

Research Article

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Numerical study of cracking a medium elastic viscoplastique of polyacetal

<https://doi.org/10.2478/mme-2019-0017>

Received May 20, 2018; revised Sep 11, 2018; accepted Nov 20, 2018

Abstract: The objective of this work is the analysis of the fracture behavior of a *SENB* cylinder with a defect where stress triaxiality is more severe. Numerical simulations are carried out in a 2D mode, to overcome a disadvantageous hypothesis plane strain or plane stress. The mesh sensitivity studies were also undertaken but are not presented here. Indeed, only the results for the most relevant mesh are the subject of the discussion.

Keywords: fractures mechanics, crack propagation, J -integral, statics, polyacétal

1 Introduction

Among the failure modes of structures, fracture is the most feared phenomenon because of its severity, which makes preventive action difficult. Therefore, understanding this phenomenon is generating interest from manufacturers who want to develop the means for forecasting. The mechanical behavior of materials under elastic and plastic deformation, creep, fracture, and fatigue deserves a great interest in the scientific community and many researchers are working on these topics [1].

Nowadays, thermoplastic polymers are widely used in engineering applications (e.g. Haward and Young [2]). Among these materials, polyacetal (POM) is widely employed in urban networks of water and gas distribution.

The presence of a defect in a polymer pipe can generate leaks, leading obviously to economic/environmental prejudices and on the extreme, it can provoke a brutal fracture leading to more severe consequences. That is the reason why the quantification of the crack resistance of such structures is of prime importance [3]. The static bending of edge cracked micro beams is studied analytically under uniformly distributed transverse loading based on modified couple stress theory [4].

This kind of approach obviously cannot be applied in industries such as energy transport, manufacturing prostheses where particularly stringent security requirements require a detailed study of the behavior. Rather than introducing empirical safety factors at all levels (manufacture, use ... etc.), it seems that a more efficient method is to predict the evolution of a structure in the worst case.

The safety margin can then be defined by knowledge of what is causing defects. An important step has been taken in this direction with the fracture mechanics [5]. It is a tool that has proven itself in the description of the behavior of structures containing defects in an elastic medium. The extension to the case of materials having a nonelastic behavior still poses many problems. Thus, in the case of the elastic-plastic material or elastic-viscoplastic, using criteria based on the quantities K, J, \dots etc. remains delicate. [6–12]. However, the polymer materials have a complex microstructure. The co-existence and interaction of chains having a viscous nature are responsible for the complexity of their macroscopic behavior that could fall within the scope of elasto-visco-plastic behavior.

Given this complexity, it is necessary to ensure that the initiation and propagation laws formulated within the framework of classical rupture mechanics suitable for POM. This paper discusses the relevance of a numerical point of view method from the fracture mechanics to study the breakdown of POM.

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Table 1: Norton parameter

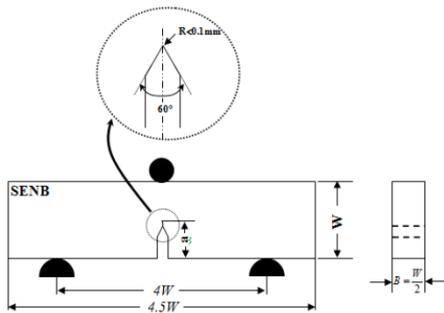
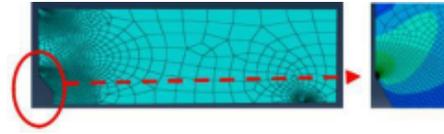
$d\epsilon/dt(S^{-1})$	$\ln(\sigma_y)$	$\ln(d\epsilon/dt)$	A	N
0.1	4.09	-2.30		
0.01	4.00	-4.60	2.84 E-64	35
0.001	3.97	-6.90		

2 Parameters identification of the visco-plastic behavior law

3 Specimen geometry

The bending test is a mechanical test used to test the resistance of a bending material. They are the so-called three-point bending and four-point bending. The one we have decided to use is also the most common, that is, three-point bending. A solution lies in a mesoscopic approach of seeking a law to locate the ultimate strength of the material for a plane stress state. Tests on rectangular plates in bending were made and in order to validate our approach, the calculation has been implemented in a nonlinear finite element [13].

