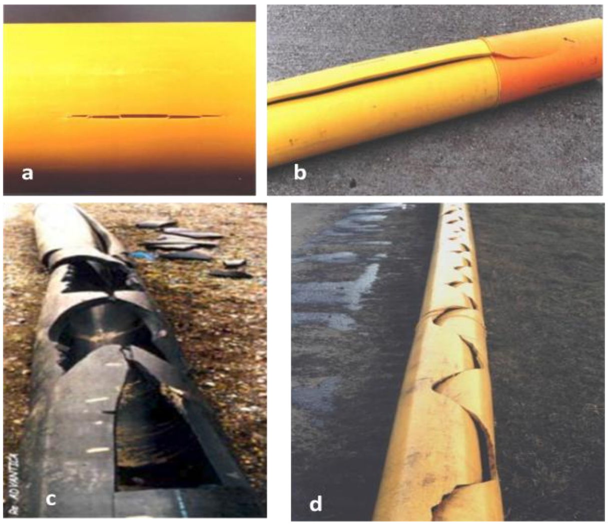


Fig. 1. Typical brittle failures of polyethylene pipes; (a) long term (no side damage), (b) critical crack propagation (rapid) (c) dynamic crack with material shattering (thick wall) and (d) long running crack (cyclic and brittle behavior with an effect of temperature).

In the presence of a crack (or notch) of size (a), according to the method of the Linear Elastic Fracture Mechanics (LEFM), the stress intensity factor is given by:

$$K_I = \sigma \cdot (\pi \cdot a)^{0.5} \cdot Y \tag{2}$$

Where Y: geometric factor given by the following formula [10]:

$$Y = 1{,}12 - 0{,}231\left(\frac{a}{t}\right) + 10{,}55\left(\frac{a}{t}\right)^2 - 21{,}72\left(\frac{a}{t}\right)^3 + 30{,}39\left(\frac{a}{t}\right)^4 \tag{3}$$

The final mechanical model adopted to describe the rupture of a pipe subjected to internal pressure and having a defect length (a) is illustrated by equation 4 obtained from the equations 1, 2 and 3.

$$K_I = \frac{P \cdot r}{t} \cdot (\pi \cdot a)^{0,5} \cdot \left[1{,}12 - 0{,}231\left(\frac{a}{t}\right) + 10{,}55\left(\frac{a}{t}\right)^2 - 21{,}72\left(\frac{a}{t}\right)^3 + 30{,}39\left(\frac{a}{t}\right)^4\right] \tag{4}$$

3. Reliability analysis

Reliability analysis of structures involves describing the state of a given system using a performance function which illustrates the uppermost limits for safe operating. This maximum – value (or minimum) function is usually denoted G(Xj). It corresponds to the conventional safety margin defined by the difference between the material critical toughness K_{IC} and the stress intensity factor at a given condition K_I. The limit state function which separate the safe region, G(Xj)>0, from the failure region, G(Xj)<0, is studied in order to obtain the reliability index. Xj are the random variables in the system. The limit state function used in this work is given as follows:

$$G = K_{IC} - \frac{P \cdot r}{t} \cdot (\pi \cdot a)^{0,5} \cdot \left[1{,}12 - 0{,}231\left(\frac{a}{t}\right) + 10{,}55\left(\frac{a}{t}\right)^2 - 21{,}72\left(\frac{a}{t}\right)^3 + 30{,}39\left(\frac{a}{t}\right)^4 \right] \quad (5)$$

Failure probability P_f is obtained by the following equation, where P[G(X)≤0] is the probability operator and Φ(-β) is the cumulative Gaussian probability function [11].

$$P_f = P[G(X) \leq 0] = \Phi(-\beta) \quad (6)$$

The reliability software PHIMECA [12] allowed us to calculate reliability index β. This parameter is defined as the inverse of the probability of failure is assessed and discussed based on the crack length, and the operating pressure. The range for K_{IC} values is determined from literature analysis and for many HDPE pipe resins and it was set in the interval [2 – 5 MPa.√m] [13].

4. Results and discussion

Figure 2 shows the variation in the reliability index as a function of the pressure service and the critical toughness K_{IC}. The horizontal line here is considered the border or boundary function (G(x)=0) that separates the security domain where G(x)>0 of the failure domain where G(x)<0.

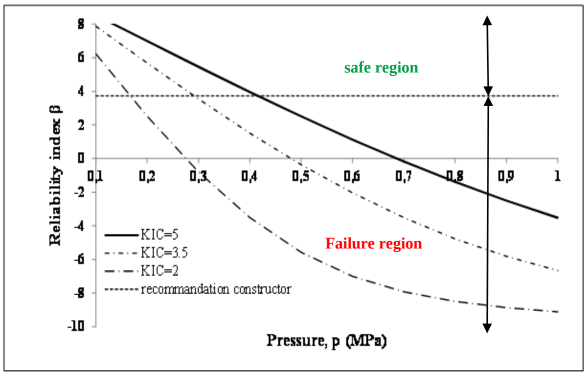


Fig. 2. Reliability index in HDPE tubes as a function of operating pressure and critical toughness (MPa.√m).

