

Calculation of the Timelife in HDPE Pipe With a Crack.

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Abstract

High density polyethylene has been widely used in marine and gas transportation, storm sewers, culverts and city drainage system. Compared with other conventional pipes, it has its own advantages, such as, chemical corrosion resistance, durability, flexibility, easy joining and subsequent easy management and fitting. In this paper, and in order to forecast the remaining lifespan of a pipe enclosing a crack and subjected to internal pressure, it is essential the assessment of K_I the stress intensity factor throughout the crack propagation. The finite element method is used to assess the values of the stress intensity factor of an axially oriented semi-elliptical crack located at the inner surface of an HDPE pipe. The crack configuration is described by the relative wall thickness (t/R), the relative crack depth (a/t) and the crack aspect ratio (a/c). The lifetimes presented are discussed in accordance to the crack size and the stress intensity factor in each case.

Keywords

HDPE, Crack, SCG, Finite Element Method, Stress Intensity Factor, Lifetime.

1. Introduction

Polyethylene (PE) pipes are progressively employed in gas applications owing to the innovation in polymerization and manufacturing technologies that facilitate the engineering to produce pipes with substantial precision in performance ([PE Pipes & Fittings, 2016](#), [Plastic pipes, 2012](#)). Transportation networks made up of tubes are exposed to common stresses such as impact loads and fatigue as a result of internal or external pressure instabilities, and incoherence in the design. Accordingly, it origins material destruction, cracking and/or failing ([Medjaji et al. 2019](#)). Subsequently, here remain double rudimentary failure types of a pipeline structure, principal rapid crack propagation (RCP) which might affect a considerable size of pipeline, and second the long-time brittle failure of the system due to a slow crack growth (SCG) hosted at a fault in the pipe and initiating a limited brittle failure ([Nezbedova et al. 2009](#)).

It is recognized that the critical failure mechanisms for long-term pipe applications is dominated by SCG, which is frequently associated to inevitable intrinsic defects. Impurities, polymer agglomerates, material inhomogeneities, otherwise cavities are often accountable for the initiation of SCG. For internal pressurized PE pipes it was confirmed that a typical size of such inherent defects is between 100 and 400 μm . Such initial defects produce stress concentrations in which micro deformations nucleate local micro voids from which crazes can originate. The creation of crazes is a mixture of local shearing in the amorphous phase and change of the crystalline phase, leading to greatly drawn fibrils that unceasingly magnify the craze. Throughout this time, which is the crack initiation time, the size of the initial defect remains basically constant. Then, the stress at the tip of the craze zone grows and endures the craze development until molecular disentanglement clues to a breakdown of the craze and the crack initiates to rise ([Frank et al., 2019](#)).

In water and natural gas distribution networks, the service life covers up to 50 years and more. Thermoplastic pipes are originally used in the low-pressure system, up to 4 and 6 bars in the case of gas and water pipes respectively. Owing to progress in the material management they are nowadays being worked at pressure stages of up to 10 bars and 16 bars for gas and water respectively. For high-quality pipes made of recent thermoplastic materials, lowest lifetimes of 100 years are commonly predictable now. It is evident that pressure pipe requests involve polymers possessing a lengthy service lifespan. However, the constraint lies in the development of adequate tests that are able to simulate the mechanism taking place and approximate the lifespan in a reasonably little time [(Chudnovsky et al. 2012). In the various models and tests, the high temperature is used as an acceleration factor in short-term tests based on the Time Temperature Superposition Principle (TTSP) principle. The models currently available for the prediction of service life of PE pipes can be divided into three groups: (1) The Rate Process Method or RPM, (2) The Bi-Directional Shift Approach, and (3) Methods of the Fracture Mechanics. In the latter category, there are several approaches: "The Pent Service Life Correlation" and "Integration of Time to Flaw Initiation and Growth to Failure" (R. Visser, 2009). The fracture mechanics is a good example to approach the life of HDPE pipes. Its main objective is to study the severity of defects at the macroscopic scale requiring the determination of stress fields and deformations in the vicinity of the crack. Several studies have been developed to understand and explain the phenomenon of breaking structures with defects. The problem remains difficult because in linear fracture mechanics theory, the stress and deformation levels tend towards infinity by approaching the crack tip (H. Moustabchir, 2008).

This paper discusses some prediction models of life based on the fracture mechanics. These approaches involve the critical stress intensity factor (K_{IC}) or K_I followed by a description of a critical applied stress. The stress intensity factor is calculated allowing to the crack length in three different cases. Mathematical models describing the propagation of the slow crack growth SCG are then used to assess the residual life of a polyethylene pipe exposed to internal pressure.

