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Numerical simulation of the severity of surface defects in HDPE Pipes

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ABSTRACT

In this paper an analysis of the evolution of a semi-elliptical crack located at different positions of the wall of an HDPE pipeline under internal pressure is made. The three-dimensional finite element method is used to calculate the integral J. The *J* integral is important in the extreme positions on the contour of integration. When the ratio (a / t) reaches a critical value (a / t = 0.6), the effect of crack depth becomes important. It's also shown that for low values of the opening angle of the curve, the crack tends to be propagated from the position *1*. The transverse cracks have a lower risk that the axial cracks and then the cracks into interior of the wall of the pipe are more dangerous than the cracks external.

1 Introduction

The development of structural polymers is related to their mechanical properties, which themselves depend on the microstructure. Semi-crystalline polymers for the most part have a high tenacity that meets the requirements of products that must withstand severe use conditions (impact, creep, fatigue). Among these materials, polypropylene "PE" is a material that is used more and more extensively, and more particularly in the urban water distribution networks and those of the distribution of natural gas [1-3].

Because of their good resistance to cracking, PE pipes have a high degree of reliability under normal use conditions. Under these conditions their life span is estimated at more than 50 years on the basis of regression curves built from accelerated hydraulic pressure tests [4]. In use, polyethylene pipes undergo internal and external loads that cause deformation and alter mechanical properties. The prediction of the lifetime of these materials has been the subject of several studies [5-9]. Benhamena et al. [10] used the local approach in fracture mechanics to study the fracture behavior of polymers pipes with defect. They have found that the temperature level has a great effect on the mechanical properties of polymers materials. In another hand, it is known that, the presence of defects during production or in service leads to the initiation and propagation of cracks. The prevention and reliability of HDPE pipes is a primary objective, given its economic and security impact. For this reason studies on the breaking behavior of pipes and the analysis of the harmfulness

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of faults in these pipes have been undertaken [8-15].The study of the breaking behavior of polymers has attracted the attention of many authors [16-19].

Among them, Garcia et al. [20] who conducted an experimental study based on the use of three arc-shaped specimen bending test specimens obtained from a pipe in the same context, Salazar et al., 2008 [21] use the method of separation of the loading parameter to determine the curve JR of a polypropylene. An experimental study was undertaken by Nishimura et al. [22] to analyze the fatigue endurance of polypropylene gas distribution pipes. From these studies, we can conclude that the shape, the geometry of the crack and its dimensions as well as the position of its location in the structure are essential to predict the evolution of defects in service. These conclusions are at the origin of the main idea of this study, where we propose to study and analyze the propagation, the direction of propagation of a semi-elliptical crack located at different positions in high density polyethylene pipes (HDPE) based on the three-dimensional finite element method.

2 Material and geometric model

In this study we consider the propagation of a semi-elliptical crack located in different positions on the wall of a pipe subjected to internal pressure. Figure 1 shows the pipe with axial and transverse cracks. The pipe is characterized by its internal diameter D and its thickness t (Figure 2).

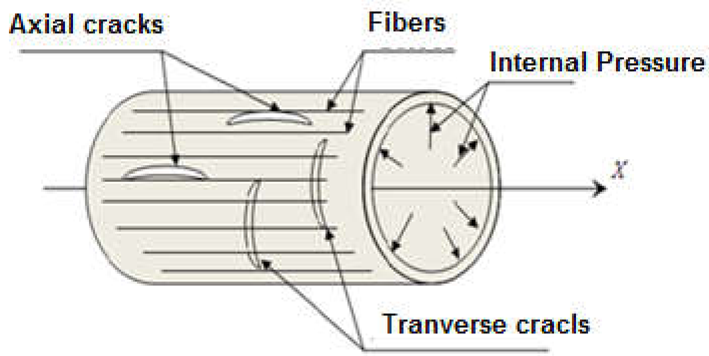

Fig. 1 – Representation of pipe with axial and transverse cracks.

