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Reliability Index of HDPE Pipe Based on Fracture Toughness

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Nomenclature

a is crack length (μm); β is reliability index; *G(Xj)* is the limit state function ; K_I is stress intensity factor in mode I (MPa.√m); K_{IC} is critical stress intensity factor (MPa.√m); *p* is operating pressure (MPa); P_f is probability of failure; *P* is probability operator; *r* is pipe radius (mm); *SDR* is standard dimension ratio; *t* is wall thickness (mm); *Xj* is random variables; *Y* is geometrical factor; σ_{max} is stress max (MPa); σ_e is yield stress (MPa); $\Phi(-\beta)$ is cumulative Gaussian probability function.

1. Introduction

Polymers are used in diverse structural requests due to their technical advantages and lower costs compared to other materials. Nowadays, thermoplastic pipes are recommended for fluid transportation such as water, sewage and gas networks [1, 2]. High density polyethylene (HDPE) is one of the widely utilized polymers in agriculture and industrial processes. Recent HDPE resins are resistant materials, which facilitate the handling operations and implementation for above and underground applications when installed according to standards. In such cases, their lifespan is estimated at more than 50 years on the basis of bursting tests used to build a regression curve correlating stress level and failure times [3]. Lifetime management of underground pipelines is mandatory for safety and the use of HDPE tubes 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. Under service loads, creep leads to significant strength reduction since it is a time-dependent phenomenon. In a recent work, a reliability-based study of pipe lifetime model was carried out to propose a probabilistic methodology for lifetime model selection and to determine the pipe safety levels as well as the most important parameters for pipeline reliability [4]. Probabilistic procedures are needed to study reliability of systems and to determine the effects of the variability of design parameters on the material behavior. Approaches based on coupling mechanical and reliability engineering must then incorporate progressively complex mechanical modeling (nonlinear, dynamic, fatigue, stress cracking…) to give more actuality and credibility to such studies and ultimately make them usable [5].

For pipelines subjected to mutually internal and external loading, an essential failure consideration is the loss of structural strength of the pipeline cross section during service time. Clearly, this materialized by confined or overall pipe material loss weakening wall thickness. Usually corrosion forms for metals evolve from typical uniform shapes to dangerously localized degradations such as pitting and/or crevice forms. The most common cause of pipelines reliability degradation is the corrosion pits as it causes failure in relatively short time [6]. The probabilistic assessment of the engineering system performance might contain a substantial number of uncertainties in system behavior. In order to implement a probabilistic evaluation for an engineering system, difficulties progress as follows: 1. appraising the relationship between the random variables (RV), 2. reducing the large number of RV involved, 3. getting data about rare scenarios, 4. taking into account the many interactive response variables when describing system performance criteria [7].

There is no general algorithm available to estimate the reliability of a buried pipeline system taking into consideration an existent environment as the number of RV is important. Therefore, 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 [8, 9]. In a probabilistic approach, the input parameters are preserved as continuous random variables and the performance of the structure consequential from diverse failure criteria is stated in a probabilistic framework, i.e., both probabilities either in terms of failure (*Pf*) or reliability index (β).

In order to standardize tolerable values of probability of safety of structures, US Army Corps of Engineers recommended that expected reliability indices would be at least 3.0 for above average performance and 4.0 for good performance as showed in Fig. 1 [10]. A methodology for reliability analysis of steel pipelines undergoing corrosion is presented by M. Ahammed and R. E. Melchers [11]. They claim that defect depth and fluid pressure have important effect on pipeline integrity. The reliability index β and probability of failure Pf were found to be 4.5 and 3.3 x 10-6, respectively (Fig. 1). In another study done by J. Sulikowski and J. Kozubal for the purpose of estimating the durability of a concrete sewer pipeline under deterioration by sulphate and chloride Corrosion. The results show a significant detrimental effect on a construction reliability caused by deterioration. For example, the probability of failure of 10^{-1} corresponding to relatively little rigorous reliability index β of 1.3 and β close to 2.3 corresponds to a lower probability of failure equal to 10^{-3} [12] (Fig. 1).

