A Numerical Approach of Elasto-Plastic Critical Energy Release Rate (J_{IC}) of HDPE-100 Pipes

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Article Info

Article history:

Received 05/12/2023
Revised 11/06/2024
Accepted 11/06/2024

Keyword:

Polyethylene, Pipes HDPE 100, J-Integral, ABAQUS

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ABSTRACT

Today, the use of high-density polyethylene (HDPE) pipes dominates underground fluid transport sector especially when replacing traditional and costly steel, cast iron and copper pipes. The failure of polyethylene pipes can occur due to a variety of factors such as excessive external loads, environmental stress cracking phenomenon, thermal gradients, manufacturing methods of and effective service conditions. It is essential to have as complete understanding as possible of the HDPE fracture behavior from modeling methods. This work is focused to quantify fracture energies of highly resistant polyethylene (PE) pipe by finite element method using the J-integral fracture criterion for different length of notch. The initiation of a crack is described by a critical value, J_{IC} (kJ/m^2) and a critical displacement (u_c).

1. INTRODUCTION

Polyethylene pipes have been used successfully for several decades in the past century mainly in natural gas distribution networks, and recently in drinking water systems. They present a good adequacy between long-term durability against environmental degradation and the requirements in terms of costs. Secondly, such piping systems are easy to install and maintain [1,2]. The latest generation of pressurized HDPE-100 pipes is sized to withstand constant hydrostatic pressure exceeding for a period exceeding 50 years of service at 20°C. Despite these advantages, this material remains sensitive to long-term creep fracture via a stable or slow crack growth (SCG) mechanism [3,4].

Analyses involving both mechanical behavior and property assessment of HDPE pipes continue to be the subject of many interesting and innovative studies [5-8].

The presence of a defect in a HDPE pipe can cause leaks resulting in economic losses or environmental accidents or even, in extreme cases, unexpected rupture can have more serious consequences for users. It is therefore essential to understand the fracture behavior of polyethylene pipes and to predict behavior within time. That is why the quantification resistance to crack propagation in likewise structures becomes essential. Some studies [9,10] focused their work on the mechanisms that govern the phenomenon of slow crack growth, which is caused by different parameters. In other studies [11-14] fracture of PE pipe has been approached experimentally and numerically considering the geometry of the test specimen, the shape of the notch and the type of applied stresses. Several methods have been developed for the determination of the resistance to cracking. As a result, different values of J_{IC} are proposed in the literature for HDPE pipes ranging from 3.7 to 100 kJ/m^2.

In this work, the critical energy release rate (J_{IC}) for a propagating crack in an HDPE-100 pipe is investigated using a numerical scheme. The loading is monitored by means of an imposed displacement providing information on the level of applied loading and covering a radial crack span from 2 mm up to 10 mm. The obtained trends of the critical displacements and J_{IC} values are discussed as a function of reference crack length.

2. MATERIAL

The HDPE-100 is defined in the ABAQUS calculation code as an elastic-plastic material [14, 15]. The mechanical properties introduced into the model are the elasticity modulus and the yield stress. Measured values are E = 983 MPa and σ_y = 9.4 MPa respectively. A Poison's coefficient of 0.42 is adopted.

The high density polyethylene resin was obtained by addition polymerization. Typical properties of such an HDPE-100 polymer are provided in Table 1 [16].

Table 1: Some mechanical properties of HDPE pipe material (HDPE-100).