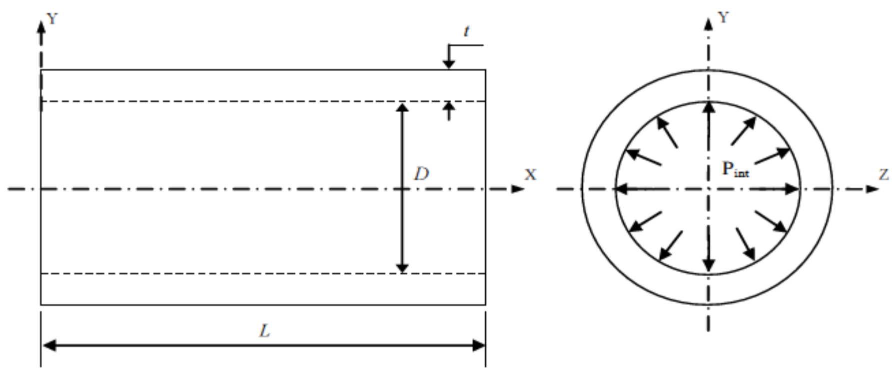

Fig. 2 – Schematic representation of a pipe under internal pressure P.

Figure 3 presents the geometric models and the four crack configurations studied. The shape of the cracks with their positions relative to the X axis is given in figure 3e.

The initial crack is defined by the crack depth ratio divided by the pipe thickness a / t and the ratio of the crack depth to the half length a / c. Two configurations of cracks are studied: the first configuration corresponds to two internal cracks located at different positions of the pipe wall: internal axial crack (IAC) and internal transverse crack (ITC). The second configuration is similar but the two cracks are located on the outside of the pipe wall: external axial crack (EAC) and external transverse crack (ETC). The material studied is high density polyethylene (HDPE), widely used in engineering applications such as drinking water pipelines, gas and pressure vessels. It is a semi-crystalline thermoplastic material. HDPE is supplied by STPM CHIALI located in Sidi Bel Abbés (Algeria) certified according to ISO 9001-2000 [23] and characterized at different strain rates and temperatures by Aour et al. [24].

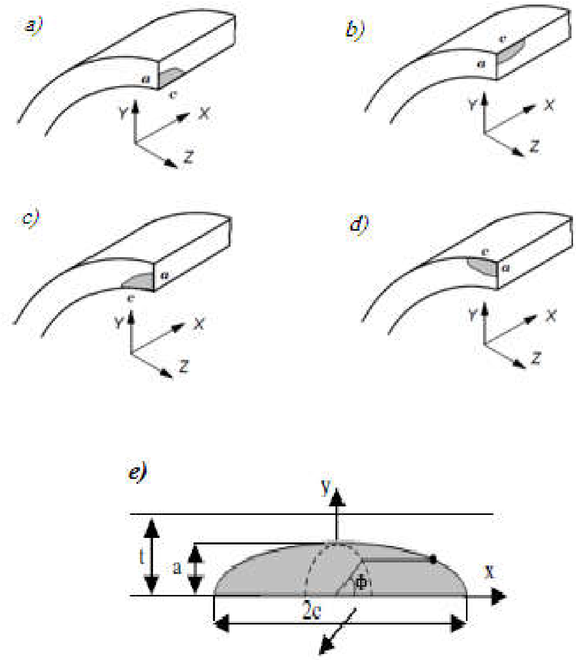

Fig. 3 – Cracks studied. a) Internal axial crack (IAC), b) External axial crack (EAC), c) Internal transverse crack (ITC), d) External transverse crack (ETC) e) Shape of the crack.

The elastic properties at room temperature obtained were: Young's modulus, E = 500 MPa, Poisson's ratio, ν= 0.38 and the yield strength, σ_Y= 19.5 MPa.

In this study, the integral J approach defined by Shih et al. [25] is used to calculate the rate of released mechanical energy, denoted J (s), at each point s at the crack front (Figure 4), it is expressed by:

$$J(s) = lim_{\Gamma\to 0} \int \left[w_{ni} - \sigma_{ij}\frac{\partial u_i}{\partial x_i} n_j\right] d\Gamma \quad (1)$$

Where: W is the strain energy density due to stress work, σ_{ij} is the stress tensor, u_i is the displacement vector, Γ is a contour surrounding the crack tip at each point s, n_j is the normal unit vector at contour Γ, and x_i is the local Cartesian coordinate system at location S on the crack front.

