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Analysis of the harmfulness of the water hammer phenomenon in high density poly-ethylene (HDPE) pipes

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A R T I C L E I N F O

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Pipe
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A B S T R A C T

In this numerical study, the three-dimensional finite-element method is used to analyze the degree of harmfulness of the water hammer phenomenon in high-density polyethylene (HDPE) pipes damaged by cracking. The fracture criterion used in this study is the integral J, which was calculated in semi-elliptical cracks in four different positions. The effect of the flow rate and crack configuration on the J-integral is analyses. The pipe section was constructed simulating a commercially available model. A 3D finite-element analysis was performed in Warp Software. All materials used in the models were considered to be isotropic, homogeneous, and linearly elastic. The results obtained show that an increase in pressure caused by the water hammer phenomenon leads to a remarkable increase in the J-integral. It is also shown that an internal longitudinal crack in a pipe is the most dangerous. It can also be seen that an increase in the flow velocity leads to an increase in the J-integral.

1. Introduction

The water hammer is a phenomenon of overpressure which appears at the time of the sudden variation in the speed of a liquid, following a rapid closing/opening of a valve, a tap or the start/stop of a pump. This overpressure can be significant; it often results in a characteristic noise, and can lead to the rupture of the pipe in large installations, due to the quantity of fluid in motion. It has been known that the failure of polymer pipes is a complex problem [1–3]. In many cases, we simply ensure that they are held by a large oversizing, which gives a margin of safety that we consider sufficient without knowing it well. Rather than introducing empirical safety coefficients at all levels (manufacturing, use), it seems that a more effective method consists in carrying out a real safety calculation to predict the evolution of the structure in the most unfavorable cases. The safety margin can then be defined with full knowledge of the facts. Concurrently, recent studies concluded that the high-density and low-density polyethylene (HDPE–LDPE) compound short-section-based inline strategy provided substantial attenuation of pressure magnitude [4,5].

The semi-crystalline polymers are materials with a complex microstructure consisting of a disordered amorphous phase with viscous nature and a structured crystalline phase. The coexistence and the interaction of these two phases with very different natures are the origin of the complexity of their macroscopic behavior, which is classified as an elastoviscoplastic behavior [6–8]. In micromechanical models, the crystalline and amorphous phases in semicrystalline polymers, including HDPE, are separately modeled owing to their different specific characteristics, and the two phases are combined to form a homogenized model that represents the bulk material. Therefore, the micromechanical models are capable of studying the link between the mechanical properties and the chemical composition of the material. Macromechanical models are generally phenomenological models, and the differential or

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integral constitutive equations are expressed as functions of stress, strain rate, and strain or time [9].

The presence of a crack in a pipe under internal pressure caused by the water hammer requires, for obvious safety reasons, to know precisely its degree of harmfulness. When this crack propagates, it is important to quickly assess the evolution of this degree of harmfulness of the cracked structure. The resolution of this type of problem, within the framework of fracture mechanics, is classically carried out by the finite-element method [10]. There are many numerical analyses of three-dimensional fracture, which are definitely needed to better understand the fracture behavior of mechanical structures [11,12]. Our objective is to expose and to analyze the various ways of possible studies by the determination of the integral J in the various positions on the front of crack (Φ), and to choose the most adequate approach to the description of our pipes.

2. Geometrical and materials models

In this study we have considered four identical high-density polyethylene pipes of the same geometry used for drinking water (Standard reference: NF EN 12201) [13] subjected to internal pressures and containing semi-elliptical cracks of length ($2c$) and depth (a), situated in four different positions (Fig. 1). The geometrical characteristics of the pipe used (Fig. 2) are the following: R_i (= 194.2 mm) is the inner radius; L (= 2000 mm) is the length; and t (= 55.8 mm) is the wall thickness.

The material used in this study is a high-density polyethylene (HDPE) pipe (PE100) subjected to a nominal pressure P_N equal to 20 bars. The corresponding elastic properties at ambient temperature are shown in Table 1.

