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The relationship between mixed-mode II/III delamination and delamination migration in composite laminates

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ABSTRACT

Predictive models have struggled to accurately simulate progressive delamination growth in composite structures, often due to the challenges associated with modelling delamination migration phenomenon. This paper presents a methodology with which to model such migration. Firstly, the interlaminar shear at a delamination front were partitioned into axial and transverse modes, the mode-mixity of which was controlled by the mismatch between this front and the ply directions. An element formulation was presented which utilised this mismatch. Consequently, delamination migration was shown to have ensued when the transverse mode exceeded a critical mode-mixity $G_{iii}/G_T = 0.22$. This approach was verified against experimental studies on width tapered end loaded split coupons by correlating the fracture morphology against mode-mixity. In particular, the orientation of the cusps on the delamination surface were shown to be controlled by the relative dominance of the axial and transverse modes. This methodology provides a means to accurately and robustly model progressive delamination growth processes in composite structures.

1. Introduction

Delamination is one of the most common failure modes for laminated composites. Laminates subjected to bending or compressive loads are especially critical as they generate high interlaminar stresses. Fracture mechanics has been classically used to assess the criticality of these stresses. To characterise damage growth, delamination is usually partitioned into three fracture modes: pealing (mode I), sliding (mode II) and tearing (mode III). Strain energy release rates (SERR) corresponding to these three fracture modes are explicitly calculated to predict the onset of delamination, for instance if a method such as Virtual Crack Closure Method (VCCT) is used [1]. This method is particularly useful if used in conjunction with a Finite Element (FE) method as the displacement jumps and nodal forces are easily extracted. The displacement jumps near the crack tip are expressed in components normal to the crack plane (mode I) or parallel to the crack plane (shear mode). The latter is further divided in two components, one normal to the crack front (mode II) and one parallel to the crack front (mode III). The nodal forces can also be projected in these directions.

While this partition is useful for calculating mode I, II and III SERRs at isotropic interfaces, its definition may be incomplete for composite ply interfaces. It has been suggested in the past that mode II and mode III loading in cross-ply interface should produce identical results [2]. Similarly, it has been suggested that mode II loading of a 0°/0° ply interface should be equivalent to a mode III loading of a 90°/90° ply interface [3]. However, these hypotheses have not been verified experimentally.

Analysing the stresses near the crack tip under mixed-mode delamination suggests that these hypotheses may not hold. It is generally recognised [4] that damage initiates at the fibres and extends into the matrix through a series of angled microcracks that develop ahead of the crack tip (Fig. 1). The angle (φ) at which the microcracks develop is dictated by the resolved stress (σ_R) near the crack tip. When these microcracks coalesce, and provided the shear component is sufficient, the delamination effectively propagates directly adjacent to one of the plies at the interface (referred to as the fibre-dominated side). Whether it is the uppermost or lowermost ply is dictated by the orientation of the applied shear stress component [5]. After initiation, the behaviour of the delamination will depend on the orientation of the directing ply (identified hereafter with an underline), i.e. the ply close to which the delamination will propagate. This suggests that uniquely the directing ply is involved in the delamination propagation behaviour. In addition, if the direction of the directing ply exceeds a critical mismatch with the delamination growth direction [6], the delamination migrates. This would lead to secondary failure modes which would affect the fracture surface morphology and the apparent toughness.

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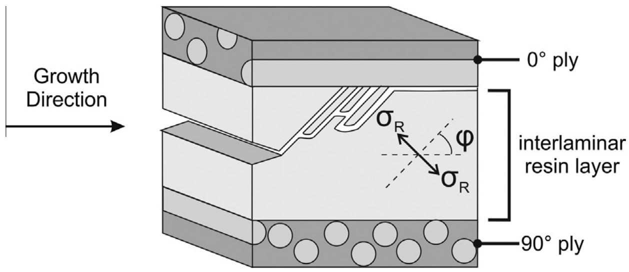

Fig. 1. Delamination growth in mixed-mode delamination starting at the interlaminar resin layer in a 0°/90° ply interface [5]. The angle φ at which the microcracks develop is dictated by the resolved stress (σ_R) in the interlaminar resin layer near the crack tip.

Traditionally, fracture toughness tests have been conducted in unidirectional laminates; however, delaminations in structures almost exclusively appear at multidirectional ply interfaces. Characterising such interfaces has proven to be problematic as delamination migration is commonly reported in test coupons when the growth direction is not aligned to the fibre direction [2].

