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Longitudinal dynamic fracture of polymer pipes

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To study the rapid crack propagation (RCP) resistance of polymer pipes, an experimental set-up and a numerical model are proposed. The way to solicit polymer pipes, imposed displacements or pressure, is discussed. Indeed, it has been demonstrated that it is necessary to load polymer pipe with imposed displacements and not internal gas pressure. For a pressurised pipe, a relevant estimation of the energy released rate is difficult because of the work of external forces which can not be precisely determined during crack propagation and of course during gas leak. An experimental set-up, with imposed displacements, has been machined to ensure an approximately \( L = 13R \) permanent RCP regime with \( L \) and \( R \) which are, respectively, the length and the radius of the pipe. The energy release rate is then calculated with the help of a finite element procedure knowing the crack tip location.

Keywords: rapid crack propagation; dynamic fracture; energy released rate; polymers; finite element

1. Introduction

The characterisation of polymer pipes fracture is a difficult matter since both viscoplasticity and inertial effects influence the dynamic of fracture (Beguelin, Fond, & Kausch, 1997, 1998; Ferrer et al., 1998). Indeed, it has been shown that the fracture energy of polymer varies considerably with the crack tip velocity which is in the range

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of a fraction of Rayleigh waves speed (Fond & Schirrer, 1997, 1998). Moving cracks have been extensively studied for many years (Broberg, 1960; Cros, Rota, Cottenot, Schirrer, & Fond, 2000; Freund, 1972; Greenshields & Leevers, 1996; Irwin et al., 1979; Rosakis & Zehnder, 1985; Sheng & Zhao, 2000; Yoffe, 1951). It has been demonstrated, considering mode I, that the energy release will vanish for crack-tip velocities approaching the Rayleigh waves speed. For a given isotropic material of \(\rho\) density, \(\mu\) shear modulus and \(\nu\) Poisson’s ratio, the Rayleigh waves speed \(c_r\) is given with an accuracy of \(\pm 0.6\%\) by \(c_r \pm \sqrt{\frac{2\mu}{\rho}} (0.878 + 0.2v - 0.05(v + 0.25)^3)\). Otherwise, it is admitted that the formalism of linear elastic fracture mechanics (LEFM) can be used because of the containment of the fracture process zone (Anderson, 2005; Dally, 1979; Kalthoff, 1985; Mauzac & Schirrer, 1992; Sharon & Fineberg, 1999). In this paper, a first part will describe the finite element model used to calculate the dynamic energy release rate \(G_{Id}\) (Anderson, 2005; Greenshields, Venizelos, & Ivankovic, 2000; Nilsson, 1972; O’donoghue, Kanninen, Leung, Demofonti, & Venzi, 1997; Popelar & Atkinson, 1980) for crack running in pre-stressed and pressurised polymer pipes. And a second part will present the “home made” experimental set-up which ensures rapid crack propagation (RCP) in pre-stressed polymer pipes. Finally, the interest to load polymer pipes with imposed displacements and not gas pressure will be discussed.

2. Finite element model

2.1. Finite element mesh

The mesh is a model of a half pipe, using the symmetry of the structure to be fractured. 4-nodes tetrahedron, 6-nodes prisms, 8-nodes cubes and 20-nodes cubes have been tested. Best results were obtained for 20-nodes elements and 8-nodes. For a good compromise between accuracy and computation time, each element corresponds to an angle of \(2^\circ\). It is currently admitted that linear elastic fracture mechanics (LEFM) models are suitable for analysing the dynamic fracture of polymers (Dally, 1979; Kalthoff, 1985; Mauzac & Schirrer, 1992; Sharon & Fineberg, 1999). Besides, as shown in previous analysis concerning mainly the steady-state regime of a dynamic fracture (Ferrer et al., 1998; Fond & Schirrer, 1998), the usage of special fracture elements at crack tips is not necessary to compute the energy release rates. In fact, the energy release rates are computed by differentiating the elastic energy integrated on the whole structure. As the geometry ensures a quasi-steady-state regime of propagation, it is assumed that a specific treatment of the singularity is not necessary since the error done concerning the energy integration at crack-tip singularity is eliminated by differentiation. The element type is selected by modelling of the dynamometric ring problem. Firstly, the analytical solution is computed. Considering quasi-static loadings, derived from the beam theory (BT), Equation (1) gives the solution of the energy release rate as a function of displacement for the dynamometric ring. This solution assumed a linear elasticity. We recall that, according to the \(S^2\) Venant hypothesis, pressures applied inside the pipe, in the case of imposed displacement at the poles, can be replaced by concentrated forces, and according to the Navier–Bernoulli assumption, plane sections remain plane.

\[
G_{IBT} = \frac{8\pi E(R_e - R_l)^2 \delta^2}{3(\pi^2 - 8)(R_e + R_l)^3}
\]  (1)
2.2. Boundary conditions