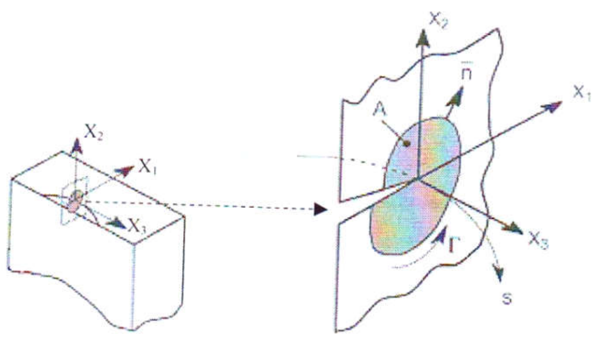

Fig. 4– Representation of the J integral in 3 dimensions

In this study the numerical simulation by the finite element method in three dimensions was made by the calculation code WARP3D [26]. The asymptotic behavior of the displacement field in the vicinity of the crack front indeed requires the local use of an extremely refined mesh with special elements. The modified Newton-Raphson method is used to solve the elastoplasticity equation. The singularity around the crack point is modeled by special elements adapted to the calculation of the quantities associated with the fracture mechanics.

3 Results and Discussions

The effects of the crack position, the loading, the crack shape and the thickness of the pipe on the evolution of the integral J are studied.

3.1 Effect of the crack position

Figures 5a to 5d show the variation of the integral J as a function of the angle ϕ of the orientation of the crack with respect to the X axis for the four configurations and the ratios a / t (a/t=0.33 ; 0.44 ; 0.55 et 0.66). These results show that the value of the integral J takes extreme values, the angles of orientation ϕ= 0 and ϕ = 90 °.

The results obtained show that whatever the position of the crack in the pipe or the position on the crack front, the integral J increases and reaches a maximum with the increase in the ratio a / t for an orientation angle ϕ = 0.

We also note the integral J decreases as the angle ϕ increases. For internal cracks, the values of the integral J obtained are greater than those obtained for external cracks regardless of their orientation (axial or transverse). This difference is more marked for values of the (a / t) ratio less than 0.5.

We also observe that the values of the integral J for the axial cracks are much larger than the values of the integral J obtained for the transverse cracks. This can be explained by the fact that the axial cracks are parallel to the orientation of the fibers, while the propagation of the transverse cracks is slowed down by those fibers which are perpendicular to the longitudinal direction (see Figure 1).

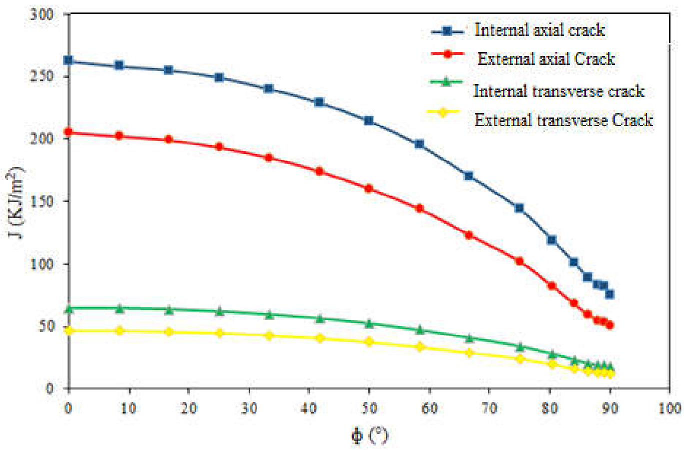

Fig. 5a– Evolution of the integral J as a function of the orientation angle (a/t = 0.33).

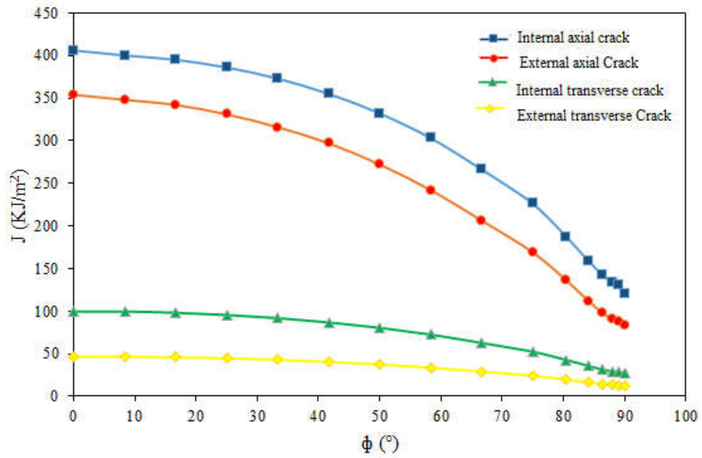

Fig. 5b– Evolution of the integral J as a function of the orientation angle (a / t = 0.44).