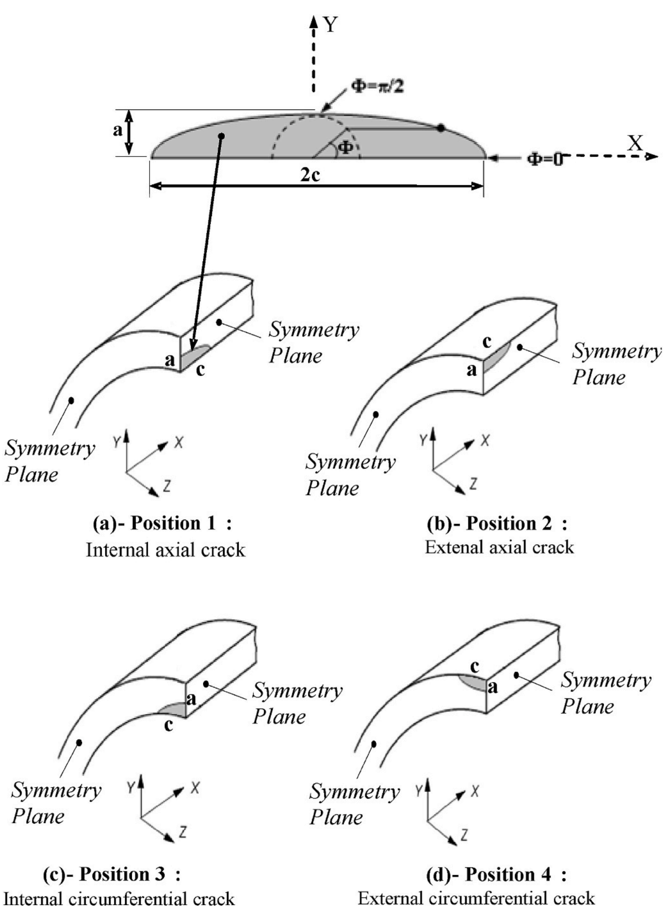

Fig. 1. Schematic representation of the four models.

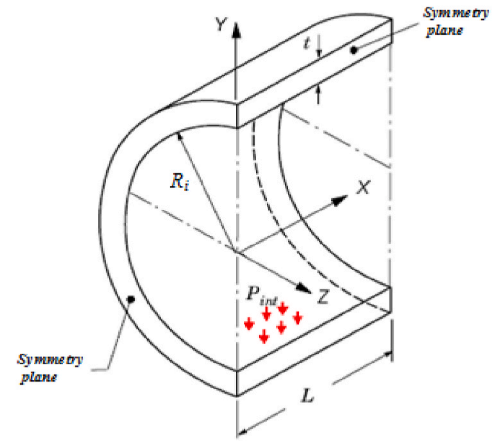

Fig. 2. Schematic representation of one quarter 1/4 of the pipe under internal pressure.

Table 1
Material properties of HDPE (PE100) [14].

Symbol	Property	Value
E	Young's modulus	1200 MPa
Σe	Yield stress	25 MPa
Y	Poisson's ratio	0.4
P	Density	1560 kg/m^3

3. J-integral formulation

The local value of the mechanical energy release rate, denoted J(s), at each point "s" for an arbitrary crack tip motion (but restricted to crack advance along the X_1 axis) under general dynamic loading is given by (1) [15,16]:

$$J(s) = \lim_{\Gamma \to 0} \int_{\Gamma} \left[(W + T)\, n_1 - \sigma_{ij} \frac{\partial u_i}{\partial X_1} n_j \right] d\Gamma \tag{1}$$

Where W and T are the stress work and kinetic energy densities respectively, σ_{ij} and u_i are the cartesian components of the stress and displacement, Γ is a vanishingly small contour which lies in the principal normal plane at s and n is the unit vector normal to Γ (see Fig. 3).

All field quantities are expressed in the local orthogonal coordinate system, X_1-X_2-X_3, at location "s" on the crack front.

4. Finite-element modelling

The mesh of the crack geometry and its neighboring environment, i.