Part of boundary conditions are taken to avoid rigid body displacements. The initial imposed null displacements along the crack path are then withdrawn to simulate the crack propagation. Two loading types are considered before the fracture. The first one considers imposed parallel displacements at the poles of the pipe with variable widths. The second one considers a uniform pressure inside the pipe. The latter one is a more or less realistic point of view only for crack running at speed larger than the sound waves speed in the gas ensuring pressure or in the case of decompression baffles inside the pipe for small-scale steady-state (S4) test (Greenshields & Leevers, 1996). For smaller crack speed a complex interaction between fluid and solid should be accounted for, included the loss of gas through the opened crack. This last point induces heavy problems to solve and is not accounted herein. Nevertheless, it is noticeable assuming that the pressure does not vary during fracture gives an upper bound of the work done by external forces, i.e. by pressure in the deformation of the pipe.

2.3. Crack length increase, time integration scheme and energy release rate computation

To simulate the opening of the crack, boundary conditions are changed between two successive computing steps. The nodal forces of the crack tip are released linearly with time during the iterations of a step. The classical $\theta$-method implemented in the CAST3M© software is used with $\theta=0.5$. Since the crack opening induces heavy numerical instabilities, it is necessary to use a damping matrix to ensure the convergence of computations. The classic systems of equations to solve is:

$$M \cdot \ddot{U} + C \cdot \dot{U} + K \cdot U = F$$

where $M$ represents the mass matrix, $C$ the damping matrix and $K$ the rigidity matrix. $F$ is the nodal loading forces and $U$ the nodal displacements. In order to keep as far as possible a realistic LEFM model, the damping matrix $C$ is set to the most minimal values. Moreover, $C$ is chosen to be proportional to the rigidity matrix $K$ such that the damping acts as a Newtonian viscosity of the material. In practice, $C = \frac{10^{0.7}}{a} K$ during the quasi-static loading and $C = \frac{10^{0.4}}{a} K$ during the crack propagation can ensure a good reduction of numerical noise. Concerning the quasi-static loading, the damping has a negligible effect on the result which can be considered as an elastic solution. Concerning the dynamic crack propagation, the way that the damping is implemented, proportional to the rigidity, allows to consider the damping as something between a linear viscosity and internal friction. For polymer materials, in absence of precise definition of the behaviour law for the anelasticity, this implementation maintains a physical meaning for energy dissipation, which is a good compromise between the real material behaviour and the hypothesis of LEFM. Hence, the present results are expected to be representative of elastic model. For most results presented herein, at least 10 time steps are computed for each crack length increase and 60 crack length increases are considered for a fracture. The energy release rate is computed by assuming LEFM (i.e. no body dissipation in the material) in the Griffith energy balance way such that:

$$G_I = \frac{\Delta W_{ext} - \Delta W_{ela} - \Delta K_{cin} - \Delta W_{dis}}{B \Delta a}$$

(3)
where \( W_{\text{ela}} \) represents the elastic energy, \( K_{\text{cin}} \) is the kinetic energy, \( W_{\text{ext}} \) and \( W_{\text{dis}} \) are the work done by external forces and the bulk dissipated energy both integrated over the entire structure. The energy release rate is estimated as a function of the amount of projected area \((B \Delta a)\) The dissipated energy \( W_{\text{dis}} \) does not involve non linear behaviour in the process zone. Indeed, the fracture toughness \( G_{\text{lc}} \) account for non linearities in the process zone by setting \( G_{\text{lc}} = G_I \) for crack length increasing. LEFM is valid since the process zone is sufficiently confined and \( W_{\text{dis}} = 0 \).

3. Numerical simulations of the fracture propagation in pipes

3.1. Modelling of the moving crack in a pipe pre-stressed by imposed displacements at the poles

A typical finite element model of the fracture propagation is shown in Figure 1. The dimensions of the modelled pipe are \( R = 4.83B \) and \( L = 20R_c \). The crack tip velocity is \( 0.35c_r \). The displacements as shown in Figure 2 are magnified by 50. The evolution of the elastic energy density could be visualised as a function of the structure opening.

For a pre-stressed pipe, it appears that a quasi-constant energy release rate can be obtained after a length larger than 5 times of the external radius \( R_c \). Complete simulation results, with the crack tip velocity varies from \( 0.01c_r \) to \( 1.1c_r \), are shown in Figure 3 for the pipe whose radius \( R \) is 4.83 times of the thickness \( B \). We can firstly observe that the quasi-staticity prevails when the crack-tip velocities are less than \( 0.1c_r \). And the validity of the numerical results is reconfirmed for quasi-static cases by comparing them to the approximate solutions given Equation (1). Due to the border effect, the energy released rates increase when the crack tips approach the opposite border within a distance of about 2 times of \( R_c \). When the crack velocities are between \( 0.1c_r \) and \( 0.5c_r \), the energy release rate increases continuously with the crack length, and as expected, decreases with the crack velocity. For the cases where the crack velocities are more than \( 0.5c_r \), the energy release rate stabilises when the crack lengths are larger than 5 times of \( R_c \).