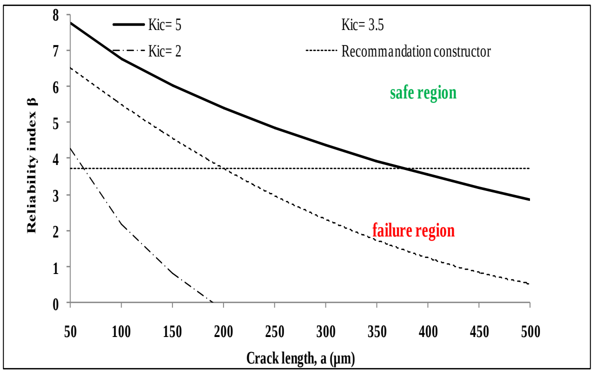


Fig. 3. Reliability index in HDPE tubes as a function of crack length (µm) and critical toughness K_{IC} (MPa.√m).

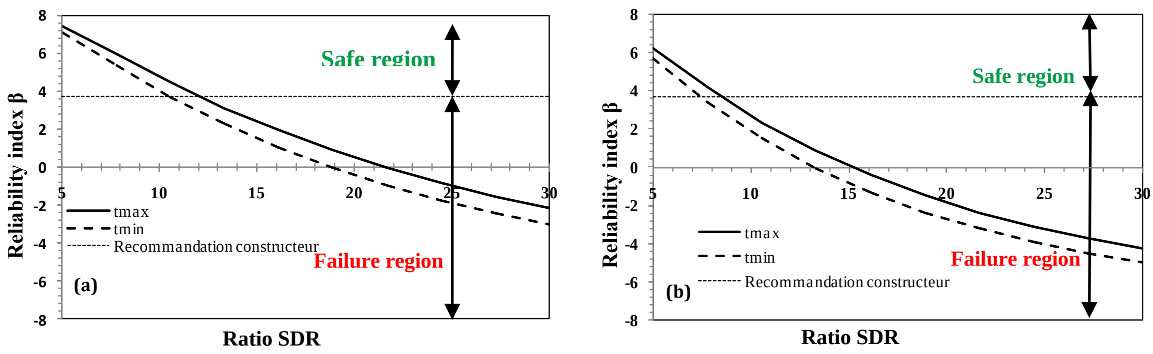
It was found that for the 3 cases, treated on the basis of toughness, the trends are the same, and that the reliability index decreases with increasing pressure. It is given that β = 3.7272, which corresponds to a failure probability of 10^{-4} ($P_f \approx 10^{-4}$), it is the recommended value for the limit of the safe zone. The reliability analysis obtained for the first case (K_{IC}=2.5 MPa.√m) shows that for all pressure levels, the tube is always in the failure domain. In the second case, K_{IC}=3.5 MPa.√m for operating pressures below 3 MPa, the reliability index ranges from 3.7272 to 5.8 and the tube is within the security domain. Finally, in the third case when K_{IC}=5 MPa. √m, the state of security is obtained when the operating pressure is less than 4.2 MPa. Figure 3 shows the variation of the reliability index β as a function of the crack length and the critical toughness. We can clearly see that increasing the size of the crack or defect reduced each time the index β in the three cases studied, K_{IC}=2; 3.5 and 5

MPa√m. The horizontal line here is that separates the security region where G (x)>0 from the failure region where G (x)<0. In the first reliability analysis, i.e., in the case where K_{IC}=2 MPa.√m, we can see that the tube is safe as long as the length of the crack does not exceed 62 µm, and in the second analysis where K_{IC}=3.5 MPa√m, the tube is safe as long as the crack length does not exceed 200 µm, and finally in the third case where K_{IC}=5 MPa.√m, the tube is safe if the crack length does not exceed a critical length equal to 370µm.

In the mechanical model used, we introduced an important geometrical parameter which describes the relationship between the outer diameter of a tube (hydraulic) D and the wall thickness t; SDR=D/t (standard dimension ratio). Standard relationships between wall thicknesses and SDR ratios for HDPE pipes are computed using a power law from tabulated data. Each standard diameter comes with a maximum and a minimum allowable thickness which enables to introduce the SDR as a probabilistic parameter in the study (involves some uncertainties). Of course, the SDR value is designed to ensure maximum strength for the given diameter. It is worth noting that larger SDR values indicate a thinner wall for a given tube, so less resistant to pressure and lower SDR's indicate a thicker wall withstanding higher pressures. SDR value of a tube identifies a distinct nominal pressure, regardless of tube diameter. The variation of SDR with the thickness of the tube wall for each diameter allowed writing power relations between thickness and SDR which are inserted in equation (5). Finally, equation (6) is obtained which allows studying β as a function of pipe SDR:

$$K_I = \frac{P \cdot D}{255{,}4} \cdot SDR \cdot (\pi \cdot a)^{0,5} \cdot \left[1{,}12 - 0{,}231\left(\frac{a}{t}\right) + 10{,}5\left(\frac{a}{t}\right)^2 - 21{,}72\left(\frac{a}{t}\right)^3 + 30{,}39\left(\frac{a}{t}\right)^4 \right] \qquad (7)$$

The results are exhibited in Figure 4. The reliability index trend is well established for the 3 KIC values for both t_{max} and t_{min}. Generally, at t_{max}, always β is higher and it seems that the gap with t_{min} increases for increasing SDR for a given diameter. Also, it is checked that at higher toughness levels, the safe region is much wider (Fig. 4a).