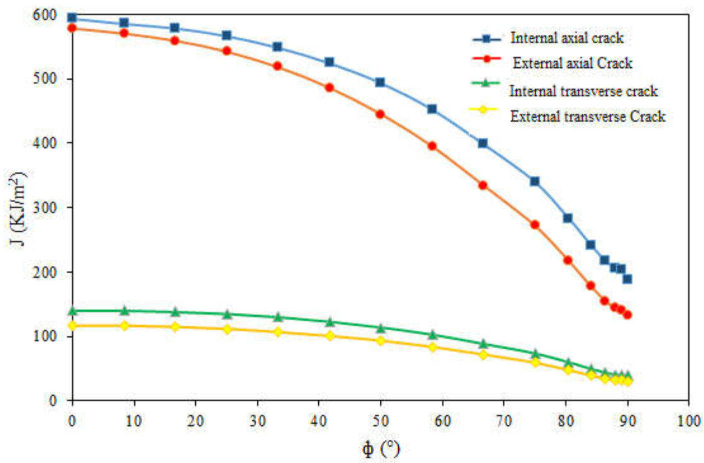

Fig. 5c– Evolution of the integral J as a function of the orientation angle (a / t = 0.55).

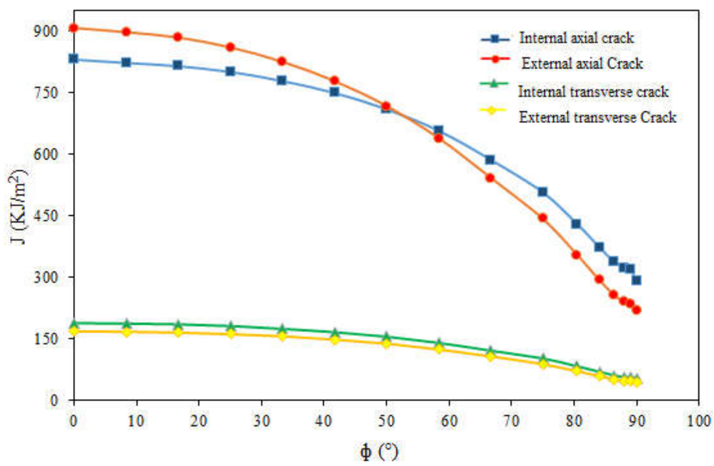

Fig. 5d– Evolution of the integral J as a function of the orientation angle (a / t = 0.66).

3.2 Load effect

The influence of the loading on the integral J is studied for cracks characterized by the ratios of the depth of crack at the half-length a / c = 0.75 and that of the depth of the crack at the thickness of the wall a /t=0.33 and for the four geometric configurations. Figures 6a-b represent the variation on the integral J as a function of the loading P for two extreme positions of the crack Φ = 0° and Φ = 90°.

We observe that the value of the integral J is directly proportional to the loading and whatever the pressure on the crack front, it increases with the increase of the crack for Φ = 0° and Φ = 90°. It should be noted that transverse cracks give reduced values of the integral J compared to those obtained for axial cracks. When Φ = 0 ° the integral J takes maximum values greater than those obtained for Φ = 90 °, this increase in the integral is due to the edge effect (Φ =0°), where the propagation requires more of energy at the tip of the crack, after propagation there is dissipation of energy and relaxation of the stresses leading to a decrease in the integral J for Φ=90 °.