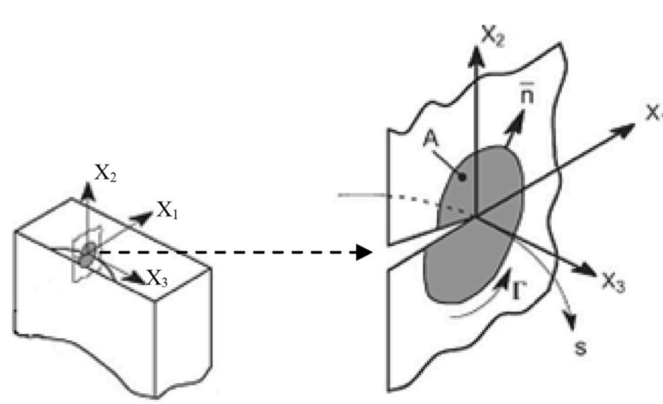

Fig. 3. J-integral in three dimensions (3-D).

e., of the zone of interest, is more refined [17,18]. Considering the symmetry conditions, only one quarter (1/4) of the pipe is modeled, using three dimensional linear elements and special elements in the front of the crack, as indicated in Fig. 4.

5. Results and discussions

5.1. Water hammer effect

In this section, we have analyzed the effect of the internal pressure caused by the water hammer on the variation of the integral J. We have made this analysis on a pipe having an internal longitudinal crack of a semi-elliptical configuration with $a/c = 0.1$ and $a/t = 0.1$. According to Allievi's formula, the speed of the waves in the case of HDPE pipes is given by the formula below [19]:

$$a = \frac{9900}{\sqrt{48.3 + K\ \frac{D}{t}}}\ [m/s] = 351.12\ m/s \tag{2}$$

where:

a: wave velocity (m/s);

K: coefficient depends on the nature of the pipe, $K = 105/E$ (where, $E = 1200$ MPa is the Young's modulus of the chosen pipe in MPa), so for our case the coefficient $K = 83.33$ [19];

D: outside diameter of the pipe; and

t: pipe thickness.

According to Joukovski's formula [19], the pressure difference caused by the phenomenon of the water hammer, in the case of a rapid total closure is equal to:

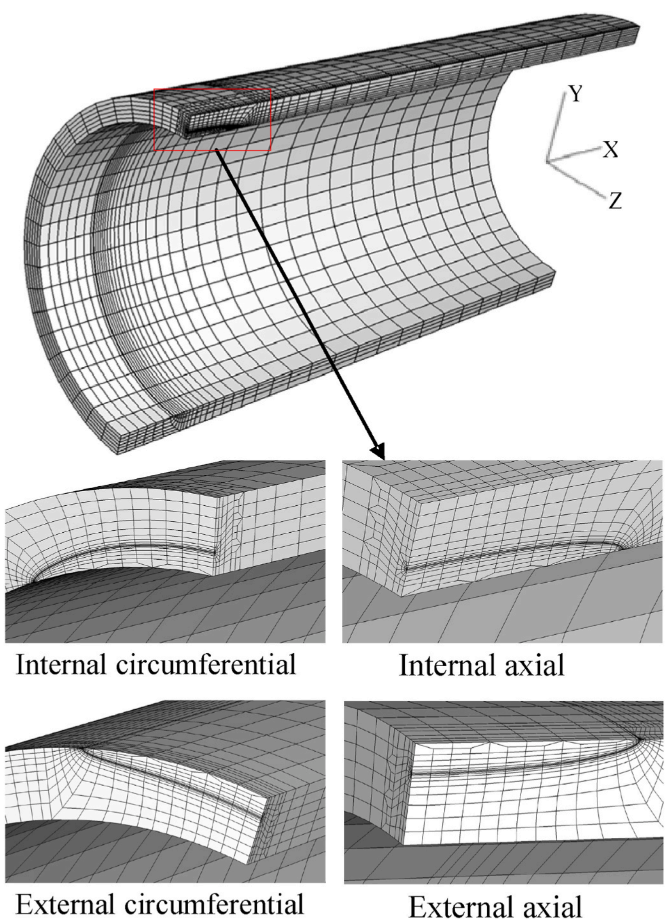

Fig. 4. Meshing model of the pipe and near the crack tips for the four positions.