In order to analyze the mechanical behavior at breakdown for large-pipe deformation in POM, numerical simulations were performed on a specimen under three-point bending with lateral fissure single-edge notched bend (SENB). Several authors have recommended the use of this type of specimen to characterize the fracture resistance of pipes through energy approaches such as the integral J , [6, 15].

**Figure 1:** Geometry of SENB specimen**Figure 2:** Geometric representation bending three points by ABAQUS

4 Governing equations

The integral J was developed by Lairinandrasana *et al.* [7, 16] and was used as an alternative to the stress intensity factor in the case of an elastoplastic behavior. The integral J is defined for a two-dimensional problem by the following equation:

$$J = \int_{\Gamma} W dy - \int_{\Gamma} T \left(\frac{\partial u}{\partial x} dx \right) \quad (1)$$

In this equation, (x, y) are the coordinates normal to the crack front, W is the strain energy density, T is the stress vector at the outer side of the contour Γ surrounding the crack tip, u is the displacement and x is the arc length.

The J integral, under elastic assumption, is the potential energy decrease per unit area required to create new surfaces. This energy interpretation of J allows to write it under the following form:

$$J_{pl} = -\frac{1}{B} \frac{dU_{pl}}{da} \quad (2)$$

where B is the specimen thickness, a is the crack area and U_{pl} is the potential energy. For ductile fracture, the potential energy is replaced by the total work (*i.e.* the area under the load–displacement curve). But, in this case, the J parameter includes both the energy required for crack propagation and that dissipated in plastic deformation.

Many methods to experimentally determine the J parameter were proposed in the literature. By using the energy interpretation of J in Eq. (2), Begley and Landes [17] introduced their so-called multispecimen technique. To minimize the number of the required specimen, several single-specimen methods were also proposed following the pioneering works of Rice and Merkle [18, 19]. Briefly, the authors state that if the applied load could be written in a separable multiplicative form depending on the crack length and on the applied displacement, then J can be also seen as a multiplicative form of a geometrical factor η (generally depending on the normalized crack length) and the expended energy per unit area of remaining crack ligament:

$$J = \frac{\eta U}{B(W - a)} \quad (3)$$

where η is a parameter defined by Clarke and Landes, [20, 21].

For elastic-plastic problems, the J integral could be divided in two components. Sumpter has expressed J as the sum of elastic and plastic components, J_{el} and J_{pl} , respectively:

$$J = J_{el} + J_{pl} \tag{4}$$

where

$$J_{el} = \frac{\eta_{el}U_{el}}{B(W-a)} \quad \text{and} \quad J_{pl} = \frac{\eta_{pl}U_{pl}}{B(W-a)} \tag{5}$$

The terms η_{el} and η_{pl} are elastic and plastic correction factors that depend on the specimen geometry. U_{el} and U_{pl} are the elastic and plastic area under the load versus load-line displacement curve, respectively. W and B are respectively the thickness and width of the specimen, a is the crack length.

Generally the elastic part of the J integral could be also determined by using the compliance method or derived from stress intensity factor calculations. For the plastic part, it is necessary to identify the η_{pl} factors for each geometry. This could be done by using the finite element method or experimental data. Note that for SENB specimens, the geometry factor was found constant in a given interval of normalized crack length:

$$0.4 < \frac{a}{W} < 0.6 \text{ and } \eta_{pl} = 2 \tag{6}$$

In our work, we consider that the method proposed by Sharobeam and Landes [22] for the determination of the plastic factor η_{pl} . This method is based on the charge separation event.