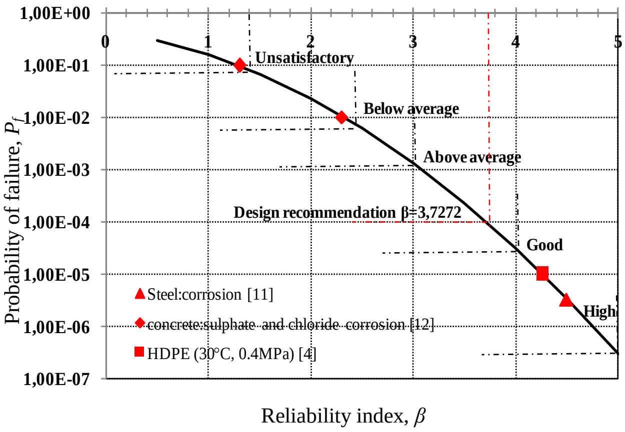

Fig. 1 Guidelines for reliability index β and equivalent probability of failure P_f

In this research, the aim is to assess the reliability index in a gas HDPE distribution pipeline under internal pressure based on fracture mechanics parameters. The critical stress intensity factor (K_{IC}) is adopted as a criterion for the highest limit of K_I values before fracture can occur.

2. Mechanical model

Underground pressured pipelines are exposed to stresses developed by external soil loads and by internal fluid pressure. In this work, only the fluid pressure is taken into account and it is admitted that pipe shape is rigid enough to overcome external backfill ground. Internal pressure yields uniform circumferential strains across the wall if the wall thickness (t) is relatively small compared to the diameter and the fluid density is relatively small as is supposed 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. The tensile stress σ_{hoop} resistant to internal fluid pressure p is given by the following equation [13]:

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

where σ_{hoop} is stress due to internal fluid pressure (MPa); p is internal fluid pressure (MPa); r is radius of pipe (mm); and t is thickness of pipe wall (mm). It is accepted that two failure modes can occur if the applied stress becomes too great; they are: deformation by plasticization when $\sigma_{max}=\sigma_e$ (yield stress limit) and brutal break when σ_{max} reaches the limit expressed by $[K_C/\sqrt{(\pi a)}]$.

In the presence of a crack (or notch) of size a, according to the methods 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 is the geometrical factor given by the following formula [14]:

$$Y = 1.12 - 0.231\left(\frac{a}{t}\right) + 10.55\left(\frac{a}{t}\right)^2 - 21.72\left(\frac{a}{t}\right)^3 + 30.39\left(\frac{a}{t}\right)^4. \tag{3}$$

The final mechanical model adopted to describe the rupture of a plastic pipe subjected to internal pressure and having a defect length (a) is illustrated by equation 4:

$$K_I = \frac{p \cdot r}{t} \cdot (\pi \cdot a)^{0.5} \cdot Y. \tag{4}$$

3. Reliability analysis based on PHIMECA Software

In our case, the first step of the reliability analysis should involve describing a function of HDPE pipe performance or what is called "state of the system" designated by $G(X_j)$, where X_j are the random variables of the system. We choose it to correspond to the conventional safety margin defined by the difference between the material critical toughness (K_{IC}) and a given service working level described by K_I value. The limit state function which separate the safe region, $G(X_j)>0$, from the failure region, $G(X_j)<0$, is measured to assess the reliability index. Therefore, the limit state function used in this work is given in Eq. (5):

$$G = K_{IC} - \frac{p \cdot r}{t}(\pi \cdot a)^{0,5}\left[1.12 - 0.231\left(\frac{a}{t}\right) + 10.55\left(\frac{a}{t}\right)^2 - 21.72\left(\frac{a}{t}\right)^3 + 30.39\left(\frac{a}{t}\right)^4\right] \tag{5}$$

Failure probability P_f is obtained by equation (6), where $P[G(X)\leq 0]$ is the probability operator and $\Phi(-\beta)$ is the cumulative Gaussian probability function [15, 16]:

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

The reliability software PHIMECA [17] allowed us to calculate reliability index β. This parameter is defined as the inverse of the probability of failure which is expressed based on crack length and operating pressure. The range for K_{IC} values is taken from literature analysis dealing with HDPE pipe resins. It is found that K_{IC} are within the laying from 2 to 5 MPa.√m [18]. Fig. 2 shows the variation in the reliability index as a function of the pressure service and the critical toughness K_{IC}. The discontinuous 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 $G(x)<0$.

We have considered 3 cases of HDPE pipe resistance in terms of tenacity (low: 2; mean: 3.5 and high: 5 MPa.√m) and as expected the trends are following similar behaviors and the reliability index decreases with increasing pressure. It should be noted that β equal to 3.7272 (corresponding to $P_f \approx 10^{-4}$) is the recommended value to set the limit of the safety margin (or the state limit), beyond which the pipe would work in security; otherwise the tube may fall in the failure domain.

