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Delamination in cross-ply laminates: Identification of traction–separation relations and cohesive zone modeling

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ABSTRACT

Identification of traction–separation relations is at the forefront of damage and fracture mechanics of composite laminates. Such relations are of particular interest in fracture of laminates consisting of layers of different fiber orientations. In this study, an iterative method based on internal strain measurements and parametric numerical modeling is employed to identify a traction–separation relation in quasi-static mode I dominated delamination of a cross-ply carbon fiber epoxy laminate. The results demonstrate that crack propagation is accompanied by a large bridging zone which is smaller than the zone in a uniaxial composite specimen of the same materials and linear dimensions. While the initiation value of the energy release rate (ERR) is the same, the ERR at steady state propagation and the maximum stress in the bridging zone are respectively 1.7 and 3.1 times larger than the corresponding values of the unidirectional specimen. The obtained traction–separation relation is employed in a cohesive zone model to predict the loading response and crack growth. The adopted approach is a step towards a better understanding of delamination in cross-ply composites.

1. Introduction

It is well accepted that the various damage events taking place in the wake of delamination, in fiber reinforced composites, constitute major toughening mechanisms. In a phenomenological approach, these mechanisms are described by bridging tractions (or traction–separation relations) and employed in cohesive zone models in contemporary approaches to delamination [1–3]. Therefore characterization of such relations is of great importance in modeling and prediction methods of delamination. In several cohesive zone models, bilinear traction–separation expressions, shown via a maximum traction (cohesive strength) and the critical energy release rate (ERR) at initiation are conveniently assumed. This approach might be valid in the modeling of small scale crack bridging, however it is not sufficient for taking large scale bridging condition into account (i.e. a bridging zone length comparable to the specimen linear dimensions) since the tractions profile is a function of specimen geometry and not a material characteristic [4,5]. Independently to the adopted forms, extraction of traction–separation relations requires local measurements in the vicinity of the crack, such as monitoring crack opening displacement (COD) or strain fields, and a subsequent identification analysis using direct or iterative approaches [6–8]. The double cantilever beam (DCB) specimen is often used for characterization of mode I delamination in fiber reinforced composites. As argued in the literature, the fracture of a DCB specimen involves large scale fiber bridging after crack initiation, which depends on the specimen geometry, loading mode and ply orientation as well as the properties of constituent materials [5,9,10]. Such a toughening mechanism is not taken into account, as suggested by standard test procedures (e.g. ASTM D5528), as they are aimed at the critical vales of ERR at crack initiation. Nevertheless, a thorough analysis of crack propagation in composite laminates requires accounting for bridging effects especially in efforts to develop damage tolerance design methods. While fiber bridging is evident in unidirectional specimens, it can occur in other ply-layouts. Pertinent studies have shown significant differences between crack growth behavior in unidirectional DCB specimens and those of different ply orientations [10–16]. Moreover, it has been shown that delamination growth in multidirectional laminates results in a more pronounced crack growth resistance (i.e., R-curve behavior) compared to the unidirectional laminates of the same materials [10,14]. In previous works [7,17], an iterative approach has been proposed in order to identify

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traction–separation relations representing the damage process zone in delamination of unidirectional fiber reinforced composites. This method is based on distributed strain measurements along the delamination direction using embedded fiber Bragg grating (FBG) sensor(s) and inverse identification of the bridging tractions using parametric finite element (FE) analysis.

The objective of this work is to identify a traction–separation relation in delamination of cross-ply carbon-epoxy laminates subjected to monotonic loads. Subsequently, the identified tractions are employed in a cohesive zone model to predict the load–displacement response and crack growth.

2. Experimental methods

2.1. Materials and specimens

Carbon/epoxy prepreg SE 70 from Gurit ST™ is used to fabricate cross-ply composite plates (3.95 × 200 × 200 mm and thickness variation of 0.05 mm) with an asymmetric layup $[0/90]_{10}$. An initial crack starter is introduced at the mid-plane of the plate, at the 0/90 interface, by inserting a 60 mm long and 20 μm thick release film A6000® made of polytetrafluoroethylene copolymer with ethylene. During fabrication, a single mode optical fiber (SM28, 125 μm in diameter), with several FBG sensors is placed at 3 layers above the pre-crack plane along the longitudinal z-direction and referred to hereafter as 0° carbon fibers direction. The lay-up is cured using the standard procedure suggested by the prepreg manufacturer. Each cured plate is cut into 25 mm wide beams so that the optical fiber is centered in the beam. Specimens of DCB type are prepared according to the ASTM D5528 using steel loading blocks (10 × 25 × 10 mm) thus the initial crack length is reduced by 5 mm–55 mm. Details of the FBG sensors preparation and the means to locate the sensors in the specimen can be found in Refs. [5,17].