Another way to get η_{pl} estimates consists in using the load separation criterion following the procedure given by Sharobeam and Landes [22]. The authors state that, if the applied load could be written in a multiplicative separable form of two functions, namely, a crack geometry function G and a material deformation function H :

$$P = G\left(\frac{b}{W}\right) H\left(\frac{\delta_{pl}}{W}\right) \tag{7}$$

Then, J_{pl} could be written in the form of relation (5). In Eq. (7), b is the remaining ligament length. To check the validity of Eq. (7), a separation parameter S_{ij} defined as the ratio of loads $P(a, \delta_{pl})$ of same specimens but with two different crack lengths $a(i, j)$ must be found constant over the whole domain of the plastic displacement:

$$S_{ij} = \frac{P(a_i, \delta_{pl})}{P(a_j, \delta_{pl})} \Bigg|_{\delta_{pl}=\text{const}} = \frac{G\left(\frac{b_i}{W}\right)}{G\left(\frac{b_j}{W}\right)} \Bigg|_{\delta_{pl}=\text{const}} \tag{8}$$

5 Results and discussions

As indicated in the literature, the breakdown of calculations was carried out with a speed ratio equal to $(w/10)$. To highlight the first characteristic elements of the failure mode of POM, and check the feasibility of the method of calculation used to characterize the toughness, we will first present the evolution of the plastic energy for all crack lengths considered in this study and for the same plastic displacement.

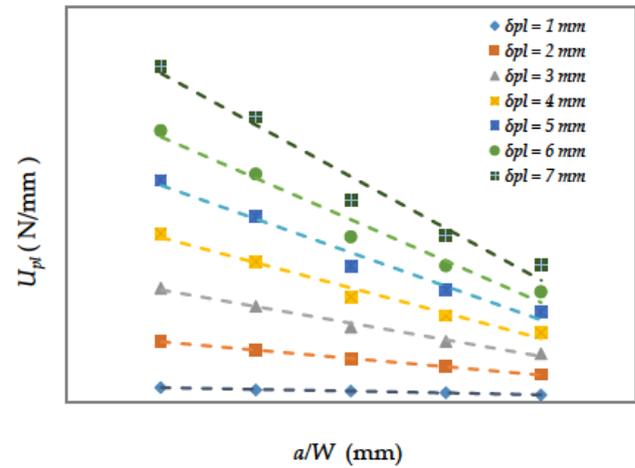


Figure 3: Plastic energy versus the normalized crack length fitted by straight (dashed lines) functions for SENB specimens

Figure 3 shows the change of the plastic energy relative to the specimen thickness (U_{pl}) versus the crack length. For many identical plastic displacement values, changes in energy can be estimated linearly as a first approximation. However, it was found that the plastic energy depends on the initial crack length and the imposed displacement. At this stage, we can estimate the slope obtained as a crack propagation rate.

Figure 4 shows a representative example of the evolution of this parameter as a function of the plastic displacement for a given reference b_j in the typical case of the SENB specimen configuration. It is clearly pointed out that the separation parameter is constant except for smallest plastic displacement values. Even this evolution is only shown for a given reference and specimen geometry, the same trends are observed in the other cases.

The evolution of the separation parameter S_{ij} versus the ratio (a/W) is shown in Figure 5-a. We notice similar trends for the five considered crack lengths.

As mentioned in the previous section, in order to determine the form factor η_{pl} , we have integrated the loga-

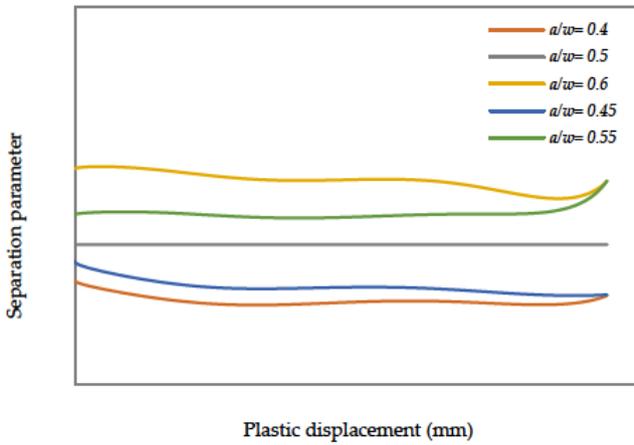


Figure 4: Separation parameter versus the plastic displacement for a SENB specimen (reference $a/b = 0.5$)