Property	Valuer
Density	0.95 to 0.98 g/cm3
Fluidity index at 190°C	0.75 g/10 min
Back carbon content	2.0 to 2.6 %
Vitreous transition temperature Tg	-100 °C
Melting temperature	137°C
Young's modulus	550–1460 MPa
Yield strength	20–30 MPa
Ultimate elongation	≥ 350 %
Toughness	2 to 5 MPa $m^{1/2}$
Thermal expansion coefficient	150 to 300 m K^{-1}
Oxydation stability	≥ 20 min

3. FINITE ELEMENT ANALYSIS

The J-integral is considered as a principal parameter to characterize the fracture behavior of ductile materials.The theoretical concept of J-integral was developed in 1967 by G. P. Cherepanov [17], and independently in 1968 by Rice who showed that an energetic (called J) was independent of the path around a crack [18]. The fracture mechanics concepts are now commonly used to examine the toughness of materials. The fracture tougness can be expressed as followes (Eq.1):

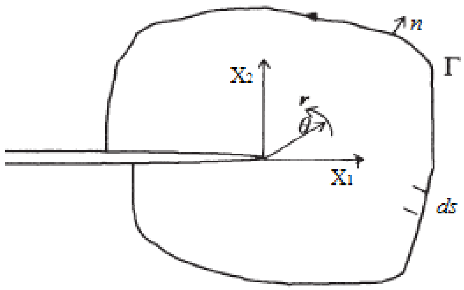


Figure 1. Path for the calculation of J-integral

$$J = \int_{\Gamma} \left(W n_1 - T_i \frac{\partial u_i}{\partial x_1} \right) ds \qquad (1)$$

Where Γ is the path along which the J-integral is calculated.

$$W = \frac{\sigma_{ij}\varepsilon_{ij}}{2} \qquad (2)$$

W:is the strain energy density for linear elastic material.
n_1: is the component of the outward unit normal n in the x_1 direction.

$$T_i = \sigma_{ij} n_j \qquad (3)$$

Ti: is the traction vector.
u_i: is the displacement vector along Γ.
ds: is differential arc length.

3.1. Geometry, Boundary conditions and Loading

In engineering critical assessments, a parameter of the fracture mechanics (J or CTOD) calculated as a crack tip of a structure, is compared to a critical value (J_{IC} or $CTOD_C$) chosen as a criterion. These critical values do not only depend on material but also on the specimen geometry used for their measurement. The Single-Edged Notched Tensile (SENT) specimen for toughness tests presents a very good transferability with regards to the pipe. The stress level of the SENT specimens can be adjusted by varying the crack depth or the distance between clamps. In the following subsection, the results of a numerical analysis based on FEA in terms of the J-integral approach are presented [19,20].

The thin single SENT edge notch tensile specimen geometry is adopted for the finite element calculation and its dimensions are 120x20x3mm^3 as shown in Figure 2. The choice of this specimen geometry is dictated by the fact that it is the most adapted for the calculation of the J_{IC} and CTOD for ductile materials with sharp notches. One-half of the specimen geometry is modeled due to symmetrical form which will help reducing the computation time. To apply the axial load to the specimen, a reference point was tied to the specimen end area. The rigid body constraint option available in ABAQUS is what is called lamped nodes. The reference point at the column end can distribute uniformly the load to all nodes of the specimen end.