2. Mechanical model

The crack structure shown in Figure 1 is designated here by some non-dimensional parameters, specifically, the relative wall thickness (t/R), the relative crack depth (a/t), the crack aspect ratio (a/c). The code ANSYS with interface Workbench is employed here to simulate the cracked pipe. The suggested code permits the operator to get automatically the differences of stress intensity factor sideways the crack front for a specified set of non-dimensional parameters. It precedes with the materials properties and the geometric parameters of pipe and the applied loads, here the pressure of the transported liquid, and then makes a finite element model of the pressurized pipe with a 3D semi-elliptical crack. In our simulation, the tetrahedral elements are used to discretize the mesh of the entire structure with a refined mesh used exclusively in the singularity zone, i.e. of around the crack. The symmetry settings in the longitudinal direction were used to decrease the computational time. Primary, a part of the pipe was modeled then evaluated. Like stated previously, the crack front would be confined by individual modules, therefore a minor size termed tunnel including the singular elements were designed round the crack front. (Figure. 2)

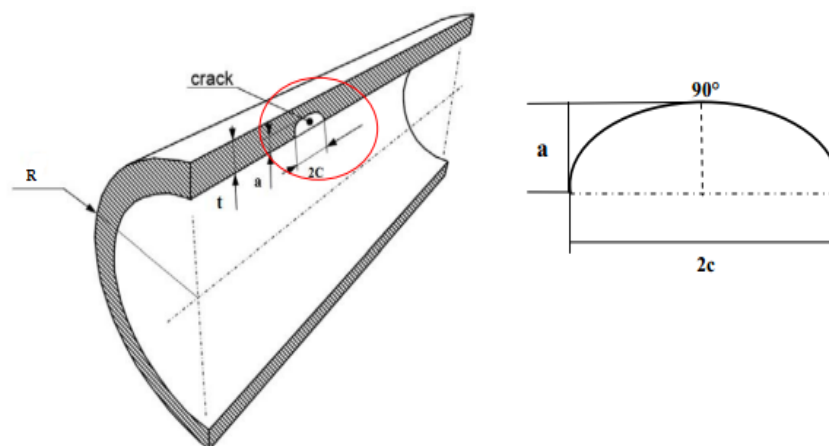


Figure 1. Scheme pipe inner surface, semi-elliptical crack dimensions (a , $2c$).

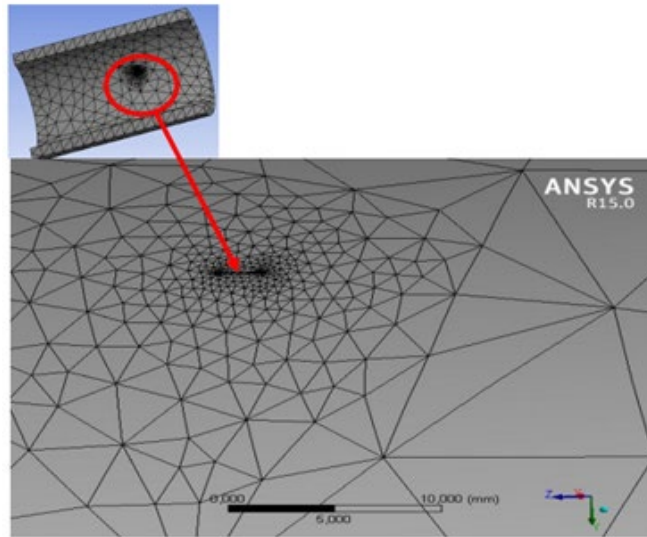


Figure 2. Finite Element Model pipe with crack.

3. Stress intensity factor calculation

SIF is one of the main considerations in fracture mechanics. Fragile rupture in fractured manufacturing parts is generally inspected by Stress Intensity Factor. The stress intensity factor is also essential for analyzing ductile fracture which is a more common mode of failure in pipelines. Once the crack is identified in a construction, SIF can be intended by numerous experimental or theoretical approaches like finite element analysis. When SIF is identified, the possibility of fragile or ductile rupture can be assessed with a suitable fracture criterion (Khoramishad et al. 2009). Usually, the mechanisms of SCG can be defined by approaches grounded on Linear Elastic Fracture Mechanics (LEFM). Initially advanced for metals, two main necessities must be encountered for the applicability of LEFM on polymeric materials: (i) the global loading condition of sample or element is within the range of linear viscoelasticity and (ii) the creation of plastic deformations at the crack tip is restricted to an insignificant zone. The driving limitation for SCG is the stress intensity factor in crack opening mode K_I , which designates the stress field in the area of a crack tip and is a function of the global loading s , the crack length a and a geometric factor Y that is well known for several specimens and component shapes, or may also be derived from Finite Element Methods (FEM) simulation (Frank et al., 2014).