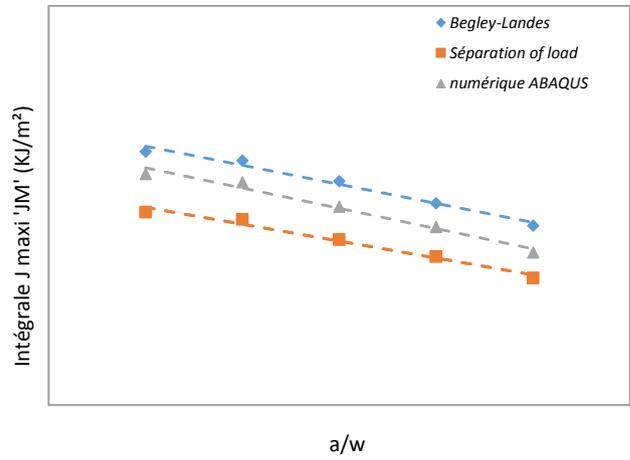


Figure 6: J_M evolution versus to a/w for the three methods

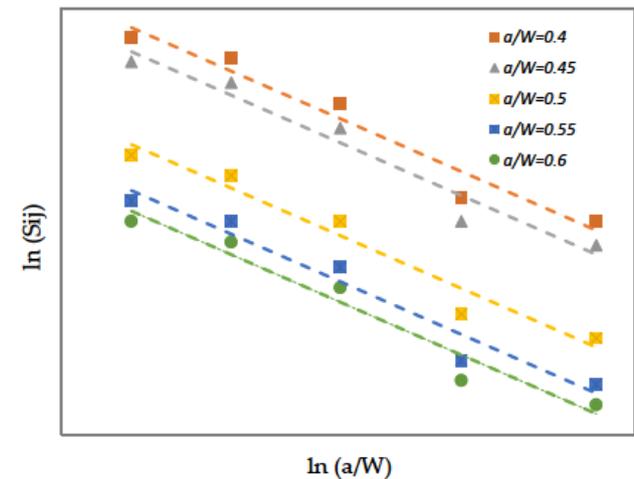
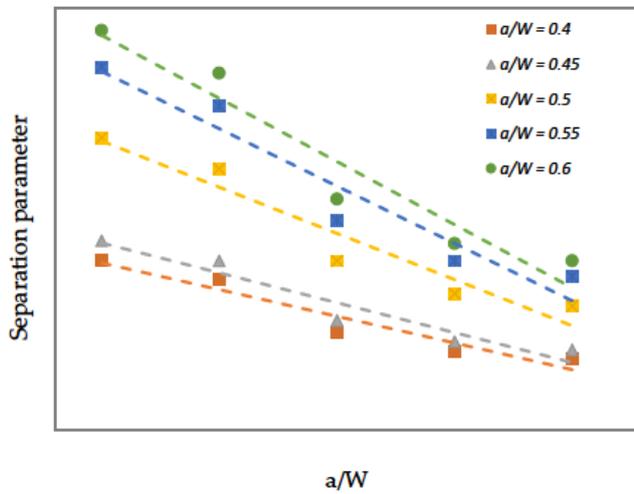


Figure 5: Evolution of the separation parameter: a) S_{ij} versus to $\frac{a}{W}$; b) $\ln S_{ij}$ versus to $\ln \frac{a}{W}$

ritms in each of both the functions (separation parameter S_{ij} and the ratio (a/W) and we have drawn their evolution in Figure 5-b. The slope of each line represents the plastic form factor η_{pl} .

In Figure 6, J_M values obtained for any length of crack and the three integration methods are presented. For each method, taken separately, we found that the value of J_M is independent of the crack length. However, the values found for each method are relatively for a part. We can thus conclude that J_M is not an intrinsic material parameter, since it depends on the geometry and the type of test (and thus load conditions).

6 Conclusions

This study was conducted to study the fracture behavior of POM, while using the approaches of fracture mechanics. Five types of tests were carried out to highlight the main features of the fracture behavior. This is three-point bending test (SENB) of Charpy ductility on SENB. The results show a very ductile behavior of POM characterized by the existence of a large phase of plastic deformation. This extended lamination leads to drawback of the comprehensive approach by the J integral since no priming is detected. We were unable to access J_{IC} values through the energy approach for the test geometry (SENB).

Finally, the distributions of strain along the ligament were compared at the time of necking and at the time of rupture. Qualitatively, the results are consistent. From a quantitative point of view, it is necessary to improve the method and calculation model.

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