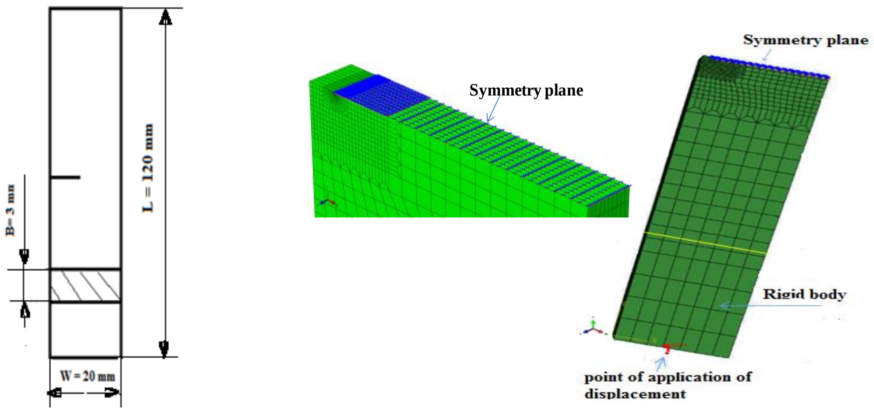


Figure 2. Specimen geometry, dimensions and 3D SENT model

3.2. Finite element mesh

The mesh is made by HyperMesh, using C3D20R which is a second order element consisting of 20 nodes. This kind of elements was used in previous studies [11,15]. The mesh is sufficiently refined near the crack-tip in order to properly define the distribution of stresses and correctly predict the mechanical behavior at the most stressed zone. The first declared contour is at the crack-tip. The direction of virtual crack extension is defined by the normal to the crack plane, as shown in Figure 3.

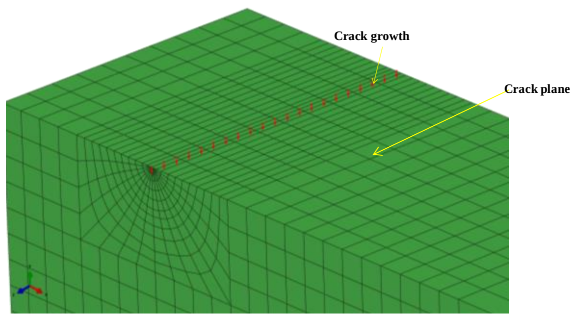


Figure 3. Crack growth direction

The evolution of the J-integral for different contours, in the normal plane at the crack-tip is studied. Figure 4a shows that the evolution of the J-integral depends on the followed path and on the very first contour, convergence was observed at the 14th contour as the results point to the same value of the energy release rate J (see Figure 4b). This convergence proves that a suitable mesh is adopted.