In this study, a numerical calculation by FE is chosen, based on modeling of the cylindrical structure. Here only half of the pipe is used. In the elastic domain, the stress intensity factor in mode I is K_I in a system of local coordinates fixed to the front of a crack and is given by Equation 1 with σ the stress applied, a the crack length.

$$K_I = \sigma \cdot \sqrt{\pi \cdot a} \cdot Y \quad (1)$$

Y is the geometrical correction factor, for a tube shape, it is given by the next formula:

$$Y = 3.74 - 0.36 \left(\frac{a}{t} \right) + 0.16 \left(\frac{a}{t} \right)^2 + 1.80 \left(\frac{a}{t} \right)^3 \quad (2)$$

4. Results and discussion

A comparison of K_I as a function of the normalized length of the crack (a/t) is illustrated in Figure 3. We used the simulation to show the influence of the size of the crack within the pipe studied on the stress intensity factor. Three fault values were chosen, the first two based on the work of Frank, assuming that the size of the crack or

the permissible defect present in a tube is in the range 100 and 400 μm (A. Frank, 2010). For the third defect, we took a ratio ($a/t = 10\%$) as cited in the work of (H. Moustabchir, 2008). We note that the stress intensity factor increases with increasing crack size, and becomes critical when the crack propagates more in the pipe wall.

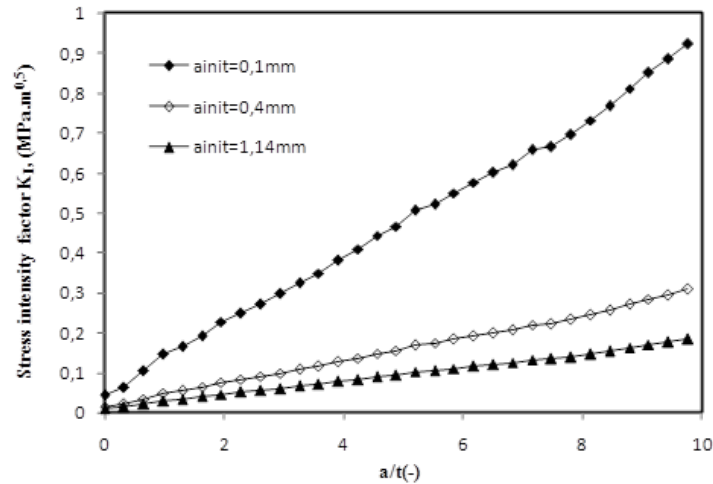


Figure 3. Variation of K_I according to crack length.

After calculating the stress intensity factor in mode I given by the simulation, it remains to calculate the residual life of the pipe using the formula proposed by (Paris et al., 1963). This suggests that the time a crack needs to grow and spread in a structure can be calculated by transforming Equation 3 in Equation 4. The total time for the rupture of the pipe consists of the sum of the time of the crack initiation t_{init} and the crack growth time t_{SCG} (Equation 5) (Hutar et al., 2011).

$$\frac{da}{dt} = A \cdot K_I^m \quad (3)$$

$$t_{SCG} = \frac{1}{A} \int_{a_{init}}^{a_f} \frac{1}{K_I^m} da \quad (4)$$

$$t_f = t_{tot} \approx t_{init} + t_{SCG} \quad (5)$$

After integration of the Equation 3, we obtain the general shape of calculating the time to failure of a pressurized HDPE pipe as shown in equation 6, according to (Pinter et al., 2007).

$$t_f = t_{tot} \approx t_{init} + \frac{2}{A \cdot (m-2) \cdot Y^m} \cdot a_{init}^{(2-m)/2} \cdot \sigma^{-m} \quad (6)$$

A and m are material parameters as explained in Table 1 (Frank et al., 2012):

Table 1. Parameters A and m for materials PE 80 and PE 100 (Frank et al., 2012).

Material	Temperature (°C)	A (mm/sMPam ^{0.5})	m (-)
PE 80	60	1.1.10 ⁻³	6.8
	23	1.4.10 ⁻⁶	6.3
PE 100	23	8.5.10 ⁻⁷	6.8

For the prediction of pipe life, we assume that the crack initiation time t_{init} is neglected and that slow crack growth occurs immediately after the pipe is loaded or pressurized. This assumption is taken with caution because the studies on time initiation of crack HDPE are not yet established. The results obtained are shown in Table 2, which gives the time of rupture of a pipe exposed to a stress equal to 2.192MPa and working at an operating temperature of 23°C. For a defect of 0.1mm, we found that the fracture time t_f which is the time required for

propagation of the crack (t_{SCG}) is very large (about 363 years or 3.18×10^6 hours), and that the crack can take a lot more time to propagate in the wall of the pipe by comparing it with the other defects studied (a_{init} : 0.4mm and 1.14mm). Under the present conditions presented (σ , $T^\circ\text{C}$), the estimated lifetimes in the three cases treated are in good agreement with the recommendations dictated by the MRS classification and which have a minimum lifetime of 50 years (MRS : Minimum Required Strength).

