Composite Structures 182 (2017) 164–175

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Fracture toughness and crack resistance curves for fiber compressive failure mode in polymer composites under high rate loading

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ARTICLE INFO

Keywords:
Fiber-reinforced composites
R-curve
Dynamic fracture
Size effect

ABSTRACT

This work presents an experimental method to measure the compressive crack resistance curve of fiber-reinforced polymer composites when subjected to dynamic loading. The data reduction couples the concepts of energy release rate, size effect law and R-curve. Double-edge notched specimens of four different sizes are used. Both split-Hopkinson pressure bar and quasi-static reference tests are performed. The full crack resistance curves at both investigated strain rate regimes are obtained on the basis of quasi-static fracture analysis theory. The results show that the steady state fracture toughness of the fiber compressive failure mode of the unidirectional carbon-epoxy composite material IM7-8552 is 165.6 kJ/m^2 and 101.6 kJ/m^2 under dynamic and quasi-static loading, respectively. Therefore the intralaminar fracture toughness in compression is found to increase with increasing strain rate.

1. Introduction

Recently proposed strength analysis methods [1–5] require the specification of fracture toughness parameters associated to the main failure modes in order to predict damage evolution after the material strength has been reached. The softening laws used in the material models with progressive damage are dictated by the crack resistance curves (R-curves) [6] and therefore reliable experimental methods to measure the fracture toughnesses and corresponding crack resistance curves are needed.

While well established static test standards and procedures are available for the interlaminar matrix failure modes [7–9], no test standards exist to measure the intralaminar fracture toughness associated with the longitudinal failure of fiber-reinforced composites. Pinho et al. [10] suggested Compact Tension (CT) and Compact Compression (CC) tests to obtain fracture toughness values for fiber tensile and fiber compressive failure, respectively. However, the CC test specimen is inadequate to measure the R-curve, since i) the kink band onset and propagation is accompanied by secondary damage mechanisms (e.g. delamination) that are neglected and will results in a exaggerated estimation of the fracture toughness; ii) the crack tip cannot be easily identified; iii) the tractions within the fracture process zone are not taken into account properly [11]. Hence only the initiation value for the fiber compressive fracture toughness can be measured confidently using the CC specimen. Similar work has been done by Zobeiry et al. [12], testing CC and over-height compact tension (OCT) specimens with a quasi-isotropic layup. Initiation values for compressive fracture toughness of polymer composites have also been obtained by Laffan et al. [13] using a four-point bending configuration. Soutis et al. [14] tested multidirectional centre-notched compression specimens with various layups and notch lengths to investigate the influence of the number of 0° plies on the laminate compressive fracture toughness. To overcome the limitations of the CC test method, Catalanotti et al. [15] proposed a static test method using double-edge notched (DEN) specimens and the relation between the size effect law and the R-curve. In follow-up works, the method was extended to tensile [16] and shear loading [17] and recently used by Pinto et al. [18] to measure the intralaminar crack resistance curves at extreme temperatures.

Taking into account that automotive and aeronautical polymer composite structures are subjected to dynamic loading scenarios (e.g. crash, foreign object impact), strain rate effects should be captured by advanced composite material models to predict initiation and evolution of damage accurately. The strain rate sensitivity of the stiffness and strength components of polymer composites has been intensively investigated and reviewed over the last decades [19,20]. In addition, the experimental investigation of the dynamic interlaminar fracture

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http://dx.doi.org/10.1016/j.compstruct.2017.09.040
Received 6 July 2017; Received in revised form 15 September 2017; Accepted 16 September 2017
Available online 18 September 2017

toughnesses has received significant attention, motivated by the need to understand the delamination damage within composite laminates after low-energy impact. Published work on dynamic interlaminar fracture toughness was summarized by Jacob et al. [21], concluding that there is no agreement, either, on the trend of fracture toughness with regard to strain rate or on the best suitable experimental and analysis procedure.

In contrast to the interlaminar fracture modes, very little is known regarding the effect of dynamic loading on the energy intensive intralaminar fiber failure modes. McCarroll [22] used a servo-hydraulic machine to test carbon-epoxy CT specimens at cross-head velocities up to 12 m/s. With increasing loading speed, a possible small decrease of the intralaminar fiber tensile fracture toughness was found. However, the range of values was within the scatter of the results.

Therefore, there is the need to develop experimental methods to measure the intralaminar fracture toughness in a dynamic loading scenario. In the presented work, the methodology proposed by Catalanotti et al. [15] to measure the mode I intralaminar R-curve in compression is extended to the case of dynamic loading. This approach uses the relations between the size effect law, initially proposed by Bažant and Planas [23], the energy release rate (ERR) and the R-curve. The method does not require the optical measurement of crack length, whose determination is found to be a main source of errors in fracture mechanic tests [24], and is particularly critical for high loading rate experiments, where high speed cameras with reduced resolution are used. The dynamic tests are conducted on a split-Hopkinson pressure bar (SHPB), which is a widely-used setup for dynamic fracture tests [25]. Following Catalanotti et al. [15], double-edge notched compression (DENC) specimens are used for the determination of the size effect law. This specimen type is well suited for SHPB testing, as it is found to be nonsensitive to complex wave deflections that might cause undesirable mixed mode stress state during the loading of the specimen.