For the case 1 (K_{IC}=2MPa.√m), the reliability analysis indicates that safe domain is far away for actual service values. This curve presents the low down values of β most of them in the failure region. For the case 2, K_{IC}=3.5 MPa.√m, at operating pressures of roughly 3 MPa, the reliability index reached the safe limit (β=3.7272), beyond that pressure, failure is dominant. Finally, in case 3 (K_{IC}=5MPa.√m), minimum recommended β is attained at 4.2 MPa.

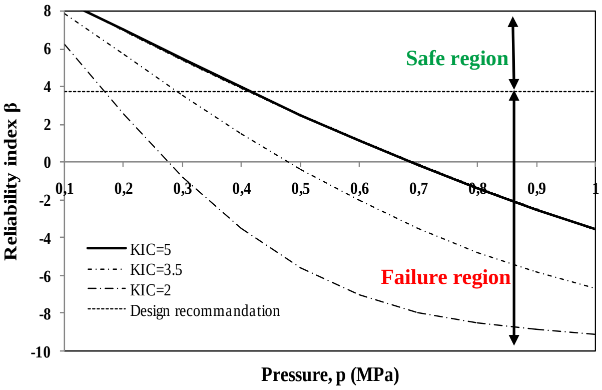

Fig. 2 Reliability index in HDPE tubes as a function of the operating pressure and critical toughness K_{IC} (MPa.√m)

Such type of analysis is sought by pipe manufacturers and maintenance teams in order to estimate networks safety knowing resistance degradation with time and service conditions. The limit state from Eq. (5) shows a strong dependence on defect size (crack length). At this stage, it is interesting also to study the evolution of β as a function of crack length. From experience, defects will always exist on HDPE pipes but for sizes approaching 300µm, cracks may initiate and cause premature failure. For our study, we have chosen to scan the range (50-500 µm). Fig. 3 illustrates the variation of the reliability index β as a function of the crack length and the critical toughness K_{IC}. We observe that increasing the size of the crack (or defect) reduced each time the index β in the 3 K_{IC} cases. The horizontal line here separates the security region [where $G(x)>0$] from the failure region [where $G(x)<0$]. For the case 1 (2 MPa.√m), we can see that the tube is safe as long as the length of the crack does not exceed 62µm (non observable defect) while for case 2 (K_{IC}=3.5 MPa√m), the tube is safe as long as the crack length does not exceed 200 µm. For case 3 (K_{IC}=5 MPa.√m), the tube is safe if a<370 µm.

Plastic pipes are mainly recognized by resin type, diameter and thickness. The two last parameters are combined in a dimensionless geometrical parameter describing the relationship between pipe outer diameter (*OD*) and its wall thickness (*t*). It is designated by standard dimension ratio and noted *SDR*. Plastic pipe (HDPE and other) manufacturers should stick to the standard products in terms of *SDR* as indicated in Fig. 4 for 3 diameters (125, 200 and 355 mm). Larger *SDR* ratios point to thinner wall pipe which would be less resistant to increasing pressures and temperatures. In other words, *SDR* values of a tube identify a defined nominal pressure regardless of the diameter. Also, the standards impose for a given *SDR* a maximum and a minimum thickness since it is not easy to control it precisely for plastics. The dispersion in the values can be important at lower *SDR* and higher *OD* (Fig. 4).

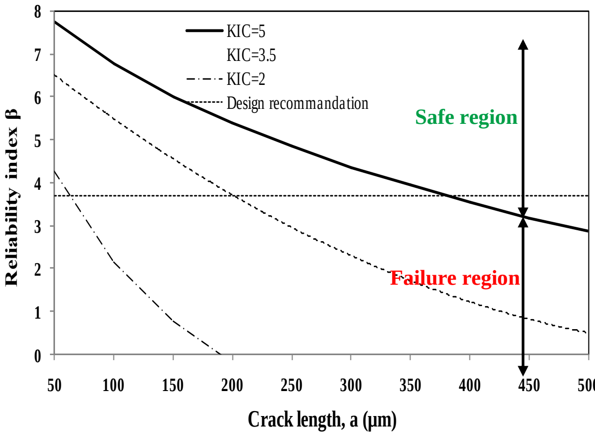

Fig. 3 Reliability index in HDPE tubes as a function of the crack length and critical toughness K_{IC}