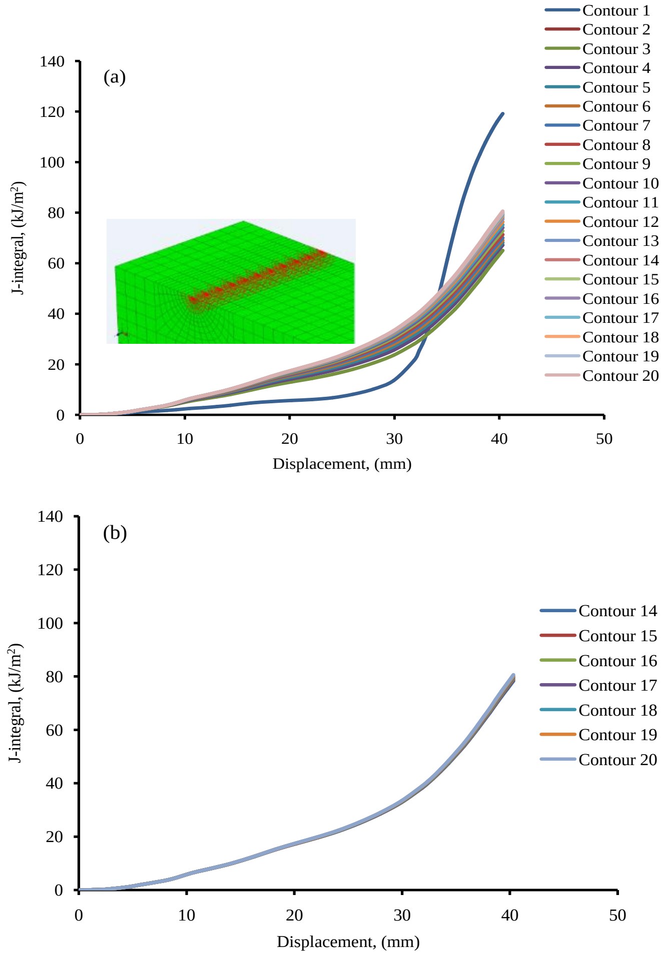


Figure 4. Evolution of the J-integral

Figure 5 shows how the distribution of opening stress along line of the ligament (P_1-P_2) changes with displacement u over time. It is clear that the appearance the damaged zone (hardening at the crack-tip) for the crack depth a = 2 mm is reached at a displacement of the order of 3.834 mm. Then, the damaged region is much more remarkable. The energy needed for crack propagation is associated with viscous dissipation in the area surrounding the crack tip. This phenomenon involves not only the plastic work necessary for crack tip blunting but also various other dissipative processes, such as plastic, viscous, and damage, that can occur in the area surrounding the deforming crack tip [20]. The damage region is due to the work hardening which is a consequence of plastic deformation. Therefore, it is more conservative to considered the value of 13.43 kJ/mm² which corresponds to displacement of 3.834 mm, Figure 6-a, as the critical value of J required to initiate the crack [20]. For the other depths of crack, the damaged zone is noticed starting from displacements of the order of 2.248, 1.527, 1.636, 1.554 and 1.540 mm.

For conservative reasons, as previously explained, the value of critical J corresponding to the appearance of the damage zone will be considered as the resistance to crack initiation J_{IC} (in mode I). This is a good indicator, specific to the material resistance to crack propagation and is a measure of the toughness of the material [16,20]. However, the determined values of J_{IC} from the displacement-J-integral curves are shown in the Figures (6a-e).

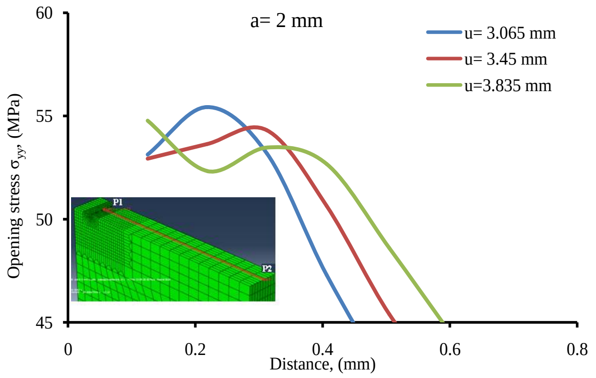
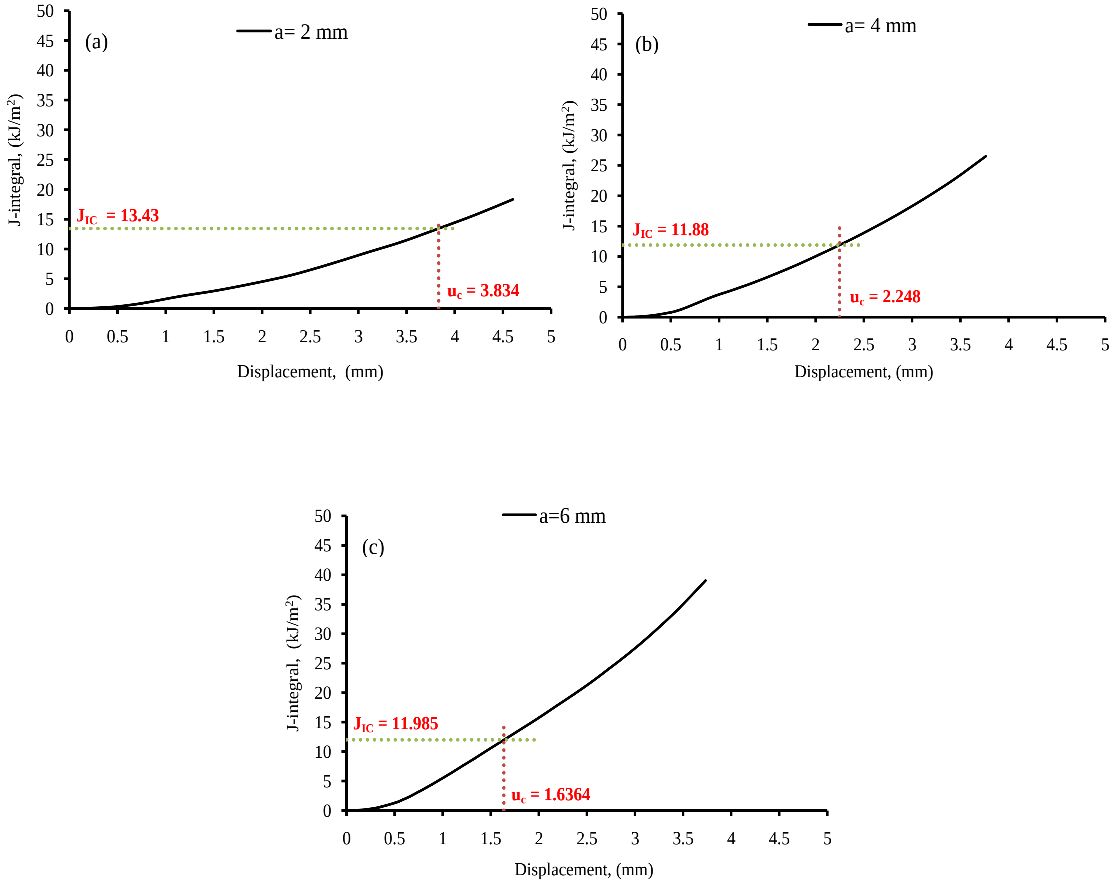