2. Analysis scheme

The analysis scheme of this work is based on the relations between the energy release rate, the R-curve and the size effect law. According to Bažant and Planas [23], if the energy release rate is an increasing function of the crack length (the specimen has a positive geometry) the ERR-curves G_I for different specimen sizes w_k, corresponding to the peak loads P_{uk}, are tangent to the R-curve R (Fig. 1). This relation can be used to measure the intralaminar R-curves of fiber reinforced polymers, as shown by Catalanotti et al. [15,16].

The energy release rate G_I in a balanced cross-ply laminate (with x and y as the preferred axes of the material) under tensile or compressive loading normal to the fracture surface (mode I) reads, for a crack propagating along x [26]:

$$G_I = \frac{1}{E}\sqrt{\frac{1+\rho}{2}}K_I^2 \tag{1}$$

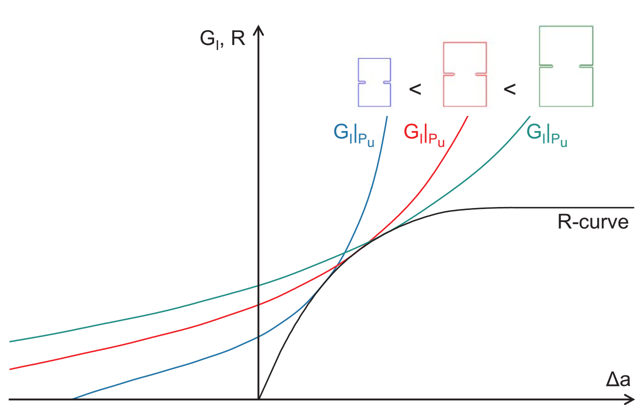

Fig. 1. Crack driving force curves G_I for different specimen sizes at respective peak load P_u and R-curve.

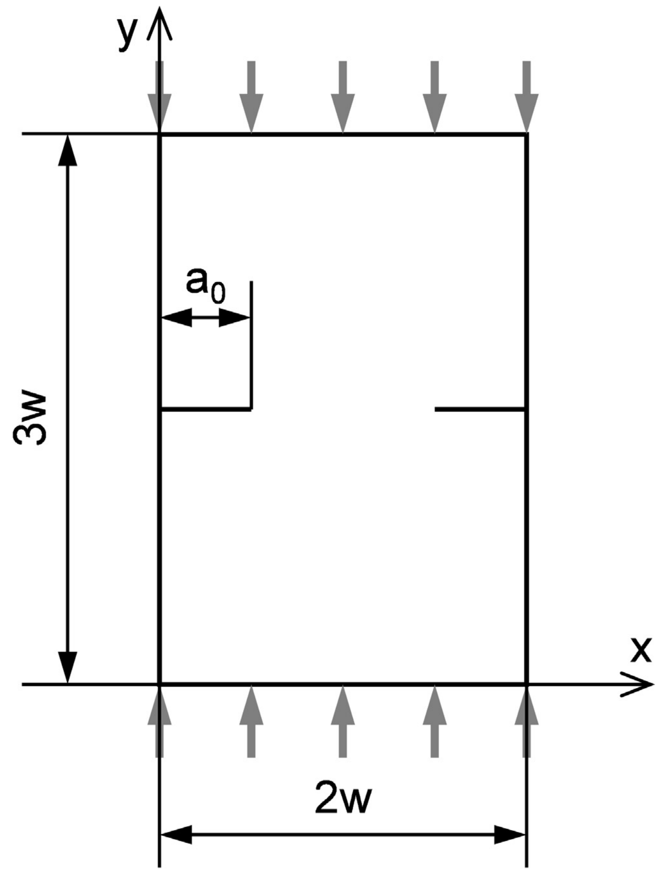

Fig. 2. Double edge notched compression (DENC) specimen.

where E denotes the laminate Young's modulus ($E = E_x = E_y$), K_I is the stress intensity factor and ρ is the dimensionless elastic parameter defined as [26]:

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

where s_{lm} are the components of the compliance matrix computed in the x–y coordinate system. The stress intensity factor, K_I in Eq. (1), depends on the specimen geometry and can be written for a double edge notched specimen (Fig. 2) as [26,27]:

$$K_I = \sigma\sqrt{w}\sqrt{\phi(\alpha,\rho)} \tag{3}$$

in which σ is the remote stress, w is the characteristic size of the specimen (see Fig. 2) and $\phi(\alpha,\rho)$ is the dimensionless correction function for geometry and orthotropy including the shape parameter $\alpha = a/w$. Replacing Eq. (3) in Eq. (1), G_I yields:

$$G_I(a + \Delta a) = \frac{1}{E}\sqrt{\frac{1+\rho}{2}}w\sigma^2\phi\left(\alpha_0 + \frac{\Delta a}{w},\rho\right) \tag{4}$$

where $\alpha_0 = a_0/w$ is the initial shape parameter (see Fig. 2) and Δa is the crack increment.

Since there are not analytical solutions available, $\phi(\alpha,\rho)$ can be calculated numerically by applying the Virtual Crack Closure Technique (VCCT) [28]. Following [15], a two-dimensional Finite Element Model of the DENC specimen is built in the commercial software Abaqus [29] using 4-node reduced integration elements (CPS4R) with assigned elastic properties of the laminate (Fig. 3). The energy release rate, calculated with the VCCT, is equal to:

$$G_I(a^\star,\rho) = Y_m(a^\star,\rho)u_n(a^\star,\rho)/l_e \tag{5}$$

where $a^\star$ is the crack length of the given FE model, Y_m and u_n are the load and the displacement in the y-direction of the nodes m and n,