Composite Structures 184 (2018) 961–968

Contents lists available at ScienceDirect

Composite Structures

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

An improved power law criterion for the delamination propagation with the effect of large-scale fiber bridging in composite multidirectional laminates

Yu Gong[a], Libin Zhao[a,*], Jianyu Zhang[b,*], Ning Hu[b]

[a] School of Astronautics, Beihang University, Beijing 100191, China
[b] College of Aerospace Engineering, Chongqing University, Chongqing 400044, China

ARTICLE INFO

Keywords:
Laminates
Delamination
Fiber bridging
Finite element analysis (FEA)

ABSTRACT

Large-scale fiber bridging can significantly enhance delamination resistance, which makes the use of traditional delamination propagation criterion failed to accurately evaluate the delamination behavior in multidirectional laminates. This paper proposed an improved power law criterion to take account for the effect of fiber bridging on the delamination behavior. The key of the improved criterion lies on the introducing of *R*-curves, which can typically be determined by the standard delamination tests. A numerical delamination model based on the available cohesive elements was established with implementation of the improved criterion. The efficacy of the improved criterion is validated by the simulation of mixed mode bending delamination tests. Numerical results in terms of load-displacement curves agreed well with the experiment ones. The improved criterion can accurately evaluate the mixed-mode delamination with the effect of fiber bridging in a cost and time effective way, is convenient for applications.

1. Introduction

Delamination is one of the most common failure modes in carbon fiber reinforced laminated composites due to the weakness of these laminates in through-the-thickness direction [1]. It significantly reduces the global stiffness and strength of a structure, which is exceedingly detrimental to the structural integrity and safety and even engenders catastrophic structural failure without any external signs [2–4]. Researchers have paid keen attention to this issue in the last decades, due to the increasing application of advanced composite materials in engineering. In practice, damage tolerance philosophy is more and more used for the design of composite structures, which can benefit weight reduction as well as increase fuel efficiency. And this leads to urgent requirements of in-depth understanding on the delamination behavior and reliable prediction models assume a position of prominence.

In the last three decades, various methods have been developed to simulate initiation and propagation of delamination in composite structures, within which the cohesive zone model (CZM) has been extensively used for the investigation of delamination. The advantages of CZM are the unification of delamination initiation and growth within one model and the prediction of delamination onset without prior knowledge of the pre-crack location [5]. In the CZM, the cohesive law relates the traction (σ) to the displacement (δ) at the interface where a crack may occur. Researchers have developed various forms of cohesive laws, such as bilinear, trapezoidal and cubic forms [6]. Among these laws, the bilinear one is the most popular on account of its simplicity and straightforward physical meanings [2]. And it has been shown that the bilinear cohesive law can capture the delamination propagation in unidirectional laminates, where no fiber bridging or only trivial fiber bridging exists [7].

For the multidirectional (MD) laminates most applied in engineering, large-scale fiber bridging [8] (where the process zone length may be large relative to other length scales in the problem) in the wake of delamination front is often observed. The large-scale fiber bridging makes the delamination behavior geometry-dependent as reflected in the increasing fracture toughness with the increase of delamination growth length [8,9]. This phenomenon is described by the resistance curve or the *R*-curve [8,10–14]. The *R*-curve and the material softening are directly related to each other and the bilinear cohesive law is insufficient to accurately represent the fiber bridging mechanism that causing the *R*-curve response [15]. Tri-linear cohesive law [15,16] is therefore proposed by some researchers to take into account the effect of large-scale fiber bridging and a relatively good accuracy in the prediction of delamination growth is obtained. However, the tri-linear cohesive law is established on certain assumptions lack of physical foundation and it is not easy to accurately define the detailed constitutive law [17], which greatly tampers its application. In addition,

---

* Corresponding authors.
E-mail addresses: lbzhao@buaa.edu.cn (L. Zhao), jyzhang@cqu.edu.cn (J. Zhang).

http://dx.doi.org/10.1016/j.compstruct.2017.10.076
Received 16 July 2017; Received in revised form 13 October 2017; Accepted 23 October 2017

the tri-linear cohesive law is often restricted to pure modes of delamination fracture while delamination initiation and propagation in engineering practice essentially proceed in mixed-mode.

In order to accurately evaluate the mixed-mode I/II delamination behavior in MD laminates, Gong et al. [18] proposed an improved B-K criterion. The predictions obtained by applying this criterion had a good agreement with experimental results, which giving evidence to the applicability of the improved B-K criterion. Introducing the *R*-curves to include the effect of fiber bridging is the key of the improved criterion. To further check the effectiveness of this idea, this paper extends related studies to another widely used criterion, the power law criterion. An improved power law criterion is firstly proposed. Afterwards, the capability and applicability of this criterion are validated by experimental results.

2. An improved power law criterion including the effect of fiber bridging

2.1. The mechanism of fiber bridging

Fiber bridging, which has been always observed in the wake of delamination front in various composites [3,19], is an important crack shielding mechanism during delamination growth in MD laminates. Bridging fibers will hinder delamination growth in composites by restraining the fracture surfaces. With the delamination propagating forward, more bridging fibers develop because the amount of bridging fibers is actually dependent on the length of delamination growth [20]. Therefore, more strain energy should be applied and subsequently dissipated to overcome the constraint in the forms of fiber pullout or bridging fiber failure. The delamination resistance is thus significantly enhanced due to the occurrence of fiber bridging. As a consequence, the fracture toughness increases as delamination advances [14,15,21], from an initial value to a plateau. In Ref. [22], the plateau values are founded to be 3–4 times higher than those of the initial G_{IC} values. De Moura et al. [23] quantitatively studied the effect of fiber bridging on the interlaminar fracture toughness by cutting the bridging fibers and concluded that fiber bridging is the main factor causing the *R*-curve effect. Hence, to accurately evaluate the delamination propagation with large-scale fiber bridging, the bridging contribution must be taken into account [2,12].

