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Determination of the crack resistance curve for intralaminar fiber tensile failure mode in polymer composites under high rate loading

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ABSTRACT

This paper presents the determination of the crack resistance curve of the unidirectional carbon-epoxy composite material IM7-8552 for intralaminar fiber tensile failure under dynamic loading. The methodology, proposed by Catalanotti et al. (2014) for quasi-static loading conditions, was enhanced to high rate loading in the order of about 60 s^{-1}. Dynamic tests were performed using a split-Hopkinson tension bar, while quasi-static reference tests were conducted on a standard electromechanical testing machine. Double-edge notched tension specimens of different sizes were tested to obtain the size effect law, which in combination with the concepts of the energy release rate is used to measure the entire crack resistance curve for the fiber tensile failure mode. Digital image correlation is applied to further verify the validity of the experiments performed at both static and dynamic loading. The data reduction methodology applied in this paper is suitable for intralaminar fiber failure modes without significant delamination. Sufficient proof is given that quasi-static fracture mechanics theory can also be used for the data reduction of the dynamic tests. It is shown, that the intralaminar fracture toughness for fiber tensile failure of UD IM7-8552 increases with increasing rate of loading.

1. Introduction

Using energy-based damage models ([2–9] among others) is a promising approach to further enhance the prediction quality of composite simulation models. In these models, the softening law for each failure mode is defined by the fracture toughness and related crack resistance curve (R-curve) [10], which has to be measured experimentally.

For the measurement of the intralaminar fracture toughnesses for fiber tensile failure, the compact tension (CT) specimen, originally developed for the fracture toughness characterization in metals [11,12], is commonly used [13–19]. In contrast to the centre-notched (CN) [20–26], the double-edge notched (DEN) [27–29] and the four-point bending (4 PB) [27] specimens, the CT specimen shows a stable crack propagation, which enables the determination of the R-curve. Unfortunately, the CT specimen has several limitations: i) the tendency of buckling/twisting at the back side (because of the reduced thickness of the specimen [30] or because of the high load that occurs especially when testing high toughened material systems [31]); ii) failure at the back side (because the compressive stress reaches the compressive strength of the material); and iii) failure at the load introduction point.

Overcoming these limitations of the CT specimen, Catalanotti et al. [1] recently measured the fracture toughness for fiber tensile failure using double-edge notched tension (DENT) specimens and the size effect law. The proposed methodology was also used for the determination of the R-curve at further loading conditions: i) mode I in compression [32] (allowing for the first time the measurement of the full R-curve associated with the propagation of a kink-band); ii) mode II in shear [33]; and iii) testing at extreme environmental conditions [34].

To enable the reliable simulation of highly dynamic loading events (e.g. crash, foreign object impact), the strain rate sensitivity of the material properties should be known. Under dynamic loading conditions, no standardized tests exist to measure neither the elastic properties, nor the strength, nor the fracture toughness. Nevertheless, as a result of many studies over the past decades, the strain rate dependency of the stiffness and strength of polymer composites is well known and corresponding review articles were presented by Sierakowski [35] and Jacob et al. [36]. Regarding the dynamic characterization of fracture properties, there is no agreement neither on the rate definition (e.g. as a function of strain rate or crack growth rate) nor on the best suitable experimental and analysis procedure [37].

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A methodology to measure the mode I dynamic intralaminar R-curve for compressive fiber failure was recently proposed by Kuhn et al. [38]. Using a split-Hopkinson pressure bar (SHPB), which is a widely-used setup for dynamic fracture tests [39], the R-curve for fiber compressive failure was determined for the carbon-epoxy material IM7-8552 by testing double-edge notched compression (DENC) specimens of different sizes at a strain rate of about 100 s^{-1}. The steady-state value of the fracture toughness under dynamic loading was found to be 63% higher than the quasi-static reference value. DENC specimens were also tested at an SHPB in a recent study by Leite et al. [40], who tested woven carbon-epoxy specimens at strain rates up to 770 s^{-1}, noticing a significant increase of the compressive fracture toughness with increasing strain rates.

In the presented work, the methodology proposed by Catalanotti et al. [1] to measure the quasi-static R-curve associated with the fiber tensile failure mode is extended to dynamic loading. The R-curves for both quasi-static and high rate loading are obtained by using the relations between the size effect law, initially proposed by Bažant and Planas [41], the energy release rate (ERR) and the R-curve. For the determination of the size effect law, a split-Hopkinson tension bar (SHTB) compatible DENT specimen configuration is used, enabling a symmetric stress state and therefore the desired mode I loading condition during the dynamic tests. Following [42], this would not be the case when testing CT specimens under dynamic loading, as the unsymmetrical opening of the CT specimen, caused by inertia effects, would induce mixed mode fracture in the specimen.