Figure 5. Opening stress (σ_{yy}) distribution along the crack line of the ligament (P_1-P_2), notch of 2mm



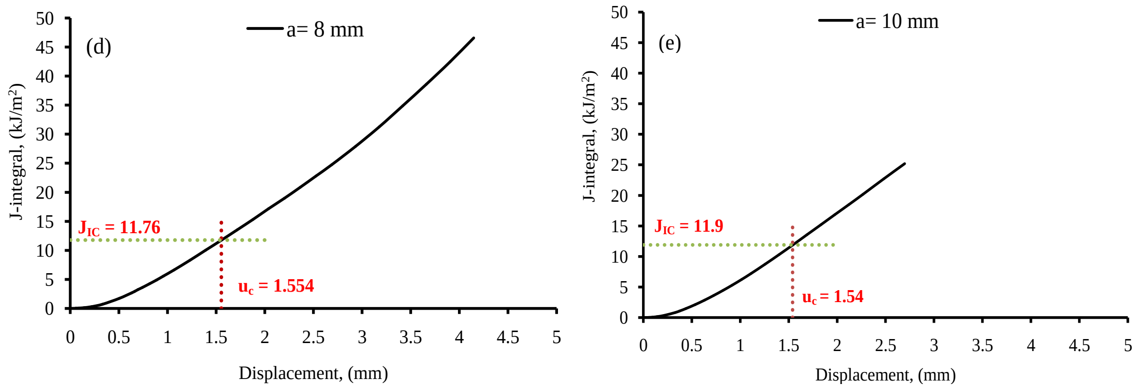


Figure 6. Variation of fracture toughness J_{IC} vs displacement for different crack length

Figure 7 shows the numerical results of the critical values of the J-integral as a function of the crack length, it is notable that the greatest value of J_{IC} is obtained for a crack of 2 mm, a variation of 11.39% between 2 mm and 10 mm depth. It is also found that the variation of J_{IC} remains insignificant for the other length.

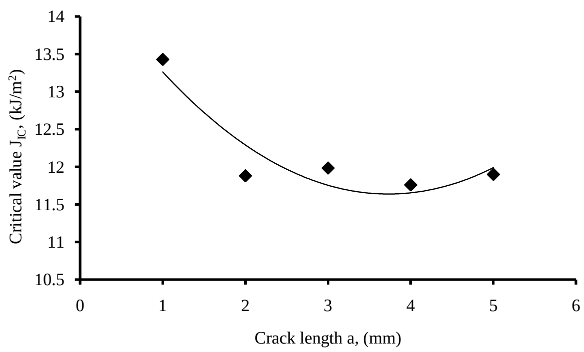


Figure 7. Variation of J_{IC} vs crack length a

Figure 8 illustrates the influence of crack length on critical displacement u_c, which indicate clearly that the u_c decreased from 3.834 to 1.54 mm respectively.