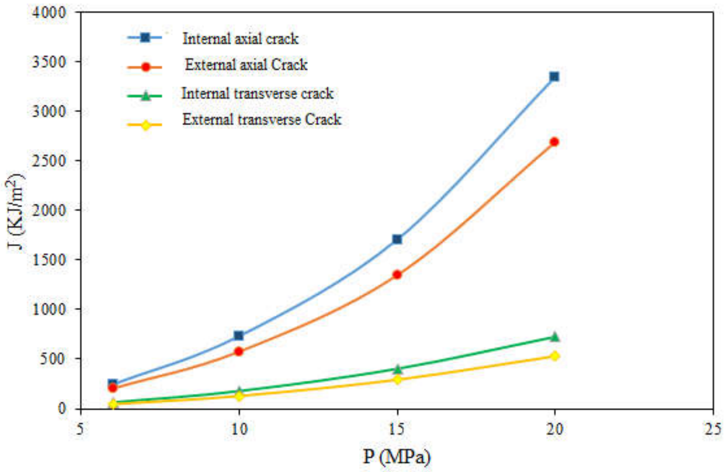

Fig. 6a– Evolution of the integral J as a function of the load P (ϕ=0, a/t =0.33 and a/c=0.75).

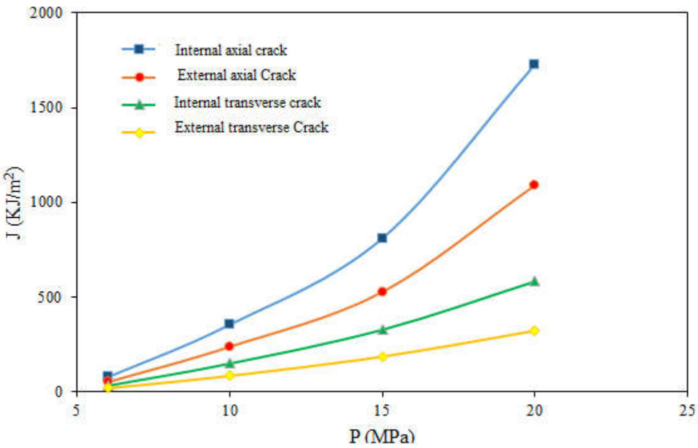

Fig. 6b– Evolution of the integral J as a function of the load P (ϕ=90, a/t =0.33 and a/c=0.75).

3.3 Effect of crack shape

Figures 7 to 14 show the variation of the integral J as a function of the different sizes of the cracks characterized by the ratio a / c for a ratio a / t = 0.33 in the two extreme positions on the crack front Φ = 0 ° and Φ = 90 ° and for different pressure values (P= 6 ; 10 ; 15 et 20 MPa).

It is noted that for the same ratio a / t, the integral J reaches a maximum value for a lower a / c ratio then decreases with when the a / c ratio decreases, in other words a large crack length leads to a decrease in the integral J. Except that for the internal transverse crack in position on the crack front Φ = 90 ° there exists a critical a / c ratio (a / c = 0.45) beyond which the integral J strongly decreases with the development of the crack.

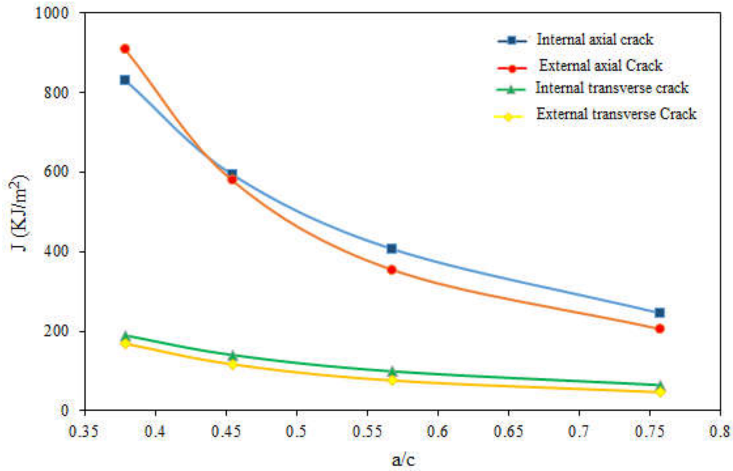

Fig. 7– Evolution of the integral J as a function of the a / c ratio (ϕ=0; a/t =0.33 P= 6 MPa).

