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Influence of curved delamination front on toughness of multidirectional DCB specimens

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ABSTRACT

Mode I delamination toughness (G_{Ic}) of a laminated composite depends not only on the stacking sequence or indirectly coupling parameter of $D_c = \frac{D_{12}^2}{D_{11}D_{22}}$, but also on specimen geometrical ratios a_0/b and a_0/h. In this study, a non-uniformity ratio, $\beta = (G_{Imax} - G_{Iavg})/G_{Iavg}\%$, is introduced to take into account the influence of above factors on the energy release rate distribution along the width of double cantilever beam (DCB) specimens simultaneously. Results show that the G_{Ic} of multidirectional DCB specimens with 0°//0° crack interface and $\beta < 20\%$ can be predicted by measuring the G_{Ic} of the unidirectional plies with an error less than 10%. Moreover, a methodology is proposed to predict the maximum delamination toughness (G_{Imax}) of multidirectional DCB specimens from β parameter without performing any experiments. With the present method, the effect of curved thumbnail shape of energy release rate along the delamination front is considered on the available closed-form relations for G_I.

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1. Introduction

Delamination is one of the most common failure modes in layered composite structures. The remote loadings applied to composite components are typically resolved into interlaminar tension and shear stresses at discontinuities that create different modes of delaminations. This mechanism of damage is particularly detrimental to the compressive strength due to localized buckling phenomena. So, the characterization of the delamination resistance of composites is of considerable interest [1]. Double cantilever beam (DCB) test (Fig. 1) has been frequently used for measuring the mode I delamination toughness (G_{Ic}) of unidirectional (UD) $[0°]_n$ laminates according to available standards [2–4]. The standard test methods only focus on the fracture toughness of UD laminates, whereas most applications involve multidirectional (MD) laminates. This is due to high flexural stiffness and ability to maintain self-similar crack propagation in UD laminates [5] and some difficulties occurring during the delamination growth in MD laminates. It is therefore essential to obtain the G_{Ic} values of MD specimens for the development of accurate fracture criteria. To this end, the main object of the present research is to investigate which laminate parameters affect the delamination resistance. Shokrieh et al. [6] mentioned a list of parameters may affect the mode I strain energy release rate (ERR) of MD DCB specimens, *e.g.*, delaminating interface, specimen geometry, stacking sequence and intralaminar damage or crack jumping. Also, Prombut et al. [7] and Gong et al. [8] discussed about the effect of these factors on the delamination toughness. Many studies are already conducted on the mode I fracture of MD laminates with different delamination interfaces [9–16]. When delamination propagates between layers of different orientations, two phenomena may occur: crack jumping to neighbor interface and mode-mixity. The reported results have shown that if a crack is initiated in a $\theta_1//\theta_2$ interface (// stands for the location of starter delamination in DCB specimens) with θ_1, θ_2 = 0°, 15°, 30° and 45°, the resistance heavily depends on the fracture surface morphology [8–10]. Delamination fracture toughness can be invariable, increasing or decreasing with adjacent ply angles. For example, Chai [10] confirmed that the measured G_{Ic} values are practically independent of the delaminating interface. As a result, there is no a general rule about the effect of the delaminating interface on the G_{Ic} in the literature.

Another important parameter is the non-uniformity of energy release rate along the width of DCB specimen or curved thumbnail shaped delamination front due to elastic bending–bending and bending–twisting couplings [17,18]. Davidson et al. [18] showed that the non-uniformity is proportional to the parameter $D_c = \frac{D_{12}^2}{D_{11}D_{22}}$, where D_{ij} are the bending stiffness coefficients of each specimen arm. Also, Olsson [19] mentioned that the anticlastic curvature of strain energy release rate increases from zero to a constant value with increasing crack length-to width ratio (a_0/b). In other words, he showed that for small values of a_0/b, the specimen is in a state of plane strain and for large aspect ratios it is globally in a state of plane stress. It was also indicated [20,21] that the average of G_I decreases as specimens transfer from plane stress to plane

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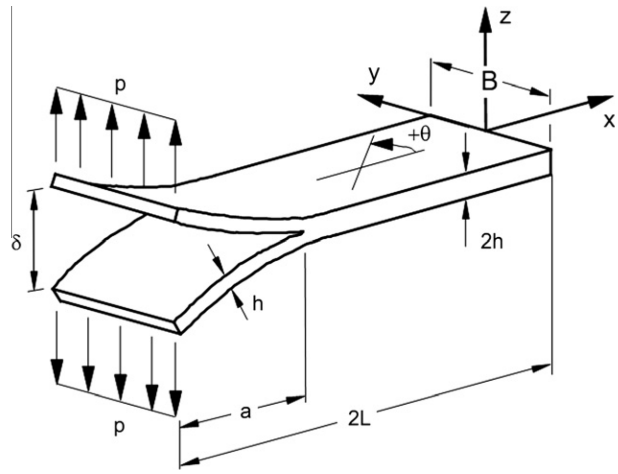

Fig. 1. Configuration of a DCB specimen.

strain. Therefore, size of DCB specimens such as initial delamination length (a_0), thickness (h) and width (b) significantly affect the behavior of the specimen and subsequently affect the G_{Ic} value. The condition of $D_c < 0.25$ is not sufficient to assure a uniform G_I width-wise distribution.