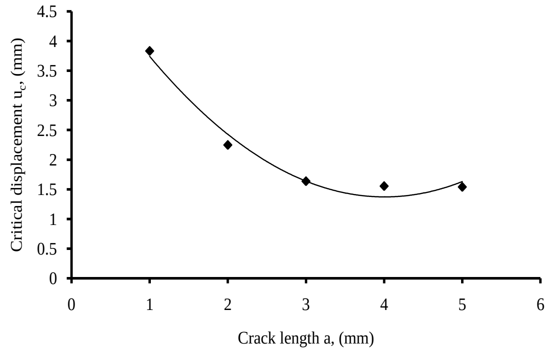


Figure 8. Variation of u_C vs crack length a

Several values of toughness for polyethylenes have been reported in the literature. However, the dispersion of these estimates is significant. The table 2 shouw some values of fracture toughness according to different method.

Table 2: Some toughness values for polyethylene.

Material product	Specimen type	Testing conditions	J_{IC} (kJ/m^2)	EWF Parameters w_e (kJ/m^2)	REF.
Extruded HDPE Sheet	CT	V = 5 mm/min	1.7	-	[24], 1991
HDPE Sheet	DENT DCNT	V = 0.50 mm/min	30	35 36	[26], 1991
Extruded HDPE Plate	DENT	V = 5 mm/min	-	75 Rolling direction 49 Transverse direction	[25], 2007
HDPE Pipe	CT DENT	V = 10 mm/min	45 for a/w =0.5 49 for a/w =0.55	144.3	[12], 2013
LDPE Sheet	Quadratic specimens	V = 0.5 mm/s	13		[21], 2018
HDPE Pipe	CT	V = 10 mm/min	$J_{0.2}$ = 10.3 to >25	-	[22], 2019
HDPE Pipe	DENT	Strain rate 0.1, 0.01 s^{-1}		137.5	[23], 2020

4. CONCLUSION

This study focuses on the quantification of fracture toughness (J_{IC}) using the J-integral approach and SENT specimens containing different crack lengths for HDPE-100 pipe.

The finite element method is chosen to analyze the fracture behavior of the HDPE-100. It is concluded that the J-integral results depend on the followed path for the very first contours and convergence is observed at the 14th contour.

The analysis of the two parameters, the evolution of the J-integral as well as the distribution of the opening stress in the vicinity of the defect is used to be able to choose J_{IC}. A damaged region (hardening zone) appears when the J-integral found by ABAQUS is equal to 13 kJ/m² which corresponds to a displacement of 3.834 mm for a crack length 2 mm. The variation of J_{IC} remains insignificant for the other depths. For each crack length, there is a corresponding critical displacement, which decreases as the depth of the crack increases.

5. NOMENCLATURE

HDPE	High density polyethylene
E	Modulus of elasticity, MPa
a	Crack length, mm
J	J-integral, kJ/m^2
J_{IC}	J-integral critical value, kJ/m^2
$J_{0.2}$	Value of J corresponding to the 0.2mm crack length, kJ/m^2
u	Displacement, mm
u_c	Critical displacement, mm
LDPE	Low-density-polyethylene
DENT	Double-Edge notched tension
DCNT	Double-Center notched tension
SENT	Single-Edged Notched Tension
CT	Compact Tension
w_e	Essential work of fracture, kJ/m^2

Greek symbols

σ_y	Yield stress, MPa
σ_{yy}	Opening stress, MPa

ACKOWLEDGEMENTS: The authors are grateful to Pr K. Chaoui for the fruitful discussion and the proposed suggestions to better elucidate the of the present.

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