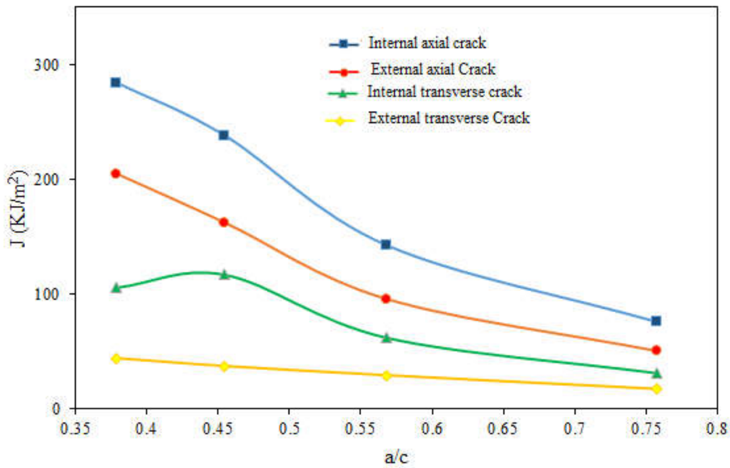

Fig. 8– Evolution of the integral J as a function of the a / c ratio (ϕ=90*; a/t =0.33 P= 6 MPa).*

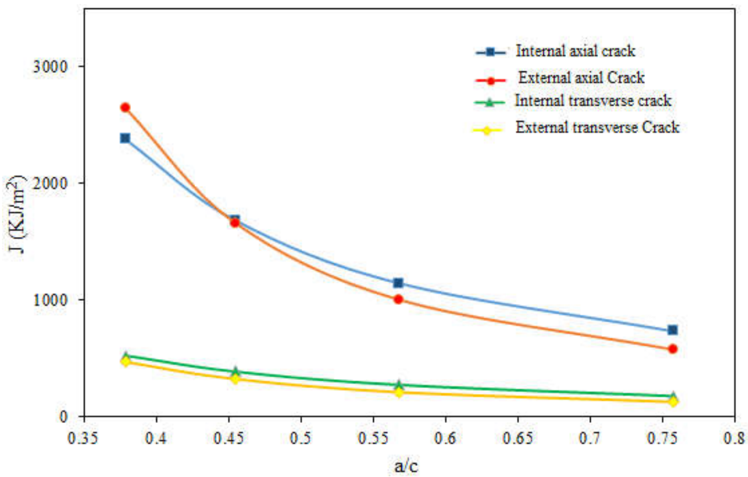

Fig. 9– Evolution of the integral J as a function of the a / c ratio (ϕ=0*; a/t =0.33 P= 10 MPa).*

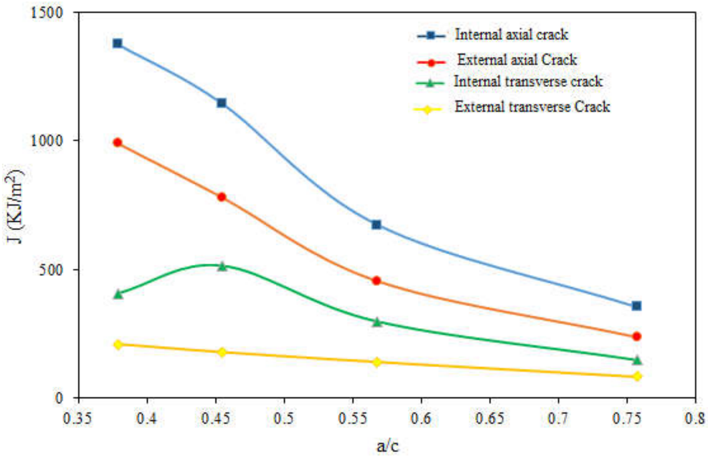

Fig. 10– Evolution of the integral J as a function of the a / c ratio (ϕ=90*; a/t =0.33 P= 10 MPa).*

