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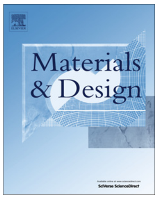

Effect of initial crack length on the measured bridging law of unidirectional E-glass/epoxy double cantilever beam specimens

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ABSTRACT

In this paper, the effect of initial delamination length is experimentally investigated on obtaining the mode I bridging law of unidirectional E-glass/epoxy double cantilever beam (DCB) specimens manufactured by hand layup method. To this end, an experimental test set-up is established for accurate measurement of crack tip opening displacement (CTOD) using digital image processing method. DCB tests are performed for three different delamination lengths and the corresponding bridging laws are calculated using *J*-integral approach. Results showed that the maximum bridging stress, the shape of bridging law and energy dissipation in bridging zone are slightly affected by changing initial crack length. In other words, the measured bridging law acts independent of initial delamination length. Therefore, the obtained bridging law can be used with the cohesive elements available in the commercial finite element software to simulate the delamination propagation behavior in unidirectional DCB specimens.

1. Introduction

Delamination is one of the most prevalent damage mechanisms in laminated composites. This phenomenon can occur due to free edge effect, accumulation of voids during processing, impact loading and fabrication defects. In order to characterize resistance to delamination in fiber reinforced composite laminates, interlaminar fracture toughness in term of critical strain energy release rate, G_c, is measured. Double cantilever beam (DCB) is one of the most recommended specimens to calculate delamination toughness in mode I loading based on ASTM D5528-01. In laminated DCB specimens, it was frequently observed that increasing the delamination length during crack growth may enhance the strain energy release rate. This phenomenon, i.e., increase of the crack growth resistance as crack advances, occurs due to fiber bridging effect and it is described by the concept of resistance curve (*R*-curve) [1–6]. Some researchers have shown that *R*-curve is a geometry-dependent property [5]. It means that different geometrical parameters such as width, thickness and initial crack length may affect the *R*-curve in unidirectional DCB specimens. Tamuzs et al. [5] investigated the dependency of *R*-curve on the thickness of unidirectional carbon/epoxy DCB specimens. They showed that the shape of *R*-curve depends on specimen thickness but the initiation and propagation of delamination toughness can be considered as material characteristics. In addition, Sou et al. [7] declared that the steady-state toughness of a slender DCB is independent of specimen size and geometry. Recently, the effects of thickness and initial crack length on *R*-curve behavior of unidirectional E-glass/epoxy DCB specimens is experimentally studied by Shokrieh et al. [8]. They concluded that initiation and propagation of delamination toughness and length of bridging zone do not change significantly in a specific range of initial crack length to thickness ratios (i.e., $8.5 < a_0/2h < 19$) and consequently the shape of *R*-curve does not change in this range. In another study, Shokrieh and Heidari-Rarani [9] studied the effect of stacking sequence on *R*-curve behavior of E-glass/epoxy DCB laminates with 0°//0° crack interface and performed some experimental tests on unidirectional, cross-ply and quasi-isotropic DCB specimens. They proved that the stacking sequence does not affect the bridging length while values of initiation and propagation of delamination toughness changes.

Above-mentioned investigations show that *R*-curve has significant effect on the propagation behavior of laminated composites. One of the common methods for modeling the delamination growth behavior in various materials such as homogenous isotropic, functionally graded materials and composite laminates is the cohesive zone models (CZMs) [10–16]. The CZMs work based upon traction–separation law and can be adopted to interface elements to simulate initiation as well as propagation in laminated composites. Up to now, different shapes of CZMs such as bilinear, tri-linear and exponential have been proposed in the literature. Heidari-Rarani et al. [6] showed that the traditional bilinear CZMs cannot

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model the *R*-curve effects in laminated DCB specimens under large-scale bridging. Also, Morais and Pereira [17] investigated the delamination growth in carbon/epoxy unidirectional DCB specimens using effective crack method and reported that the bilinear CZMs are not capable to predict crack growth behavior of such laminates. Therefore, there is need to modify traditional CZMs in order to simulation crack propagation in laminated DCB specimen under large-scale bridging. To reach this goal, many researchers characterize the bridging law experimentally and afterwards modified the CZMs based on the obtained bridging traction. The bridging traction can be experimentally measured using different methods. Using fiber bragg grating (FBG) sensor is one of the indirectly method to evaluate bridging traction. This method works based on the measuring of strain distribution close to the crack tip. Recently, Stutz et al. [18,19] and Sorensen et al. [20] characterize the bridging traction in mode I loading of unidirectional carbon/epoxy DCB specimen using this semi-experimental procedure. The other method for measuring bridging traction is the *J*-integral approach. Sorensen et al. [20] compared the bridging traction obtained by the *J*-integral approach and the semi-experimental procedure using FBG for DCB specimens, and finally concluded both methods give approximately the same bridging law.