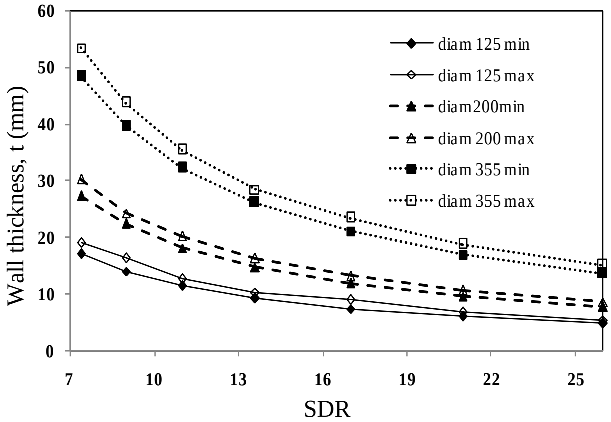

Fig. 4 SDR ratio depending on the thickness of the wall in HDPE pipes average diameters of 125, 200 and 355 mm

Consequently, it is worth studying the reliability index β based on *SDR*. The reliability analysis is conducted on HDPE pipe (minimum yield stress: 8 MPa; 3 different diameters: 125, 200 and 355 mm; Standard SDR values for HDPE-80 resin: 7, 9, 11, 13.6, 17, 21 and 26) [19]. For reliability analysis, the mathematical relationship between the variations of *SDR* with the corresponding wall thicknesses is needed for each diameter. These relations (Eqs. (7-12)) have been obtained for each diameter (t_{max} and t_{min}) using a fitted power law:

$$t_{max_{D125}} = 144.43(SDR)^{-1.002}; R^2 = 0.9901. \quad (7)$$

$$t_{min_{D125}} = 127.7(SDR)^{-1.00}; R^2 = 0.9990. \quad (8)$$

$$t_{max_{D200}} = 217.22(SDR)^{-0.99}; R^2 = 0.9996. \quad (9)$$

$$t_{max_{D200}} = 203.6(SDR)^{-1.00}; R^2 = 0.9990. \quad (10)$$

$$t_{max_{D355}} = 395.25(SDR)^{-1.002}; R^2 = 0.9996. \quad (11)$$

$$t_{max_{D355}} = 363.2(SDR)^{-1.00}; R^2 = 0.9990. \quad (12)$$

As a result, Eq. (4) becomes a function of *D* and *SDR*. The latter takes into account all variations related to thickness (Eq. (13)).

$$K_I = \frac{p \cdot D}{255.4} \cdot SDR \cdot (\pi \cdot a)^{0,5} \cdot Y. \qquad (13)$$

Then, using again the software PHIMECA, β is recalculated when thickness dispersion is between (t_{min} and t_{max}) for various K_{IC} and diameters within the range (125-355mm). In all cases, as expected, t_{min} is associated with a lower β, but the gap varies from one situation to another. The gap on β curves between t_{min} and t_{max} is globally small with minimal values of *SDR* and grows with increasing

SDR.