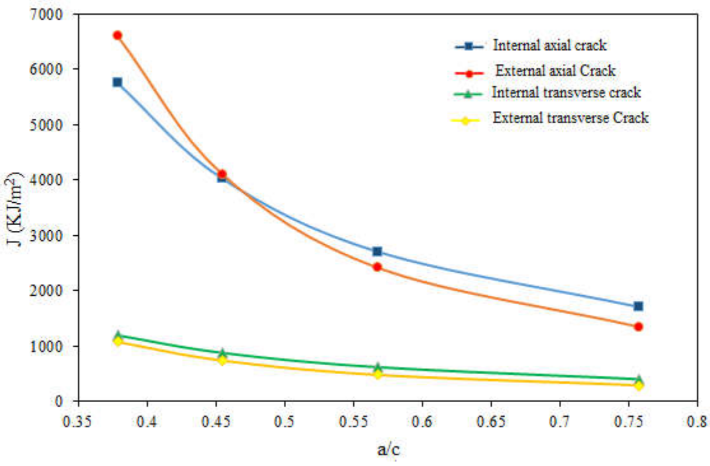

Fig. 11– Evolution of the integral J as a function of the a / c ratio (ϕ=0*; a/t =0.33 P= 15 MPa).*

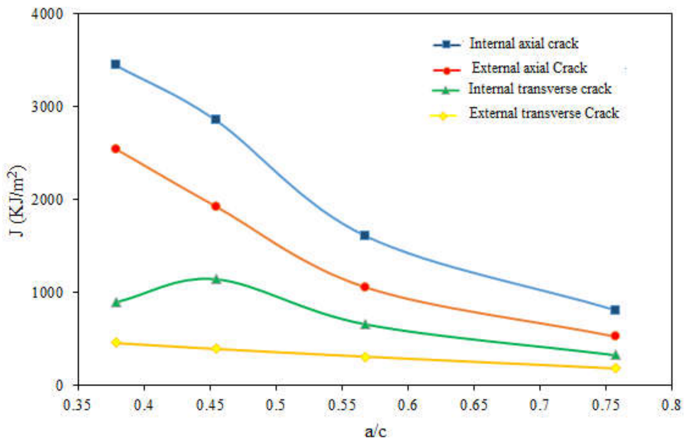

Fig. 12– Evolution of the integral J as a function of the a / c ratio (ϕ=90*; a/t =0.33 P= 15 MPa).*

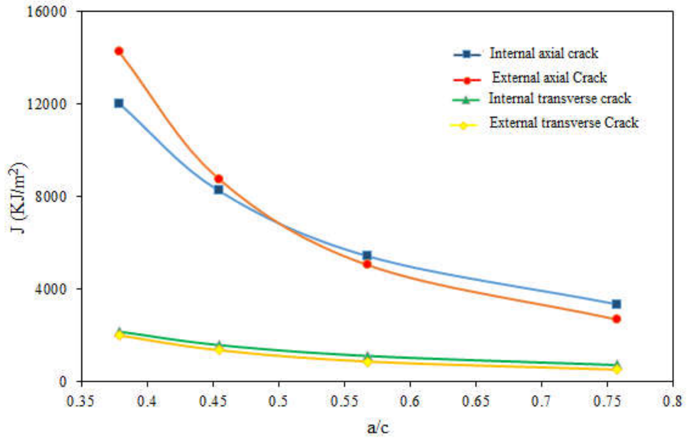

Fig. 13– Evolution of the integral J as a function of the a / c ratio (ϕ=0*; a/t =0.33 P= 20 MPa).*

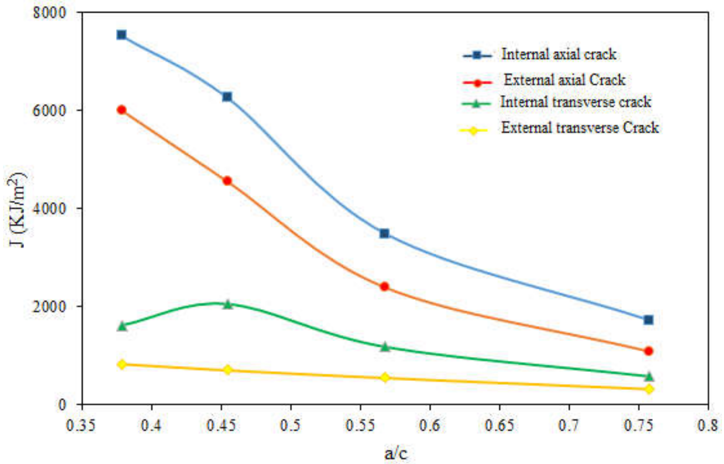

Fig. 14– Evolution of the integral J as a function of the a / c ratio (ϕ=90; a/t =0.33 P= 20 MPa).