2. Analysis scheme

According to the peak load condition in fracture mechanics, the energy release rate curve, G_I, of a so-called positive geometry (G_I is an increasing function of the crack length a) is tangent to the R-curve, R, at the peak load, P_u. This relationship is described by the following system of equations (and visualized in Fig. 3) [41]:

$$\begin{cases} G_I(\Delta a) = R(\Delta a) \\ \frac{\partial G_I(\Delta a)}{\partial \Delta a} = \frac{\partial R(\Delta a)}{\partial \Delta a}. \end{cases} \tag{1}$$

where Δa is the crack increment. Considering a two-dimensional orthotropic body in plane-stress, with the principal material directions x and y, and supposing the crack propagates along the x-direction, the energy release rate under mode I loading reads [43]:

$$G_I = \frac{1}{\acute{E}} K_I^2 \tag{2}$$

in which K_I is the stress intensity factor and $\acute{E}$ is the equivalent modulus. According to Suo et al. [43] the latter is defined as:

$$\acute{E} = \left(s_{11}s_{22}\frac{1+\rho}{2}\right)^{-1/2}\lambda^{1/4} \tag{3}$$

with the dimensionless elastic parameters λ and ρ defined as [43]:

$$\lambda = \frac{s_{11}}{s_{22}}, \tag{4}$$

$$\rho = \frac{2s_{12} + s_{66}}{2\sqrt{s_{11}s_{22}}}. \tag{5}$$

λ is an indicator of the laminates degree of orthotropy and s_{ij} are the laminate compliances. Supposing that the crack is propagating in a balanced cross-ply laminate ($[0/90]_{ns}$),as normally done when measuring the intralaminar fracture toughness of the ply [44], $s_{11} = s_{22}$, $\lambda = 1$ and Eq. (3) reads:

$$\acute{E} = E\left(\frac{1+\rho}{2}\right)^{-1/2} \tag{6}$$

where E is the laminate Young's modulus ($E = E_x = E_y$).

The stress intensity factor, K_I, depends on the specimen geometry and can be written for a double edge notched tension (DENT) specimen (Fig. 1) as [43,45]:

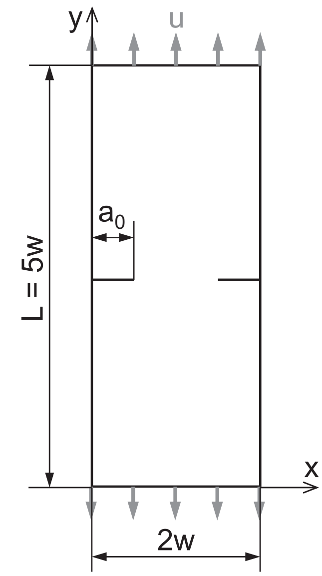

Fig. 1. Double edge notched tension (DENT) specimen.

$$K_I = \sigma\sqrt{w}\sqrt{\kappa(\alpha, \rho, \zeta)} \tag{7}$$

in which σ is the remote stress and w is the characteristic size of the specimen (see Fig. 1). $\kappa(\alpha, \rho, \zeta)$ is the dimensionless correction factor for geometry and orthotropy written as a function of the dimensionless parameters $\alpha = a/w$, $\zeta = \lambda^{-1/4}\xi$, and $\xi = w/L$, where L is the free length of the specimen. Placing Eq. (7) in Eq. (2), G_I yields:

$$G_I(\Delta a) = \frac{1}{\acute{E}} w\sigma^2\kappa\left(\alpha_0 + \frac{\Delta a}{w}, \rho, \zeta\right) \tag{8}$$

where $\alpha_0 = a_0/w$ is the initial value of the shape parameter α (see Fig. 1).

To simplify the calculation of the correction factor, the free length of the specimen is scaled with the characteristic size w ($L = 5w$ as shown in Fig. 1). Keeping in mind that the variable λ is constant and equal to 1 since the laminate is a balanced cross-ply, the correction factor will only depend on two variables α and ρ, since ζ is now kept constant. Since an analytical solution is not available, $\kappa(\alpha, \rho)$ can be calculated numerically using the Virtual Crack Closure Technique (VCCT) [46]. Following [1], a Finite Element (FE) model of the DENT specimen is built in the commercial software Abaqus [47]. A quarter of the specimen is modeled as shown in Fig. 2, and loaded applying appropriate symmetries and a uniform displacement u at the edges of the free length. For a two dimensional model with four-noded elements, the energy release G_I under mode I loading in consideration of the symmetric boundary conditions reads [46]:

$$G_I(a, \rho) = -Y_m(a, \rho)u_n(a, \rho)/l_e \tag{9}$$

where a is the crack length, Y_m and u_n are the load and the displacement in the y-direction of the nodes m and n, respectively, and l_e is the element size in x-direction (see Fig. 2). Placing Eq. (9) into Eq. (8) and applying σ, which is also available from the FE simulation, yields $\kappa(\alpha, \rho)$. For a given material data set and specimen design (ρ=const.), repeating this procedures for several α, and fitting the numerical results using a polynomial fitting function enables the calculation of $\kappa(\alpha, \rho)$.

While in classic failure theories the strength and consequently the energy release rate of a structure is independent of its size, this is not the case for geometrically similar structures made of brittle materials [41]. According to Bažant and Planas [41], using this so-called fracture mechanics size effect in combination with the peak load condition of

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