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Delamination R-curve as a material property of unidirectional glass/epoxy composites

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ABSTRACT

It is still questionable to think of delamination resistance of a double cantilever beam (DCB) as a material property independent of the specimen size and geometry. In this research, the effects of initial crack length and DCB specimen thickness on the mode I delamination resistance curve (R-curve) behavior of different unidirectional glass/epoxy DCB specimens are experimentally investigated. It is observed that the magnitudes of initiation and propagation delamination toughness ($G_{Ic\text{-}init}$ and $G_{Ic\text{-}prop}$) as well as the fiber bridging length are constant in a specific range of the initial crack length to the DCB specimen thickness ratios of $8.5 < a_0/h < 19$. Finally, a mathematical relationship is proposed for prediction of mode I delamination behavior (from the initiation to propagation) of E-glass/epoxy DCB specimens.

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1. Introduction

Delamination resistance which is usually expressed as "interlaminar fracture toughness" is often characterized in terms of the critical strain energy release rate, G_c. Since composite laminates are high performance structural materials, there is a need of accurate evaluation of the interlaminar fracture toughness for the optimal design and material selection of composite structures. Various test methods were developed to measure G_c under different delamination modes. Mode I interlaminar fracture has received the greatest attention from researchers. This is due to the fact that the delamination initiation energy is low compared to that of the shearing mode [1]. Also, double cantilever beam (DCB) test (Fig. 1) is usually used for studying mode I delamination [2,3]. Various experimental works have already been conducted on the mode I interlaminar fracture of unidirectional ($[0°]_n$) and multidirectional DCB specimens to follow a specific issue. Andersons and König [4] presented a comprehensive review on the published experimental research concerning delamination onset and growth in laminated composites under various mode loadings. In the case of carbon/epoxy unidirectional laminates, the mode I interlaminar fracture toughness has been already studied in Refs. [5–11]. For example, in the last two works, Schön et al. [10] investigated the fracture mechanical properties of DCB specimens with different interfaces for three carbon/epoxy materials under static and fatigue loadings. They mainly focused on the interface effects on the delamination behavior of multidirectional DCB specimens with respect to unidirectional one. De Morais et al. [11] performed DCB tests on $[0°]_{24}$ carbon (T300)/toughened epoxy(977-2) prepreg to compare its G_{Ic} values at initiation and propagation with values for similar cross-ply laminates. The specimens were approximately 20 mm wide, 4 mm thick and had a starter crack of 55 mm from one of the ends.

In the case of unidirectional DCB specimens with glass fiber reinforcement, Ozdil and Carlsson [12] did some experiments on $[0°]_6$ unidirectional glass/polyester laminated DCB specimens with a initial crack length of 33 mm and a total thickness of 4.4 mm. They only reported initiation fracture toughness and did not observed a steady-state crack growth in delamination growth of unidirectional DCB specimens. Szekrényes and Uj [13] developed a theoretical model to take into account the fiber bridging effects on the interlaminar fracture. Crack initiation and propagation tests were performed on $[0°]_{14}$ unidirectional E-glass/polyester DCB specimens with different initial crack lengths, a nominal width of 20 mm, and a total thickness of 6 mm.

In all the above-mentioned research, G_{Ic} values at initiation and especially propagation is reported for a definite crack length and thickness to conduct definite goals. However, the delamination behavior or R-curve behavior of unidirectional laminates was not fully characterized in detail. In the laminated composites with a delamination located between two similar layers, the fiber bridging phenomenon is extensively occurred. In this situations, the strain energy release rate (SERR) increases with advancing the crack. This feature is known as the resistance curve (R-curve) effect. Refs. [12,14,15] has highlighted a quotation from a research

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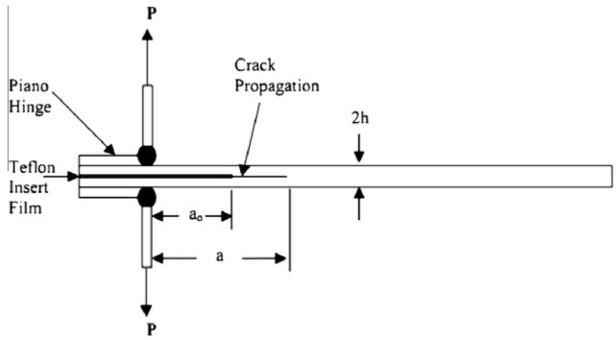

Fig. 1. Scheme of the DCB test.

by Suo et al. [16], that *R*-curve cannot be considered as a material property, since it depends on the specimen size and geometry. Therefore, they have tried to obtain a traction-separation law with three intrinsic parameters, *i.e.*, yield stress, maximum separation, and stiffness as material properties from the experimental *R*-curves.