$$\Delta H = \frac{a.u_0}{g} \tag{3}$$

where:

g: acceleration due to gravity (m/s^2);

u_0: initial velocity of the flow (m/s), such that: $u_0 = Q/S$

with:

Q: volume flow (m^3/s), for our case $Q = 0.15$ m^3/s, this flow is ensured by two pumps which operate simultaneously with a flow $Q = 75$ L/s for each; and.

S: pipe section (m^2).

The initial flow velocity (m/s) equal to:

$$u_0 = \frac{0.15}{0.11848088} = 1.26 m/s \tag{4}$$

Therefore, the total load taking water hammer considered is given by the equation below [19]:

$$H_T = H_g + \Delta H \tag{5}$$

with:

H_g: geodetic height difference in meters between the starting point and the highest point.

ΔH: load caused by the water hammer in meter (m).

So, the load taking into accounts the water hammer:

$$H_T = H_g + \frac{a.u_0}{g} = 0 + \frac{351.12 \times 1.26}{10} = 44.24 m \tag{6}$$

The maximum pressure caused by the water hammer phenomenon equal to:

$P_{max} = P_N + P_T$ (7) from where: $P_T = H_T \times 0.1 = 44.24 \times 0.1 = 4.42$ bars.

$P_{max} = 20 + 4.42 = 24.42$ bars

with:

P_{max}: maximum pressure (bars);

P_N: nominal pressure (bars); and.

P_T: the value of the pressure caused by the water hammer (bars).

So, we see that the maximum pressure caused by the water hammer is equal to 24.42 bars, that is to say a pressure difference of 4.42 bars. In Fig. 5, we have illustrated the effect of this pressure on the J-integral. The analysis of these results allows us to draw a conclusion that the pressure caused by the phenomenon of water hammer can cause a huge increase in the values of the J-integral on all positions on the crack front and especially on the crack front $\Phi = 0°$. This shows that the crack can initiate and propagate more easily along the X-direction than along the

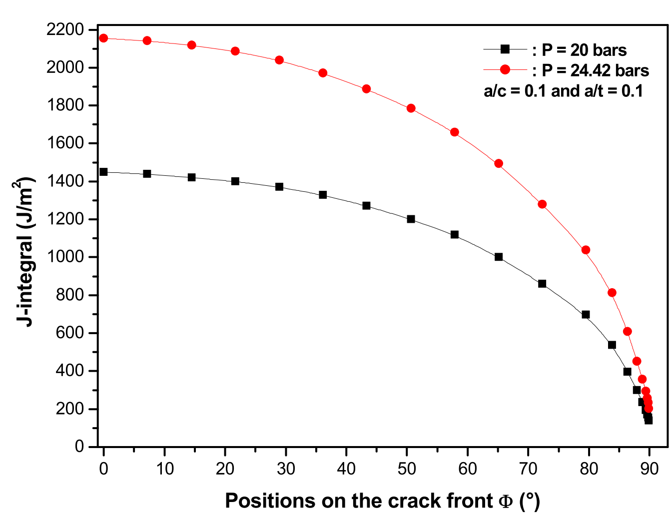

Fig. 5. Influence of the pressure caused by the water hammer on the integral J.

Y-direction, once these values of this integral exceed the critical threshold. This phenomenon can lead to the sudden rupture of the pipe ensuring the transport of water. Therefore, it can be concluded that the water hammer can harm our pipes because of the harmful effect of the sudden increase in internal pressure.

5.2. Crack position effect

The objective of this part of our study is to analyze the influence of the position of the crack on the value of the integral J. We considered four identical high-density polyethylene (HDPE) pipes of the same geometry (Fig. 2) submitted at internal pressures of 24.42 bars caused by the water hammer phenomenon and containing semi-elliptical cracks of length (2c) and depth (a), such that $a/c = 0.1$, located in four different positions (Fig. 1).

