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Experimental method for mode I fracture toughness of composite laminates using wedge loaded double cantilever beam specimens

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ABSTRACT

This study proposes a simple and accurate data reduction scheme for the wedge loaded double cantilever beam (DCB) specimen. The effects of axial loading applied by wedges were considered for the evaluation of mode I energy release rate. Furthermore, a methodology for the determination of crack length during the tests was proposed. The presented method was verified by both finite-element (FE) analyses and fracture toughness tests. The results of the FE analyses showed that the mode I energy release rate obtained by the presented method well agreed with that obtained by the virtual crack closure method. Both the wedge loaded DCB and standard DCB tests were carried out to verify the presented method with unidirectional carbon fiber reinforced composites. Mode I fracture toughness obtained by the wedge loaded DCB tests was almost identical to that obtained by the standard DCB tests.

1. Introduction

The use of carbon fiber reinforced polymer (CFRP) laminates for aerospace industry is on the rise because of their high specific strength and modulus. Since the mechanical failure of CFRP laminates are often caused by the propagation of cracks, there has been considerable interest to clarify the crack propagation behavior of CFRP laminates based on fracture mechanics approach since 1970s [1–3]. The double cantilever beam (DCB) specimen, developed by Wilkins et al. [4] and employed in standards [5–7], is one of the most widely used for mode I interlaminar fracture toughness tests of fiber reinforced composite materials [4,8–10] as well as adhesively bonded joints [11–13] because of its simplicity and reliability.

On the other hand, in-situ observation of CFRP laminates has attracted much attention in recent years to clarify the mechanisms of damage initiation and propagation. Several methods have been applied to the in-situ observation; change of electric resistance [14,15], detection of Lamb wave with a fiber Bragg grating sensor [16], X-ray computed tomography (CT) technology [17], and digital image correlation (DIC) method with a scanning electron microscope (SEM) [18]. A specimen must be fixed when the in-situ observation is conducted in small area like the vicinity of a crack tip in CFRP laminates by X-ray CT and DIC technique with a microscope. However, since a standard type of the DCB specimen moves during tests, a difficulty arises when we make an in-situ observation around a crack tip.

From the viewpoint of in-situ observation during fracture toughness tests around a crack tip, an accurate determination of energy release rate or fracture toughness and minimum movement of a specimen (it allows stationary observation) during tests are required. In addition, unloaded condition in the beginning of tests, and simplicity of both experimental procedure and data reduction scheme are also desired for the in-situ observation.

One suitable candidate for the in-situ observation of mode I fracture toughness tests is the wedge loaded DCB or similar configuration specimen. Stationary observation can be made because the fixed specimen is split apart by the wedges during the wedge loaded DCB tests. The wedge loaded DCB specimen was developed in 1970s for the dynamic fracture toughness tests of steel [19]. Since the specimen can be fixed during fracture toughness tests, a number of researches using the wedge loaded DCB specimen has been conducted not only for in-situ observation, but also impact and environmental tests.

Several data reduction schemes have been proposed for the wedge loaded DCB specimen. For example, load-independent formulation of mode I energy release rate [20] was used for impact [21,22] and durability tests for adhesively bonded joints [23–28]. The advantage of the load-independent method is determination of energy release rate

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without measuring the load. However, since the energy release rate is inversely proportional to the fourth power of crack length, the accuracy of crack length measurement can sensitively affect the experimental results.

Another data reduction scheme used load [29–31] or equivalent parameter such as strain on the surface of specimen [32,33]. Although bearings were used to reduce the effects of friction, results of finite-element (FE) analysis showed that the mode I energy release rate obtained by the wedge loaded DCB specimen and modified beam theory (MBT) was reduced by 18% compared with that obtained by standard DCB configuration due to the presence of axial loading [30]. Hence, the effects of axial loading have to be taken into consideration for the precise determination of the energy release rate. Furthermore, data reduction method with strain on the surface of specimen requires the determination of a proportionality factor using standard DCB configuration for the load and strain before the fracture toughness tests.

The other method is based on stress intensity factor approach [34–36]. The methods assumed the existence of strict linear elastic deformation fields around a crack tip. Hence, the evaluation formulations become complex for orthotropic or dissimilar materials such as CFRP or adhesive joints. In addition, it is difficult to determine a shape factor for the orthotropic materials.

In the present work, a simple and accurate data reduction scheme for the wedge loaded DCB specimen was proposed. The proposed type of the wedge loaded DCB specimen uses a similar configuration as the standard type of DCB specimen. The evaluation formula for mode I fracture toughness was proposed with the consideration of axial loading applied by wedges. Furthermore, the methodology for the estimation of crack length from reaction force and displacement of the wedge was also developed. The presented method was verified with both fracture toughness tests and FE analyses.