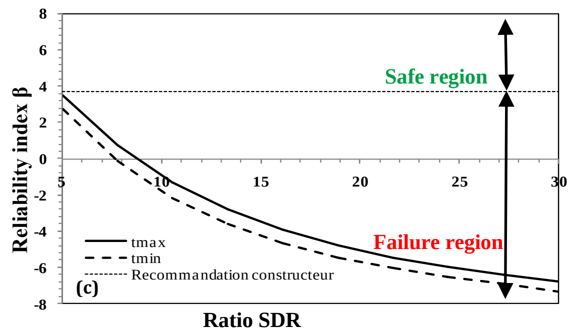


Fig. 4. Reliability index β as a function of SDR in an HDPE pipe 80, diameter 125mm; (a) at 5 MPa.√m, (b) at 3.5 MPa.√m; (c) at 2 MPa.√m

Table 1 summarizes reliability index values and the associated position compared to industry recommendations. We note that the calculation of β shows that for SDR=7.4 and for both K_{IC}=5 and 3.5 MPa.√m, regardless of the diameter, the behavior of the tube is always safe and acceptable because β>3.7272. However for a value of K_{IC}<2 MPa.√m, β is found to be not recommended by the manufacturers. Thus; it is mandatory to use a resin with a much higher K_{IC} (higher than 2 MPa.√m). Since, new HDPE resins based on copolymers are all very resistant and offer better opportunities for HDPE pipe industry, working with larger diameters becomes a new possibility.

The introduction of new manufacturing processes for HDPE pipes such as: co-polymerization of two resins, bi-layered tubes, three-layered pipes, corrugated pipes...) are techniques that have significantly improved the intrinsic resistance of HDPE pipes and opened novel applications.

Table 1. Summary of reliability index β values and relative position to industry recommendations for HDPE pipes with 125, 200 and 355 mm at a fixed SDR of 7.4. The letter X indicates no acceptable technical solution using SDR (too low than manufacturer recommendation).

	K_{IC} (MPa.m$^{1/2}$)	**Wall thickness (mm)**	**Reliability index *β***	**Manufacturer Recommendation**	**SDR lower limit**
Ø125 SDR7.4	5	t_{min}=17.10	β_{min}=5.90	Above	SDR≈11
		t_{max}=19.00	β_{max}=6.50	Above	SDR≈12
	3.5	t_{min}=17.10	β_{min}=4.00	with	SDR=7
		t_{max}=19.00	β_{max}=5.00	Above	SDR=8
	2	t_{min}=17.10	β_{min}=0.80	Below	X
		t_{max}=19.00	β_{max}=1.80	Below	X
Ø200 SDR7.4	5	t_{min}=27.41	β_{min}=5.80	Above	SDR≈11
		t_{max}=30.30	β_{max}=6.30	Above	SDR≈12
	3.5	t_{min}=27.41	β_{min}=3.7272	Above	SDR=7.4
		t_{max}=30.30	β_{max}=4.40	Above	SDR=8
	2	t_{min}=27.41	β_{min}=0.60	Below	X
		t_{max}=30.30	β_{max}=1.10	Below	X
Ø355 SDR7.4	5	t_{min}=48.50	β_{min}=5.60	Above	SDR≈11
		t_{max}=53.50	β_{max}=6.00	Above	SDR≈12
	3.5	t_{min}=48.50	β_{min}=3.7272	With	SDR=7
		t_{max}=53.50	β_{max}=4.40	Above	SDR=8
	2	t_{min}=48.50	β_{min}=0.20	Below	X
		t_{max}=53.50	β_{max}=0.80	Below	X

Conclusion

Based on the simulation tool PHIMECA, this work allowed evaluating the reliability index for HDPE pipes under various conditions. The adopted criterion uses the critical stress intensity factor K_{IC} as a limit state for safe conditions. At a K_{IC} level of 2 MPa.√m, the tube is safe as the crack length does not exceed 62 µm while the safe operating pressure is reduced to only 1.7 bars (which is a too low level). As K_{IC} increases from 3.5 to 5 MPa.√m, le crack length limit for the safe region is raised from 200 to 370 µm. At K_{IC}=5 MPa.√m, the obtained operating pressure is 4.2 bars indicating a safe pipe behavior. For the analysis based on SDR, the reliability index β decreases with increasing the ratio SDR. In the case of 5 MPa.√m, the safe region exists for tubes having the SDR's between 7.4 and

20 (Reference: β=3.7272). While for the second case, SDR<7. 4 is enough to be accepted in the practical applications. However, past a limit SDR of 7.4, β indicates unacceptable and even dangerous operating conditions.

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