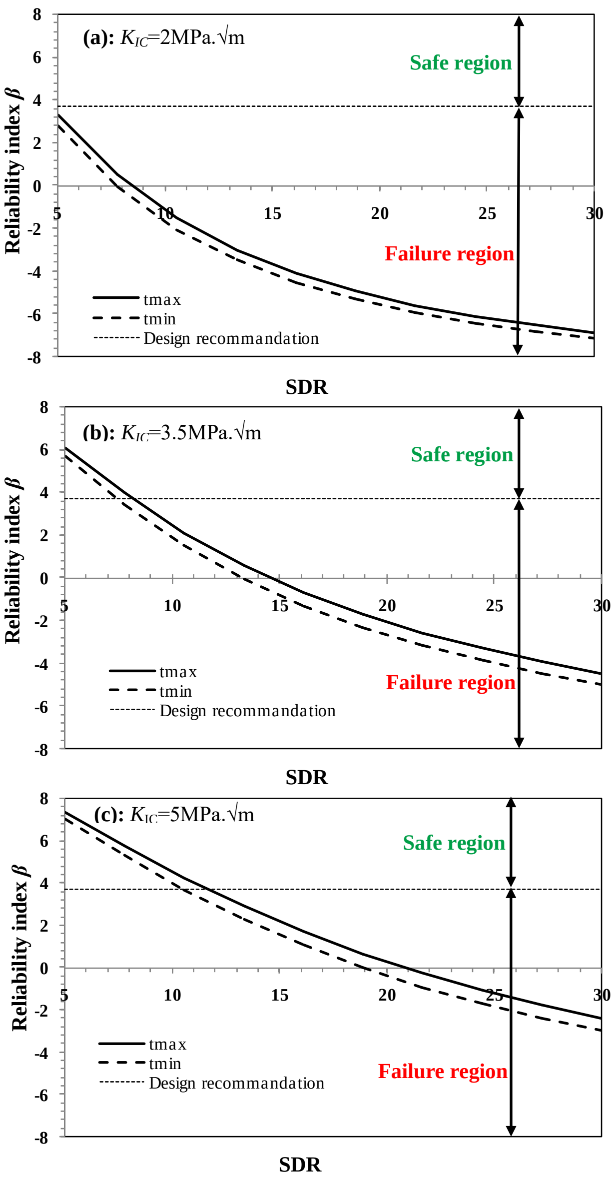

Fig. 5 Reliability index β as a function of SDR and K_{IC} for HDPE pipe 80 with OD=125 mm

For the conditions listed (as shown in Eqs. (7-12)), it is observed that β decreases with increasing *SDR*. Discussion is made as a function of the horizontal discontinuous line indicating the border limiting security and failure domains. On the basis of diameter of 125 mm, the 3 cases of K_{IC} are discussed from Fig. 5.

In the first case, i.e. K_{IC}=2.5 MPa.√m, it appears that whatever the value of *SDR* is, β is always below the reference line 3.7272. For t_{max}, β=0 is localized at *SDR*=9 and this indicates that the standard allows values of reliability index around 1 for *SDR* not less than 7 (Fig. 5, a). Regarding the second case (K_{IC}=3.5 MPa.√m) for SDR ratio values <7.4, the index β>3.7272 and the security domain is fulfilled. Beyond *SDR*=7.4, β indicates an unacceptable and even not recommended operating conditions. For t_{max}, β=0 is localized at *SDR*=15 (Fig. 5b). For the toughest case (K_{IC}=5 MPa.√m), positive non nil β values are obtained for *SDR* between 19 and 22. Of course, the safety domain is much larger compared to previous cases (Fig. 5, c). Globally, the variations of β a decaying exponential function and it is up to the designer to set the accepted reliability limit in accordance to operating condition.

Table 1 summarizes the obtained values of reliability index β and their positions compared to manufacturer's recommendation. Overall observation indicates that as *t* increases, β increases for all values of *OD* and *SDR*. However, β is shown to decrease with increasing diameter for the same level of *SDR* (in Table 1, chosen calculation steps are for the same SDR of 7.4).

At the high level of toughness (K_{IC}=5 MPa.√m), obtained β is always higher that reference (design) value while *SDR* can change from 7.4 up to 11 for t_{min} and up to 12 for t_{max}. This is true for all 3 diameter cases (125, 200 and 355mm). This result confirms that higher pipe reliability index must imply a highly resistant material for cracking. The standard for *SDR* indicates that it is really conservative (or pessimistic) as it tightens the limit from 12 (or 11) to only 7.4.

At a moderate value of toughness (K_{IC}=3.5 MPa.√m), the differences between t_{max} and t_{min} are readily noticeable. For t_{max} and for all diameters, β is always higher than reference value. However, *SDR* can change from 7.4 up to 8 only for t_{max}. For t_{min}, all diameters point out to a very close *SDR* if not exactly the same. At the same time, β is around the reference value. Again, the pessimistic consideration associated with t_{min}, which is the lowest acceptable value for a pipe to go into this standard, supports such design limit. It is clear that the relationship between *SDR* and β is highlighted in this way. In order to emphasize the idea, the 200mm pipe with t_{min} is the limit case which is designed with β=3.7272 and its *SDR* corresponds with that extracted from the analysis (*SDR*=7.4). In addition, for the diameter 355mm, β=3.7272 while the obtained *SDR* is 5% lower which believed to be risk level associated with such calculation.

At a low value of toughness (K_{IC}=2 MPa.√m), for all diameters at t_{max} and t_{min} conditions, β is always below the reference value which implies that acceptable design conditions have not been so far met. Firstly, it is possible to incriminate the weak toughness level. Secondly, it is observed that *SDR* values are not contained within the covered range by the standard. This means that such product is not allowed to be manufactured as it is unsafe. Again, the reliability analysis confirms that there is a basis for accepting a design conditions in order to have a standardized product. β values have been as low as 5.4% compared to reference level for the case with *OD*=355 mm and t_{min}=48.50 mm. On the other hand, for inacceptable design cases, the highest β has been 48.3% lower than the design level for the case with OD=125 mm and t_{max}=19.00 mm.