As stated above, many previous studies are focused on measurement of bridging law by different methods for definite goal. Now, this question arises that the obtained bridging law can be affected by size and geometry, e.g., thickness, width and initial crack length, of DCB specimen? The effect of specimen thickness on bridging law is investigated by Tamuzs et al. [5] by considering of DCB specimens with three different thicknesses. They reported that beam thickness does not affect the bridging law. In the case of specimen width, ASTM D5528-01 declares that the round-robin testing on narrow and wide specimens yielded similar results, indicating that the DCB specimen width is not a critical parameter that can be effect on fracture toughness and consequently bridging law. Therefore, in the present study, the effect of initial crack length on the bridging law of unidirectional DCB specimen is investigated. To this end, unidirectional DCB specimens with three different initial crack lengths are chosen and some experimental tests are performed on DCB specimens. As reported in the literature [11], when the initial crack length to thickness ratio is low, e.g., $a_0/2h = 4$, the transverse shear deformation effect can be dominant and the data reduction recommended in ASTM D5528-01 for delamination toughness calculation is not accurate anymore. In addition, when the initial crack length to thickness ratio is large, e.g., $a_0/2h = 20$, the large deflection occurs and the data reduction procedure based on the linear elastic fracture mechanics may not be accurate anymore due to possible damages such as matrix cracking in the arms of DCB specimens. To eliminate the above-mentioned effects, the $a_0/2h$ ratio is selected between 8 to 20 in this research.

2. Experimental procedure

2.1. Materials and preparation of specimens

Twenty four layers of unidirectional E-glass fabric with density of 2.564 g/cm^3 were used together with ML-506 Bisphenol-F epoxy resin with a density of 1.11 g/cm^3 to manufacture laminated composite plate by hand lay-up method. A thin film with a thickness of 20 μm was inserted in the mid-plane of specimen to create a starter delamination length during manufacturing. The laminates were cured at room temperature for 7 days and post-cured at 80 °C for 2 h. Afterwards, DCB specimens with geometrical properties, i.e. length, $L = 150$ mm and width, $b = 25$ mm, were cut from laminate by diamond saw. The in-plane mechanical properties of unidirectional laminate are reported in Table 1 from Ref. [11].

Table 1
Mechanical properties of unidirectional E-glass/ML-506 epoxy with $V_f = 47.3\%$.

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}	E_{fx} (GPa)
33.5	10.23	4.26	0.27	29.5

2.2. Test procedure

A universal testing machine (SANTAM STM-150) was used to conduct the DCB tests. A high precise load cell with a capacity of 50 kg was utilized to record the load. The hinges on the specimen were mounted in the grips of the loading machine to make sure that the specimen was aligned and centered. Quasi-static mode I tests were performed under the displacement control condition. The crosshead speed was set at 0.75 mm/min to ensure steady crack propagation and easy data recording. In order to obtain bridging law, four parameters, including load (P), load line displacement (δ), delamination length (a) and local crack opening displacement (δ^*) should be determined simultaneously. The configuration of DCB specimen is illustrated in Fig. 1. The load–displacement curve, P–δ, was recorded by the tensile machine. The challenging issue was to record both delamination length and local crack opening displacement in simultaneous with P and δ during the test. The delamination length and crack opening displacement were monitored using a Canon EOS 550D digital SLR camera with a Sigma 150 mm F2.8 macro lens. The camera was mounted on a tripod in front of the DCB specimen in order to monitor and record the crack length and local crack opening displacement. The experimental test set-up for DCB testing is shown in Fig. 2. To clearly detect the crack tip in the taken photos, a certain method of illumination is used with the transparency of glass/epoxy composite. A single light source is placed under the specimen, when mounted in the universal testing machine's grips, facing upward and illuminating the lower face of the DCB specimen.

The lower parts of the specimen (the part without any crack growth and the lower edge of the existing crack) are completely illuminated. The opening in the specimen due to the existence of crack does not allow the light to enter the upper edge of the crack so the corresponding part remains dark and in shade. The crack tip can be detected by detecting the shaded area created due to the specific illumination used in this study. In order to quantify the crack lengths from the photos taken during the test a measurement scale with ±1 mm divisions is attached to the lower edge of the specimen. In addition, in order to visualize the displacement of the initial crack tip, two dots made of a viscous liquid substance were placed on the edges of the DCB specimen at the initial crack section. The lighting from below makes the two dots appear as dark, shaded points in the photos due to their volume. An image processing code was developed in MATLAB software that can record the CTOD accurately from taken photos. Finally, a program was written using Microsoft Visual Studio.NET in order to capture print screens of the load–displacement curve during the test,

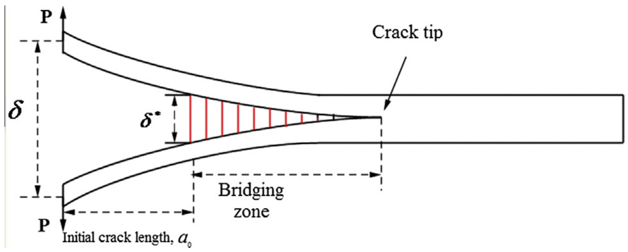

Fig. 1. Schematic of DCB specimen with fiber bridging zone.