2. Evaluation of mode I fracture toughness

2.1. Wedge loaded DCB specimen

Fig. 1 shows a schematic drawing of the wedge loaded DCB specimen. One end of the specimen is fixed, while the other end is split apart by the wedges. Hence, there is no translational movement during the test. The configuration of the specimen is similar to the standard type of DCB specimen with loading blocks [5]. The pair of wedges acts not only on the opening load, P_y, but also the axial load, P_x, to the specimen via loading blocks and pins. Therefore, bending moment, M^{axi}, created by axial load, P_x, is additionally applied to the wedge loaded DCB specimen compared with a standard DCB specimen. In other words, the effects of the axial load, P_x, has to be taken into consideration in the calculation of the mode I energy release rate, G_I, for the wedge loaded DCB specimen.

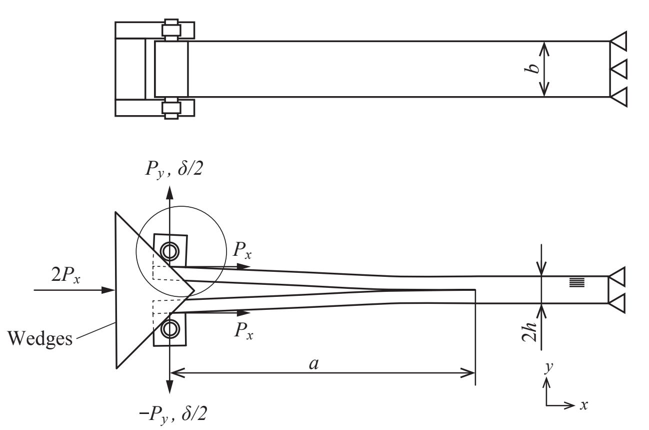

Fig. 1. Schematic drawing of a wedge loaded DCB specimen. (a) Overview. (b) Magnified view.

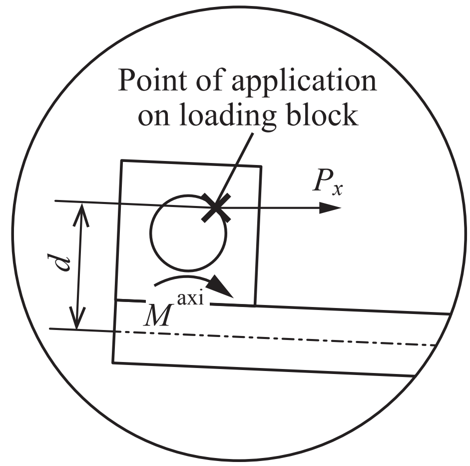

Fig. 1. (*continued*)

2.2. Determination of energy release rate

The evaluation formula of mode I energy release rate, G_I, by considering both axial load, P_x, and opening load, P_y, is derived in this section. Mode I energy release rate, G_I, for a thin sheet of total thickness, $2h$, and width, b, containing a delamination as shown in Fig. 2 is given by [37]:

$$G_I = \frac{M^2}{bE_x I} \tag{1}$$

where M is mode I bending moment applied to the delamination section, E_x is longitudinal Young's modulus of the specimen, and I $(=bh^3/12)$ is second moment of area of the specimen. Assuming bending span of wedge loaded DCB specimen is crack length, a, with a correction factor, e [38], the bending moment, M^{opn}, caused by opening load, P_y, at the crack tip is given by:

$$M^{opn} = P_y(a + e) \tag{2}$$

Similarly, a bending moment, M^{axi}, caused by axial load, P_x, at the crack tip is given by:

$$M^{axi} = P_x d \tag{3}$$

where d is distance between the neutral axis and point of application as shown in Fig. 1(b), i.e., d depends on the thickness of specimen, dimensions of loading block, diameter of pin hole, and ratio of axial load P_x and P_y. Hence, the total bending moment acting at the crack tip of the specimen is given by:

$$M = M^{opn} + M^{axi} = P_y(a + e) + P_x d \tag{4}$$

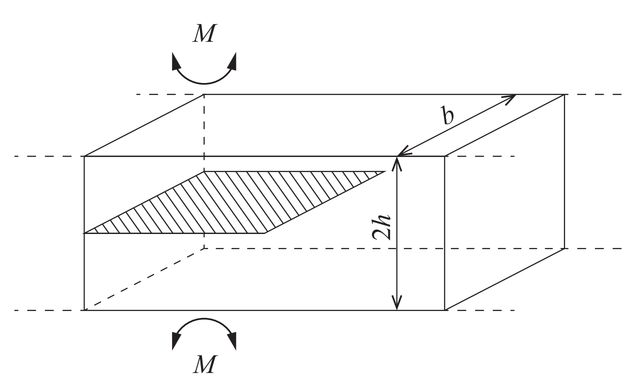

Fig. 2. Delamination geometry under mode I loading.