2.2. Improved power law criterion

The criteria used to evaluate delamination propagation behavior are usually established in terms of the strain energy release rate (SERR) and fracture toughness. Many criteria have already been proposed to evaluate the very common mixed-mode delamination [24]. Among them, the power law criterion [25] is one of the most widely used criteria due to its simplicity and ease of use, which is normally established in terms of an interaction between the SERRs:

$$\left(\frac{G_{I}}{G_{IC}}\right)^{\alpha}+\left(\frac{G_{II}}{G_{IIC}}\right)^{\alpha}=1 \tag{1}$$

where $\alpha \in (1.0 \sim 2.0)$ is an empirical parameter derived from mixed-mode tests [26,27]. The mode I fracture toughness G_{IC} and mode II fracture toughness G_{IIC} are commonly obtained by double cantilever beam (DCB) and end notched flexure (ENF) specimens, respectively. It is worthwhile to point out that values of the G_{IC} and G_{IIC} in the Eq. (1) are generally assumed to be material properties of composite materials [21,28,29], which are constants and independent on the specimen geometries and crack length.

The criterion shown in Eq. (1) is applicable for evaluating the delamination propagation without fiber bridging or with only trivial fiber bridging [25]. However, in the MD laminates with the large-scale fiber bridging, it fails to provide accurate reflection of the realistic failure process [2,7,30]. This fact is not surprising, because fiber bridging has an important effect on the delamination propagation in MD laminates while Eq. (1) does not take this effect into account. Considering the contribution of fiber bridging in MD laminates is normally figured by the *R*-curve, an improved power law criterion is hence proposed by introducing the *R*-curves to include the effect of fiber bridging, as shown in Eq. (2).

$$\left(\frac{G_1(\Delta a)}{G_{1c}(\Delta a)}\right)^{\alpha}+\left(\frac{G_2(\Delta a)}{G_{2c}(\Delta a)}\right)^{\alpha}=1 \tag{2}$$

where $\triangle a$ is the crack growth length, α is a constant parameter and its optimum value for a given material can be determined by applying the least-square fitting on the three-dimensional experimental data ($\triangle a$, φ, G_{tc}^{*}). The $G_1(\triangle a)$ and $G_2(\triangle a)$ are corresponding mode I and mode II SERR components under the mixed mode I/II loading. The $G_{1c}(\triangle a)$ and $G_{2c}(\triangle a)$ are mode I and mode II fracture toughness curves, which could be obtained by DCB [22,31,32] and four-point ENF (4ENF) tests [33,34], respectively.

Considering the *R*-curve behavior, the φ is defined as:

$$\varphi = G_2(\Delta a)/G_{tc}(\Delta a) = G_2(\Delta a)/\{G_1(\Delta a)+G_2(\Delta a)\} \tag{3}$$

From Eq. (3), $G_1(\triangle a)$ and $G_2(\triangle a)$ can be expressed as:

$$G_1(\Delta a) = (1-\varphi)G_{tc}(\Delta a) \text{ and } G_2(\Delta a) = \varphi G_{tc}(\Delta a) \tag{4}$$

Substituting the Eq. (4) into Eq. (2), the following expression can be obtained.

$$G_{tc}(\Delta a) = G_{1c}(\Delta a)G_{2c}(\Delta a)\{[(1-\varphi)G_{2c}(\Delta a)]^{\alpha}+[\varphi G_{1c}(\Delta a)]^{\alpha}\}^{-\frac{1}{\alpha}} \tag{5}$$

For a specific φ, the mixed-mode fracture toughness $G_{tc}^{*}(\Delta a)$ can be firstly obtained by the mixed mode bending (MMB) tests. The problem of determining the value of α is then posed as the minimization of a set of experimental data q, supposing n as the number of data points.

$$q = \sum_{j=1}^{n}\{G_{tc}(\Delta a_j)-G_{tc}^{*}(\Delta a_j)\}^2 \tag{6}$$

3. Material and delamination tests

3.1. Material and specimen manufacturing

Multidirectional laminates fabricated by T700/QY9511 carbon-fiber bismaleimide prepregs were manufactured and tested to validate the improved criterion. The material properties provided by the manufacturer are $E_{11} = 130\,\text{GPa}$, $E_{22} = E_{33} = 10.4\,\text{GPa}$, $G_{12} = G_{13} = 6.63\,\text{GPa}$, $\nu_{12} = \nu_{13} = 0.3$ [35]. Specimens with lay-up $(+45/-45/0_6)_S//(-45/+45/0_6)_S$ were designed based on the classical laminated plate theory, where the symbol '//' denotes the position of the initial pre-crack introduced during the fabrication process. This selected layup can ensure reduced thermal distortions during curing and minimized coupling effects. In order to quantitively characterize the coupling effect, Davidson et al. [36] proposed to use D_c to indicate the curvature due to longitudinal/transverse bending coupling. And Sun and Zheng [37] proposed to use B_t to indicate the skewness of the crack profile due to bending/twisting coupling [38]. D_c and B_t depend on the bending stiffness matrix coefficients D_{ij} according to:

$$D_c = \frac{D_{12}^2}{D_{11}D_{22}}, B_t = \frac{|D_{16}|}{D_{11}}$$

The values of D_c and B_t for each arm are 0.15 and 0.03, which are low to reduce thermal distortions during curing and eliminate unwanted effect on delamination-front loading conditions, respectively. To check the uniformity of SERR width-wise distribution [4], the test on a typical specimen was interrupted and C-scan detection was done. And the C-scan image showed that the difference of crack growth in the both sides and heart of the specimen was small. A Teflon film with a length