Fig. 6 illustrates the variation of the J-integral on the different positions on the crack front (Φ) and for the four arrangements of the cracks studied. The analysis of this figure shows that position 1 (Fig. 1a) leads to maximum values of the J-integral, this means that an internal longitudinal crack tends to propagate more easily than those of the other crack positions (Fig. 1 b, c, d). It is evident that the maximum of this integral is reached for the crack front $\Phi = 0^{\circ}$ whatever the position of the crack.

5.3. Effect of flow velocity

Flow velocity is an essential physical parameter in water transport. It is therefore important to analyze the effect of this parameter on the durability of the pipeline. This study was carried out on a pipe having an internal longitudinal crack presenting the maximum value of the integral J. To carry out this analysis, we used the same geometrical conditions of the preceding analysis, for that we chose three different speeds of flows 1.00 m/s, 1.26 m/s and 1.5 m/s. The results obtained are represented in Fig. 7. In this figure we have represented the variation of the integral J as a function of the positions on the crack front. The analysis of this figure allows us to say that whatever the flow velocity used, the value of the integral J decreases as one approaches the front of the crack $\Phi = 90^{\circ}$. The maximum value of this integral is marked on the position $\Phi = 0^{\circ}$, which indicates that the crack can initiate and propagate more easily along the *X*-direction than along the *Y*-direction. We find that an increase in the flow velocity leads to an increase in the J-integral at the crack front level. There is, therefore, a critical flow velocity beyond which the variation of the J-integral is very sensitive. Flow velocities exceeding this critical value can lead to rapid crack propagations, and therefore material failure.

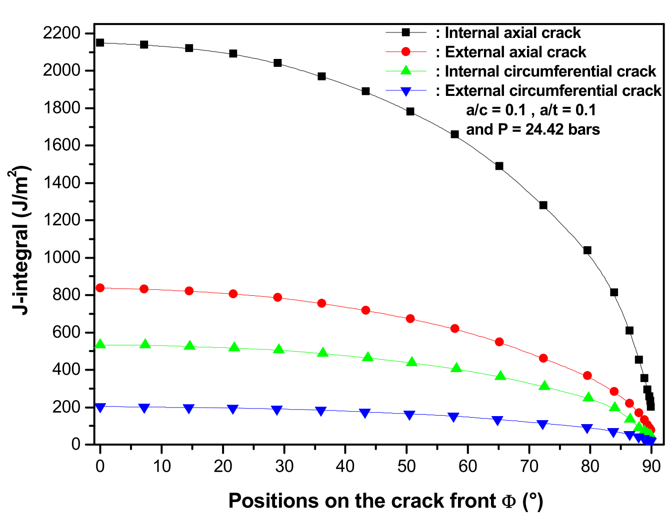

Fig. 6. Influence of the position of the crack on the integral J.

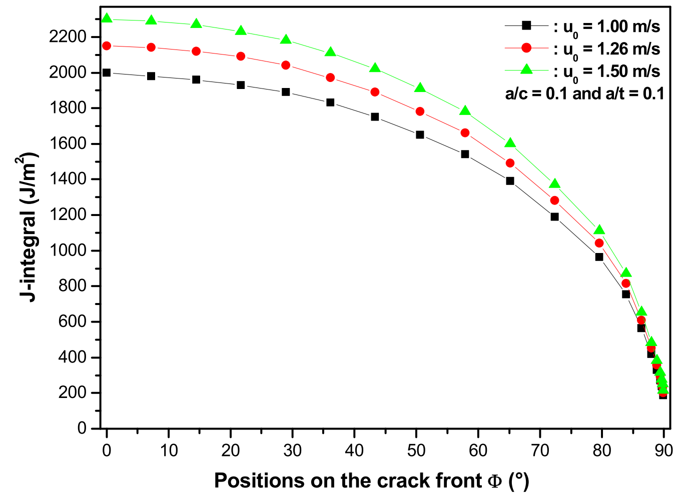

Fig. 7. Influence of flow velocity on the J-integral.