The elastic constants are measured using: (i) a four point bending test of the unidirectional laminate (ASTM D7264/D7264M–07) for the longitudinal modulus, (ii) a transverse tensile test (ASTM D3039/D3039M–14) for the transverse modulus and, (iii) a tensile test of the ±45° laminate (ASTM D3518/D3518M–13) for the in-plane shear modulus. The specimens used for those measurements are produced with the same material and curing condition as mentioned above. For the 0° layers, the following properties are obtained and used for the numerical analysis: $E_z^0 = 120.2$ GPa, $E_y^0 = E_x^0 = 7.3$ GPa, $G_{zy}^0 = G_{zx}^0 = 3.9$ GPa, $\nu_{zy}^0 = \nu_{zx}^0 = 0.28$, $\nu_{yx}^0 = 0.48$. The properties of 0° plies are rotated by 90° to obtain the elastic constants of the 90° layers.

2.2. Fracture testing

Monotonic DCB tests are performed using an Instron® machine equipped with a 2-kN load cell under displacement control with a constant rate of 2 mm/min. A representative photograph of a loaded cross-ply specimen is shown in Fig. 1a. In total six specimens are tested with the same conditions. Due to large scale bridging, non-linear material and/or geometrical effects may be important. In the present study, the strains as measured with the embedded sensors are below the yield limit of the epoxy matrix (Section 3.2). Regarding the load–displacement curves, small non-linear effects become apparent at relatively long cracks in the steady phase of propagation. A measure of the non-linearity in the load–displacement curves is obtained by comparing the energy under the load–displacement curve during unloading and its approximation by a linear unloading curve. For the cross-ply specimens examined in this paper, the differences in energy are up to 9%. Such differences are within the experimental error and considered acceptable. Thus, the total ERR G_t, associated with delamination growth, is calculated using the equation:

$$G_t = \frac{P^2}{2b}\frac{dC}{da} \tag{1}$$

here b is the width of the specimen; P is the reaction force; a is the crack length; C is the compliance of the specimen. Visually measured crack length data at every millimeter of crack growth and corresponding values of the specimen compliance, calculated as the ratio of the applied displacement over the measured load, are fitted to the following power expression $C = Ba^n$ to obtain sufficiently smooth data for subsequent differentiation. After testing, transverse and longitudinal sections are polished and examined under an optical microscope to reveal the morphology of the crack path and the surrounding microstructure (see Fig. 1b and c). Fracture surface of selected specimens are examined using scanning electron microscopy.

2.3. Strain measurements

Embedded single mode optical fibers with an array of 10 wavelength-multiplexed FBGs, each one having a 1 mm in gauge-length and equally spaced at 3 mm, are employed in order to measure the longitudinal strain distribution in the vicinity of the crack. The corresponding Bragg wavelengths are located between 1520 and 1565 nm (spaced by 5 nm) with a bandwidth of 1.2 nm. During fracture testing, the wavelength of the FBG sensors are simultaneously recorded using the Micron Optics SM130® interrogator with an acquisition rate of 100 Hz. It is observed that the Bragg peaks are only shifted in response to crack growth and do not split indicating a uniform strain field on the short gratings. Thus, considering the axial strain ε_z in each sensor as the dominant strain component, the Bragg wavelength shift $\Delta\lambda_B$, can be converted to the corresponding axial strain values $\varepsilon_{z,i}$ as follows:

$$\frac{\Delta\lambda_{B,i}}{\lambda_{B0,i}} = (1 - p_e)\varepsilon_{z,i} \quad i = 1, \ldots, 10 \tag{2}$$

here i indicates an FBG sensor along the optical fiber; $\lambda_{B0,i}$ is the initial Bragg wavelength value measured before the test and p_e is the effective photoelastic constant, equal to 0.2148 [17]. Fig. 2 shows the changes in Bragg wavelength recorded during the fracture test of a cross-ply DCB specimen. Each curve represents the response of an individual FBG to the applied displacement during the entire experiment. Note that the steep rise of each strain curve reflects the crack approaching an individual sensor and the linear decrease at the end indicates the specimen unloading. The local jumps are due to the stick-slip crack propagation in the cross-ply laminate. After specimen testing, the Bragg wavelengths are measured and compared with the corresponding values before testing in order to assess the release of the residual strains as a result of fracture. To obtain a quasi-continuous strain distribution for the subsequent analysis, the recorded strain-time data is combined with the crack length-time data to obtain strains vs. crack length. Subsequently, this data is expressed in the local crack tip coordinate system at the crack length a = 107.7 mm, corresponding to the position of the last FBG sensor, and used in the iterative identification method (Section 3.2) [17]. Note that, when several measurements are carried out, the experimental data are given as the mean value and the standard deviation of the measurements.

3. Numerical analysis

In this study four plane-strain models of the DCB testing