Obtaining a traction-separation law for composite materials with variety of fibers and matrices is so complicated and may not be applicable in a finite element analysis of large structures due to high run-time. Therefore, in this study, it is focused on investigating the possibilities of determining specimen size-independent delamination resistance with a standard DCB test. In general, three parameters that may affect on the delamination toughness are the initial crack length (a_0), the thickness (2 h) and the width of DCB specimen (b). In the case of specimen width, ASTM D5528 standard [2] 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. Thus, it is better to consider it between 20 and 25 mm to show a better curvilinear of the delamination front and eliminate the effect of boundary layer at two edges of DCB specimen on the SERR values at the center; the point which is usually considered as a criterion for the initiation of delamination growth. For the initial crack length and the thickness of DCB specimen, to the best knowledge of authors, a comprehensive study is not available in the literature. Moreover, there is nothing in the standard test methods about the limit of these two factors to obtain *R*-curve independent of the specimen size. The ASTM standard recommends that the delamination front formed by the film should be 50 mm from the load line, while ESIS [17] suggests the distance from the forward edge of the loading block (or piano hinge) to the film front should be at least 45 mm. These values of initial crack lengths are supposed to obtain only acceptable initiation fracture toughness. Thus, in the present study, DCB tests are conducted at different initial crack lengths and thicknesses for each unidirectional specimen, which enable the investigation of *R*-curve behavior for mode *I* delamination growth. In each *R*-curve, three parameters, *i.e.*, initiation, steady state propagation toughness, and the length of fiber bridging are carefully investigated. Finally, a mathematical relation is proposed to simulate the whole delamination process independent of the specimen size. This is very important since, for instance, even a comparison between failure behaviors in different materials cannot be performed unless the specimen geometry effects are eliminated or understood.

2. Experimental procedure

2.1. Materials and specimen preparation

The specimens are made of 18 and 24-ply unidirectional E-glass/epoxy laminate, produced by hand lay-up method. E-glass unidirectional fabric with a density of 2.564 g/cm^3 and ML-506 Bisphenol-*F* epoxy resin with a density of 1.11 g/cm^3 and a polyamine hardener (HA-12) were used. The laminates were cured at room temperature for 7 days and post-cured at 80 °C for 2 h. Average fiber volume fraction was obtained 48.8% from the burn-out test for DCB specimens. Also, the obtained void content according to ASTM D2743 standard [24] was less than 1%. In-plane properties were measured by ASTM D3039 [25] (tensile properties), ASTM D3410 [26] (compression properties) and ASTM D3518 [27] (shear properties) on 0°, 90° and ±45° specimens, respectively (Table 1). To create a starter delamination crack, a 17 μm Teflon film was placed at the mid-plane of the laminate during the lay-up process. DCB specimens with a total length of L = 150 mm, a width of b = 25 mm and initial crack lengths of a_0 = 15, 35, 45, 55, 65 and 75 ± 0.3 mm were cut from the plates, using a diamond saw. Specimen edges are sanded to remove imperfections that may interfere with the crack growth, in order to have a clear image of the crack tip position. The load was transferred to the specimen using hinges to avoid extraneous bending moments. Piano hinges were bonded to both specimen faces using Araldite 2014 epoxy adhesive as load application points. Specimen and aluminum hinge bonding surfaces were sanded with 240 grit sandpaper and wiped clean with acetone before adhesive application. A measurement scale with 1 mm divisions is attached to the lower edge of specimen for measuring crack length from the photos taken during the testing. To provide a better contrast for the visualization of the crack growth, the specimen was exposed to LED light. In this work, three DCB specimens are tested for each crack length.

Table 1
Mechanical properties of unidirectional E-glass/ML-506 epoxy with V_f = 48.8%.

E_1 (GPa)	E_2 (GPa)	ν_{12}	G_{12} (GPa)	E_{fx} (GPa)
33.5	10.23	0.27	4.26	30.54

2.2. Test procedure

A universal testing machine (Santam STM-150) was used to conduct the tests on the DCB specimens. A high precise load cell with a capacity of 50 kg is used for recording the load. The hinges on the specimen were carefully mounted in the grips of the loading machine to make sure that the specimen is aligned and centered. Quasi-static mode *I* tests were performed under displacement control conditions. The crosshead speed is set at 0.5 mm/min to ensure steady crack propagation and recorded easily. The tensile machine recorded a curve of load (P) versus displacement (δ). The onset of crack growth from the starter insert was determined by carefully inspection of the specimen edge with a *Canon Macro lens* 150 mm and by observation of the load–displacement curve. A computer program was written to print screen the load–displacement curve during testing which is synchronized with the digital camera connected to the computer for a live viewing of the crack propagation. After the visual inspection of the first initiation of the crack growth, the camera starts to capture real time images of the delamination. This set-up allows recording various crack lengths, corresponding loads and displacements at any arbitrary time interval from the crack initiation. The crack lengths were measured directly from high-resolution photos. The crack is extended approximately to 35 mm from the initial crack length. The DCB test setup is shown in Fig. 2. The delamination growth front for DCB specimens has generally an anticlastic shape across the specimen width. In the case of unidirectional DCB specimens, the delamination growth front generally is uniform due to a low bending–bending coupling or a low magnitude of non-dimensional

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