Table 2. Failure time in an HDPE pipe 80, σ : 2.192MPa (4bar), T : 23°C

Crack size (mm)	Stress intensity factor (MPa.m ^{0.5})	Failure time (years)
$a_{init}=0.1$	$K_I = 0.623 \left(\frac{a}{t} \right)^{0.497} ; R^2 = 0.91$	$t_f=363 (>10^6 \text{ hours})$
$a_{init}=0.4$	$K_I = 0.990 \left(\frac{a}{t} \right)^{0.472} ; R^2 = 0.94$	$t_f=176 (>10^6 \text{ hours})$
$a_{init}=1.14$	$K_I = 1.844 \left(\frac{a}{t} \right)^{0.159} ; R^2 = 0.96$	$t_f=89 (>10^5 \text{ hours})$

Frank made a study on PE 80 pipes; tests at different temperatures were carried out and compared with the ISO 9080 standard. In pressure tube tests, a large, near-brittle fracture was only detected at a temperature of 80 ° C. Considering that the ductile-brittle transition threshold was reached for the tests at 60 ° C, the measurements at 20 ° C only showed the ductile failure within a maximum test time of 10⁴ hours. Another comparison was also made where the author presented the results of the numerical FE simulation carried out on a PE 80 D4 pipe with an external diameter of 40 mm and a thickness t of 3.6 mm. A particular point has been studied which is the influence of the size of the initial crack while considering the variation of the geometry of the crack front from a semi-elliptical crack to a semi-circular crack. To demonstrate the influence of the initial crack length a_{init} , the prediction was made for two values $a_{init} = 400\mu\text{m}$ and $100\mu\text{m}$. The two hypotheses give different results where a deviation of the rupture times of more than a decade in time is observed (A. Frank, 2010).

5. Conclusion

The fracture mechanics is a good example to approach the life of HDPE pipes. Its main objective is to study the gravity of the defects on the macroscopic scale requiring the determination of the stress and deformation fields in the locality of the fissure. This study made it possible to evaluate the residual lifetime of an internal pressure pipe on the basis of the relation $da/dt=AK_I^m$.

A finite element model of a pipe with an initial defect was suggested in order to calculate the stress intensity factor. A comparison of the stress intensity factor K_I as a function of the normalized length of the crack (a/t) was established. We note that K_I increases with increasing crack size, and becomes critical when the crack propagates more in the pipe wall.

For predicting the lifetime of the pipe, assuming that the crack initiation time t_{init} is neglected and that the SCG occurs immediately after the pipe is loaded or pressurized. Under the present conditions presented (σ , $T^\circ\text{C}$), the estimated lifetimes in the three cases treated are in good agreement with the recommendations dictated by the MRS (MRS : Minimum Required Strength) classification and which have a minimum lifetime of 50 years

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Biographies

Latifa Alimi is a researcher in the field of polymer materials, composites and biomaterials. She obtained her BS and MSc degrees in Mechanical Engineering from UBM Annaba. In 2016, she finalized a PhD degree in Mechanical Engineering at UBM Annaba (Algeria). Her research is mainly concerned with material design and degradation, industrial and technological applications. She worked specifically on piping systems to establish durability, environmental stress cracking, mechanical characterization and reliability. She is the author of several published articles and she participated in many conferences devoted to advanced materials.

Kamel Chaoui is a research professor who works in several fields such as: Industrial processes, Mechanics and Characterization of Materials, Sizing thermal and pressure equipment, Protection of distribution networks, Management (Quality, Environment, Technological Resources and Maintenance), Diagnostics and Technical Expertise, Industrial Risks, Methodology of Research, Standards and standardization, Impact studies of materials on environment and biodiversity, University-Business Relations. In 1998 he obtained the Diploma of Consultant, Quality Management (PME), PEM / GTZ Germany. In 1989, PhD Macromolecular Science and Polymer Engineering, Case Western Reserve Univ., Cleveland, Ohio, USA. 1986, Masters of Science, Engineering Mechanics, Case Western Reserve Univ., Cleveland, Ohio, USA. 1983- State Engineer, Option: Transport and Distribution of Natural Gas (TDG), Institute Algerian Petroleum (IAP), School of Engineers (EI), Boumerdès, Algeria.

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