For this type of resins and according to the proposed geometries, the study suggests working with much higher resistant pipe material. New resins based on co-polymers and sophisticated polymerization processes offer better opportunities for HDPE pipe industry to be installed in much more aggressive environments for longer service life. The introduction of bi-materials (hybrid polymers), three-layer polyethylene and corrugated pipes are techniques that have significantly improved the intrinsic resistance of HDPE pipes. These are being considered for high pressure applications.

Table 1

Summary of calculated reliability index β values compared to manufacturer SDR recommendations

Diam. (mm)	K_{IC} (MPa.√m)	Standard wall thickness (mm)		Reliability index β		Manufacturer Recommendation ■ Above, ▲ Below or Close ≈			SDR lower limit
		tmin	tmax	βmin	βmax				
Ø125	5	17.10	-	5.90	-	■			~11
		-	19.00	-	6.50	■			~12
SDR 7.4	3.5	17.10	-	4.00	-			≈	7
		-	19.00	-	5.00	■			8
	2	17.10	-	0.80	-		▲		*
		-	19.00	-	1.80		▲		*
Ø200	5	27.41	-	5.80	-	■			~11
		-	30.30	-	6.30	■			~12
SDR 7.4	3.5	27.41	-	3.7272	-			≡**	7.4
		-	30.30	-	4.40	■			8
	2	27.41	-	0.60	-		▲		*
		-	30.30	-	1.10		▲		*
Ø355	5	48.50	-	5.60	-	■			11
		-	53.50	-	6.00	■			12
SDR 7.4	3.5	48.50	-	3.7272	-			≡**	7
		-	53.50	-	4.40	■			8
	2	48.50	-	0.20	-		▲		*
		-	53.50	-	0.80		▲		*

* No technical solution using SDR; ** Identical β design value.

4. Conclusion

A reliability study for HDPE pipes, based on FORM/SORM approach and implanted in the software PHIMECA, is presented. The developed mechanical model for pipe resistance is constructed using fracture mechanics critical stress intensity factor (K_{IC}) which is taken as a limit design value. Simulations of the reliability index β used operating pressure, crack length and SDR parameter (standard dimension ratio) as a function of 3 levels of K_{IC}.

At 2 MPa.√m, β analysis indicated that there is no safe domain for actual service pressures, while the safe limit is reached at 3MPa for 3.5MPa.√m. It is only at higher K_{IC} that minimum recommended β is attained (β_{design}=3.7272).

When considering increased crack length, β decreased systematically as expected for all toughness cases. It is known that reliability and fracture toughness designate similar properties in terms of safe service life or material resistance to cracking and associated damage. It is concluded that a crack length as low as 62 μm can be catastrophic if toughness is low but for 5 MPa.√m, the pipe is considered safe if crack length is less than 370μm.

The reliability index β is shown to decrease with increasing diameter for the same level of SDR which confirms that higher pipe reliability index must imply a highly resistant material to cracking. In other words, SDR basis indicates that it is a really conservative design approach incorporating both upper and lower limits on thickness.

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RELIABILITY INDEX OF HDPE PIPE BASED ON FRACTURE TOUGHNESS

S u m m a r y

This work presents a contribution to evaluate the reliability of a high density polyethylene (HDPE) pipe using the PHIMECA Software. The critical stress intensity factor (K_{IC}) is adopted as a criterion to the maximum limit of a numerically calculated K_I. The reliability index β is obtained using failure probability and a mechanical model. It is found that at lower K_{IC}, no safe domain for actual service pressures existed while for moderate and higher values of K_{IC} (above 3.5 MPa.√m); the β design index is reached and even exceeded. In terms of increasing crack length, β decreased systematically for all toughness cases supporting the idea that reliability and fracture toughness designate similar properties for service life or material resistance to cracking. For a K_{IC}=5 MPa.√m, the pipe is considered safe when crack length is below 370μm. Finally, it is shown that *SDR* basis is a reasonable and conservative design approach for plastic pipes.

Keywords: HDPE pipe, critical stress intensity factor, crack length, SDR, reliability index, PHIMECA software.

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