5.4. Effect of crack configuration

In this section, we studied the influence of the fault configuration on the variation of the integral J. This study was carried out on a pipe subjected to an internal pressure driven by the water hammer equal to 24.42 bars containing a crack internal longitudinal and an a/t ratio equal to 0.1. This effect is illustrated by Fig. 8, in which we have presented the variation of the J-integral as a function of the positions on the boundary of the crack for five different configurations ($a/c = 0.1$, 0.3, 0.5, 0.7 and 0.9). We observed from this figure that the configuration of the crack has a significant effect on the values of the integral J indeed. The defects which have semi-elliptical configurations present high values of the integral J at the level of the face $\Phi = 0^{\circ}$, this integral becomes less important in the position $\Phi = 90^{\circ}$ this shows that the crack can start and propagate more easily along the *X*-direction than along the *Y*-direction. The opposite case is observed for cracks of semi-circular configuration (a/c tends toward unity), which clearly shows that for these configurations the crack propagates better along the *Y*-direction than along the *X*-direction.

6. Conclusion

In this analysis, the J-integral was used to analyze the propagation criteria of a crack in a high-density polyethylene (HDPE) pipe subjected to an overpressure caused by the phenomenon of water hammer, the

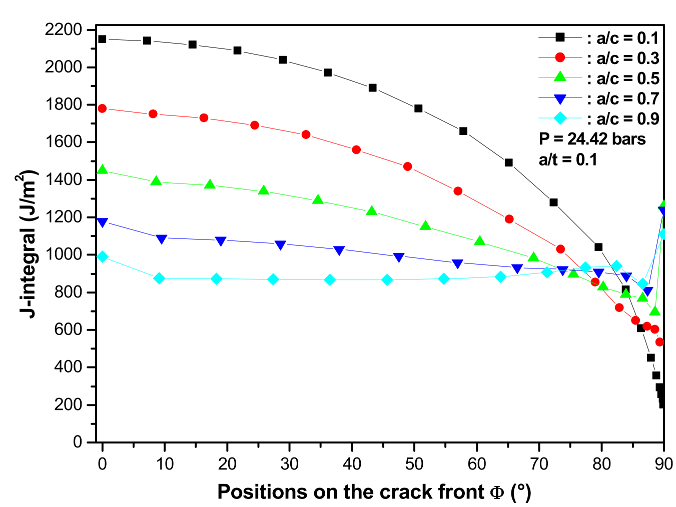

Fig. 8. Influence of the configuration crack on the integral J.

results obtained make it possible to draw the following conclusions.

- whatever the position on the crack front, the overpressure caused by the water hammer phenomenon can lead to a huge increase in the values of the J-integral. The increase in this failure criterion is significant at the crack front $\Phi = 0^\circ$. This behavior can have a detrimental effect on the durability of the pipeline.
- an internal longitudinal crack position tends to propagate more easily than other crack positions, and the maximum of the J-integral is observed for the crack front $\Phi = 0^\circ$ regardless of the position of the crack.
- the increase in the flow velocity leads to an increase in the J-integral at the crack front level, there is therefore a critical flow velocity beyond which the propagation of the crack is rapid, which facilitates the rupture of our pipeline.
- the direction of the propagation of the crack depends on its configuration. In other words, the cracks that have semi-elliptical configurations propagates more easily along the *X*-direction than along the *Y*-direction, whereas for the case of semi-circular configuration defects the cracks propagation is confined along the *Y*-direction rather than the *X*-direction.

Author contribution

Abdelkader Daikh: Data curation, Formal analysis, Investigation, Methodology, Visualization, Roles/Writing – original draft Laid **Aminallah**: Supervision, Conceptualization, Formal analysis **Ali Merdji**: Supervision, Investigation, Methodology **Laouni Gaidi**: Validation, Visualization **Hashem Alkhaldi**: Formal analysis **Sandipan Roy**: Methodology, Writing – review & editing, **Velaphi Msomi**: Review & editing Osama Mukdadi: Review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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