The objective of this paper is to evaluate quantitatively the effects of stacking sequence (curved delamination front), initial delamination length, thickness and width on G_{Ic} calculation of MD laminates with 0°//0° crack interface. The 0°//0° crack interface is selected to eliminate the unexpected effects of fiber orientation and intralaminar damages. From the above literature survey, it is found that the prediction of fracture toughness of MD laminates without doing any tests is a controversy problem yet. However, presenting a procedure for determining the G_{Ic} of MD laminates with respect to the material toughness measured on UD laminates is of great importance. Therefore, the DCB specimens are initially analyzed with three-dimensional finite element models and a non-uniformity ratio (β) is finally introduced to interpret the observed influence of the above-mentioned factors on the G_{Ic} value.

2. Finite element analysis of multidirectional DCB specimens

A commercial finite element package (ANSYS 12) was used to simulate mode I delamination tests. To investigate ERR distribution, three-dimensional finite element models have been used in this study to analyze the MD DCB specimens. A typical 3D finite element model of the DCB specimen is shown in Fig. 2. Delamination was modeled as a discrete discontinuity in the center of the DCB specimen with separate unconnected nodes on the upper and lower surfaces of the delamination section. Along the length, the model was divided into different sections with different mesh refinement. Across the width, the model was also divided into 21 sections and uniformly meshed to carefully capture the variation of energy release rate. The whole DCB specimen is modeled by four elements through the thickness. Two plies on each side of the delamination plane were individually modeled using one element for each ply. Elements which were usually used in ANSYS software for 3D modeling of structures are: three eight-node elements: SOLID45, SOLID46 and SOLID185; and two twenty-node elements: SOLID95 and SOLID186 [24]. Some researchers investigated the sensitivity of DCB model to element type and element size [22,23]. Krueger and Goetze [23] showed that the models made of solid twenty-node hexahedral elements and solid eight-node incompatible mode elements yielded excellent results. Also, the models made of standard brick elements and elements with reduced integration did not correctly capture the distribution of the ERR across the width of the specimens. Therefore, in this study, the layered SOLID46 element is used to mesh the MD DCB specimens. The boundary conditions and loading were defined as below [25,26]:

- Lower edge displacements in the x- and z-directions were fixed, *i.e.*, $u = w = 0$.
- A z-wise force was applied to the upper edge, for which $u = 0$.
- To prevent rigid body motion, $v = 0$ was imposed on one node of the lower edge.

Strain energy release rates were calculated along the straight delamination front using the virtual crack closure technique (VCCT). The VCCT method assumes the energy dissipated during the crack growth is just equal to the work necessary to close the crack. Therefore, G can be expressed in terms of the element resultants, which are calculated for the nodes of the elements immediately ahead of the delamination front and the nodal displacements of the elements behind the delamination front. All forces and displacements were obtained from the finite element analysis with respect to the global system. The calculation of G_I for each eight-node element position along the delamination front can be summarized by the following equation (Fig. 3):

$$G_I = \frac{1}{2b\Delta a} Z_{Li}(W_{Ll} - W^*_{Ll}) \tag{1}$$

where b is the specimen width; Δa is the crack increment; Z_{Li} is the vertical force at the crack tip in column L and row i; w_{Ll} and W^*_{Ll} is the vertical displacements of nodes behind the crack tip.

Since the VCCT method is so sensitive to the element size, mesh refinement and convergence studies were conducted with respect

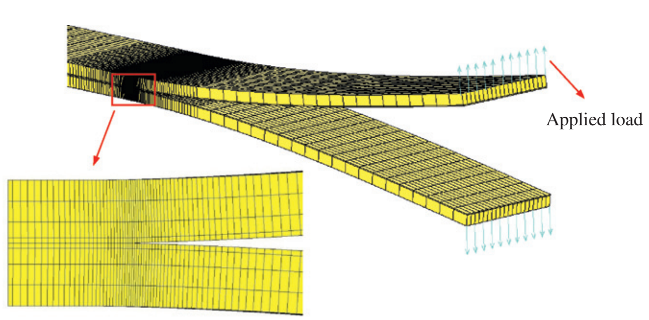

Fig. 2. Finite element mesh including a zoomed crack tip zone near the edge.

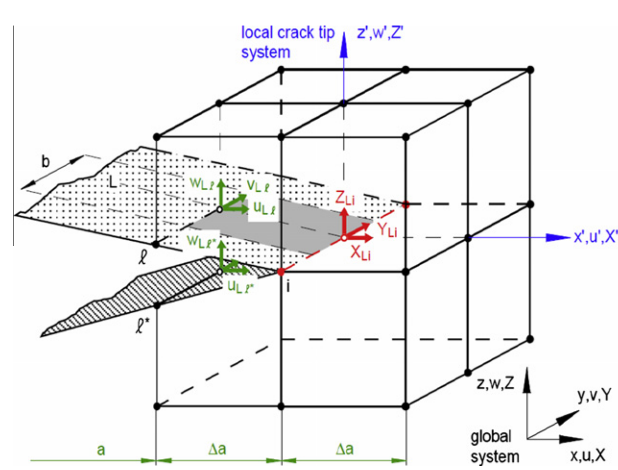

Fig. 3. VCCT for eight-node solid element [27].

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