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A simple method for determining the mode I interlaminar fracture toughness of composite without measuring the growing crack length

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ABSTRACT

The modified beam theory (MBT), compliance calibration method (CC) and modified compliance calibration method (MCC) were recommended by the ASTM standard D5528 to determine the interlaminar fracture toughness of composite materials. Their shortcomings are the requirement of measuring the growing crack length, which is tedious and the source of uncertainty. By using the solution from two dimensional elasticity analysis of orthotropic double cantilever beam, a double compliances method is proposed to determine the fracture toughness. The procedure of the present method is nearly the same as that recommended by the ASTM standard, except avoiding measuring the growing crack length. The fracture toughness determined from the present method is consistent with the results obtained by using the ASTM standard methods. However, the present method is easier to conduct and has wider applications, compared with the ASTM standard methods.

1. Introduction

Advanced composite materials are increasingly used in aircraft primary structures. Due to the low interlaminar strengths, delamination is one of the most serious failure modes in composite materials and structures [1]. Interlaminar fracture toughness is used to characterize the delamination resistance of composite materials. It is also widely used with the cohesive zone model (CZM) [2–4] and the virtual crack closure technique (VCCT) [5] to predict the delamination of composite structures subjected to tension, compression and impact loading [6]. Therefore, simple and accurate methods for determining the interlaminar fracture toughness are extremely important in the design and analysis of composite materials and structures [7].

Fracture mechanics is used to describe the interlaminar fracture of composite materials. Because the fracture toughness in each mode is usually different for composite materials, accurate fracture mode partition is very important in the characterization and analysis of delamination [8–10]. Comprehensively analytical and experimental comparisons of the partition theories are given by Harvey and Wang [11] and Harvey et al. [12], recently. In the preset paper, the pure mode I interlaminar fracture will be studied. The double cantilever beam (DCB) specimen is widely used and adopted in the ASTM standard to measure the mode I interlaminar fracture toughness, because it is easy to manufacture and test [13,14]. The critical energy release rate at which the crack propagates is called the fracture toughness. The energy release rates of orthotropic DCBs as a function of applied load, displacement and material properties were established by using various theories [15–24]. It has been well recognized that the use of the classical beam theory with the assumption of rigid boundary condition at the crack tip leads to significant error in the energy release rate [15,20–23]. The

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Nomenclature

a	length of the cracked beam	h	thickness of the DCB arm
A	fresh surface area	MBT	modified beam theory
B	width of the DCB specimen	MCC	modified compliance calibration
C	compliance	P	applied load
CC	compliance calibration	U	strain energy
CZM	cohesive zone model	W	potential work
E_{xx}	Young's modulus in the fiber direction	X, Y, Z	see Eq. (20c)
G, G_{IC}	energy release rate and fracture toughness, respectively	β	correction factor, see Eqs. (9a) and (20a)
G_{xy}	shear modulus	δ	displacement
		ν_{xy}, ν_{yx}	Poisson's ratio
		ρ	see Eq. (9b)

reason for the inaccuracy comes from the oversimplification of the complex deformation at the crack tip [20,21]. To obtain accurate energy release rate, one approach is to use the beam on elastic foundation models to account for crack tip rotation, for example the pioneering work given by Kanninen [25] and many others [15,24]. An empirical stiffness of the spring was given by Williams and his colleagues [15,26] to obtain accurate energy release for orthotropic DCB. The second method to account for the complex deformation at the crack tip is by using two dimensional finite element method [21,22,27–29]. This approach is originally used by Suo et al. [22] with the combination of orthotropic scaling method. Using the same method, very accurate solutions to various DCB, end-notched flexure (ENF) and end-loaded split (ELS) made of a wide of orthotropic materials were given in [22,27–29].

In fact, most energy release rate solutions to the DCB are not applied to measure the fracture toughness, because these solutions are either approximate or require for additional measurements of material properties or other parameter(s). Using fracture mechanics principles, the most straightforward method is the work –area method, which is directly based on the definition of the energy release rate. To obtain the work area under the load-displacement curve, periodical unloading and reloading procedure was required. However, the accuracy of the fracture toughness obtained from this tedious procedure was not satisfied, when compared to the alternative methods recommended by the ASTM standard [13]. Three data reduction methods were recommended by ASTM standard, which were modified beam theory (MBT) [26], Berry's compliance calibration (CC) method [30] and modified compliance calibration (MCC) method [31]. All of these three methods require the measurement of the applied load and its associated displacement and crack length to obtain the relation between the compliance and crack length. However, it is not easy to measure the growing crack length and to record the corresponding load and displacement simultaneously. Therefore, uncertainty is introduced in the MBT, CC and MCC methods, especially when the crack grows unstably. In addition, in some conditions, the growing crack length is hard to visually access.

There were several methods proposed to overcome the shortcoming of the ASTM methods. Gunderson et al. [32] used the J integral method to measure the fracture toughness of composite materials. The requirements of the J integral are the applied load and the derivative ($d\delta/dx$) of the opening displacement δ with respect to x at the applied load point (see Fig. 1 and Eq. (11)), which avoids the measurement of the growing crack length. The J integral method is accurate in calculating the energy releaser rate. However, the difficulty in measuring the derivative of the opening displacement hinders its practical application in the measurement of fracture toughness. Tamuzs et al. [33] found another simple equation (Eq. (7) in the present paper) for determining the fracture toughness without measuring the growth crack length. Recently, Gracia et al. [34] also proposed a new compliance method to determine the interlaminar fracture toughness of composites without measuring the crack length. These two methods are accurate in determining the fracture toughness. However, both methods require the measurement of the Young's modulus (or moduli) of the composite by conducting separated test(s) to obtain the fracture toughness, which is inconvenient. In addition, any uncertainty in the measured Young's modulus will introduce into the fracture toughness by using these two methods. A novel compliance combination method was proposed by Yoshihara and Kawamura [35] to measure the modes I and II interlaminar fracture toughness by using DCB and ENF specimens. A strain gauge was used to measure the longitudinal strain on the top of surface of the specimen to provide additional load-strain compliance, which was combined with the load-displacement to determine the interlaminar fracture toughness. By using the crack equivalent concept and compliance methods, De Moura et al. [36] devised a data reduction method for characterizing the fracture toughness of wood. This method avoids the measurement of the crack length as well. However, an iterative procedure should

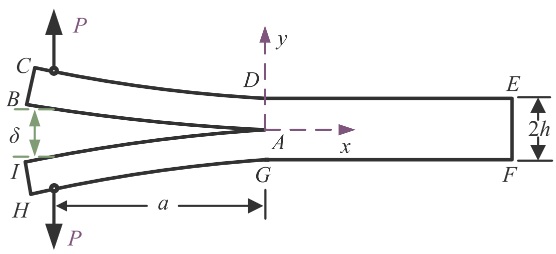

Fig. 1. Configuration of the DCB specimen.