3.2. Modelling of the moving crack in a pipe under pressure

According to the numerical results, the dynamic energy release rates are compared to the \( G_{R0} \) which is computed without the variation of the work of external forces. Figure 4
shows the ratio between $G_{Id}$ and $G_{I0}$ for the pipe whose radius $R$ is 4.83 times of the thickness $B$. The simulated moving crack has a velocity which varies from 0.01$c_r$ to 1.1$c_r$. As the results of the strained pipes, the energy released rates stabilise after a crack length of 5$R_e$ and decrease with the crack velocity. Nevertheless, the dynamic energy release rate $G_{Id}$ of the quasi-static (0.01$c_r$) state is about 300 times of $G_{I0}$. It means that the elastic energy released from that stored in the structure becomes a second-order parameter in the energy balance sheet. The value of $G_{Id}$ is in the case of pressurised pipe dominated by the work of external forces.

3.3. Experimental set-up for cracks running in a strained pipe

The material under study is a polyamide 11 (PA11) BESNO TL grade provided by ARKEMA. It was supplied as pieces of pipe, initially extruded. The PA11 under study is a semi-crystalline polymer. Differential scanning calorimetry analysis has been performed to estimate the degree of crystallinity of 22%.

An experimental set-up was designed and machined to ensure RCPs in polymer pipes. The loading method is presented in Figure 5. The main objective is to pre-stress as uniformly as possible polymer pipes with imposed interior displacements ($\delta$).
Displacements are imposed with two metallic tappets ($E \approx 210$ GPa (Sadd, 2010)) in contact with the internal wall of the pipe. Metallic tappets are machined to be in the best possible contact with the pipe. The entire test is performed at approximately room temperature. To take account time-dependence of polymer materials, the crack is initiated after a significant relaxation time (typically 15 times the loading time) with the help of an impact on a razor blade in contact with the notch tip.

4. Results

Figure 6 presents pictures, captured using a high speed camera, of a RCP in polymer pipes, typically PA11. It is observed that the crack tip velocity does not change during the propagation $\dot{a} \approx 420 \pm 20$ m s$^{-1}$, whatever be the crack propagation configuration (i.e. branching or not). This typical velocity ($\dot{a} \approx 0.6c_r$) is known to be the branching velocity. One can observe in Figure 6, the main crack branches between $A$ and $B$ points.

The quasi-static averaged fracture energy $G_{\text{av}}$ is estimated with the help of Equation (1) to be equal to approximately $7.5 \pm 0.9$ kJ m$^{-2}$. At $0.6c_r$ with an averaged dynamic correction of 0.35 estimated with the help of numerical results (see Figure 3), the
averaged dynamic fracture energy \( \langle G_{Idc} \rangle = 2.6 \pm 0.3 \text{ kJ m}^{-2} \) with the dynamic elastic modulus is \( E_d \approx 1600 \text{ MPa} \).

5. Discussion and conclusion

A numerical model and an experimental set-up have been elaborated to study the longitudinal dynamic fracture of pipes. Concerning the model, which was validated using analytical reference (Broberg, 1960), energy release rates have been calculated for cracks running in pre-stressed (by imposed displacements) and pressurised pipes. Numerical computation are stabilised using a damping matrix proportional to the rigidity matrix which agrees physical justification with the viscosity of polymer materials. This parameter is always set to be a second-order term in the calculation. The energy release rate \( G_{ld} \) obtained for a radius \( R \) which is 4.83 times of the thickness \( B \) is sensitively different between a crack running in pre-stressed or pressurised pipe. For pressurised pipe, the internal gas pressure is considered to be constant even during the propagation, i.e. the main crack is running faster than the decompression waves in the gas. The work of external forces which dominates in the Griffith energy balance is significantly higher than the elastic energy stored in the structure. That is why, in quasi-static \((0.01c_v)\), the dynamic energy release rate \( G_{ld} \) state is about 300 times of \( G_{f0} \). A relevant \( G_{ld} \) is also complicated to have without a special calculation of the pressure dissipation during the crack propagation in pressurised pipe. To obtain a material information to RCP resistance, we propose an experimental set-up associated to a numerical model for pre-stressed pipes. Indeed, experimental set-up allows to have an approximately \( L \approx 13R \)
permanent dynamic propagation regime which \( F(\delta) \) is known from BT. Fracture energy \( G_{\text{fr}} \approx 2.6 \pm 0.3 \text{ kJ m}^{-2} \) is then estimated at 0.6\( c_r \) for a typical semi-crystalline pipe using a finite element procedure. This value seems to be in agreement with the literature (Huang & Paul, 2006).

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References