3.4 Effect of pipe thickness

To complete this analysis, we studied the effect of thickness on the failure criterion of a cracked pipe. Figures 15 and 16 show the variation of the integral J as a function of the thickness of the pipe characterized by the ratio a / t for different crack position and in two cases Φ = 0 ° and Φ = 90 °. We notice that the integral J increases and reaches a maximum value with the increase of the ratio a / t, this maximum is reached when the size of the crack tends to a value greater than half the thickness of the pipe.

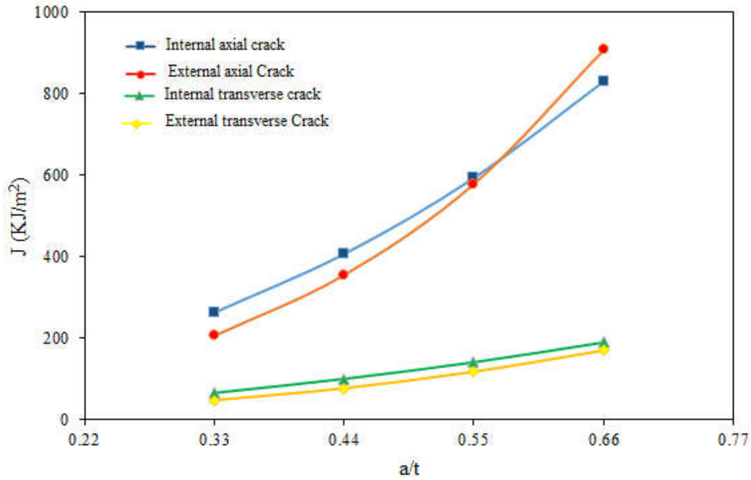

Fig. 15– Evolution of the integral J as a function of the a/t ratio (ϕ=0).

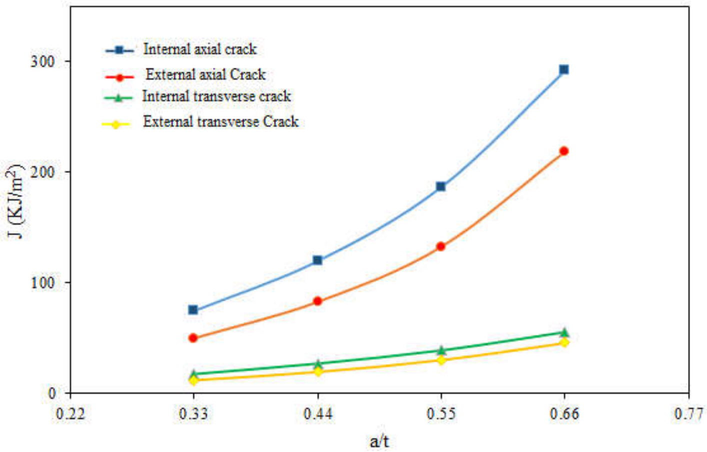

Fig. 16– Evolution of the integral J as a function of the a/t ratio (ϕ=90).

4 Conclusion

In this study, the failure behavior of a high density polyethylene (HDPE) pipe under internal pressure is analyzed using the three-dimensional finite element method based on the concept of integral J.

Regardless of the nature of the material (strain rate) of the pipe for a semi-elliptic crack, the integral J reaches its maximum for a position on the crack front characterized by $\Phi = 0$ °. This may explain why the stress field is important at this position on the integration contour and that the direction of crack propagation is in a direction perpendicular to the crack ligament (Y direction, Figure 3);

Regardless of the crack depth, for a crack size characterized by the low ratio (a / c) the integral J is very sensitive; on the contrary, for higher values (a / c) which lead to a reduction of this integral. In other words, this behavior is more marked for an elliptic-shaped crack;

There is a critical depth (a / t = 0.6) regardless of the size of the crack in which the integral J reaches its maximum. Beyond this critical value, the integral J decreases independently of the crack.

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