Attempts have previously been made to redefine virtual crack closure technique to account for the fibre effect of the directing ply [7] and the mismatch between the delamination driving forces and the controlling ply direction (β). Lord et al. [7] analysed the problem of an initially circular delamination growing in a non-necessarily self-similar manner. They created a cylindrical mesh (Fig. 2) and proposed a modified VCCT method. The method suggested (Fig. 2) defined a point (c) at the same distance (Δ) as the node used for the calculation of the displacement (b) in VCCT but aligned with the direction of the fibres at the directing ply (ϕ). The coordinate system for the extraction of nodal forces (at point a) and displacements (at point c) was also defined according to the direction of the fibres at the directing ply (ϕ). While changes of coordinate system in VCCT are commonly performed for geometrically non-linear problems and for arbitrarily shaped delamination fronts [1], the method of Lord et al. [7] is perhaps the only one in the literature to partition the shear mode in this way.

The aim of this paper is to investigate the aforementioned coordinate transformation using a width tapered end loaded split (WTELS) specimen [6] and to validate the results against fractographic observations. The numerical models reported here will utilise experimental results previously reported by Canturri et al. [6]. This transformation will ultimately relate the mixed-mode II/III mixity and the incidence of migration in laminated composites, thus providing a physically-based methodology for predicting damage development in composite laminates.

2. Experimental setup

The experimental results used for this numerical study had been previously reported by Canturri et al. [6]. For completeness, details of the geometry and layups used by Canturri et al. [6] are briefly repeated here and are detailed in Table 1 and Fig. 3. Four Configurations were considered and five specimens of each Configuration were tested. Further details of the specimen manufacture and experimental results can be found in [6]. The stacking sequences were designed to produce growth at four different interfaces with the directing ply being at 0°, +45°, −45° and 90° with respect to the beam direction. Migration was observed in all the configurations; in this paper, the initial delamination conditions along the front which led to these migrations are investigated. For the fractographic inspection, a Hitachi S-3700 N scanning electron microscope with an acceleration voltage of 15 kV was used. Specimens were mounted on stubs and gold sputtered during 40 sec in an Agar Automatic sputter coater.

3. Numerical study

Fig. 4 outlines the main difference between a one-step VCCT [1] and the proposed modifications used in this paper which are based

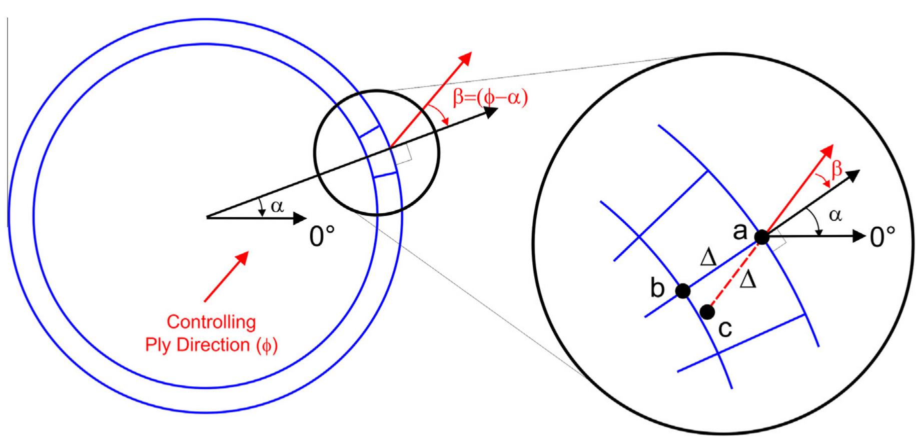

Fig. 2. Redefined nodal position for determining G_{II} and G_{III} [7]. While α defines the orientation of the crack front, crack growth depends on the orientation of the dictating ply, defined by ϕ, and their mismatch β. The points a and b are nodes in the FE mesh, point c is a point defined in this figure, all used for VCCT calculations.

Table 1
Stacking sequences for the four configurations studied and predicted engineering properties [6].

	Stacking sequence (with respect to span)
Configuration 1 Interface $90^\circ/\underline{0^\circ}$	$[(90^\circ/{+45^\circ}/{-45^\circ}/0^\circ)_s(90^\circ/{-45^\circ}/{+45^\circ}/0^\circ)_s\ //(\underline{0^\circ}/{-45^\circ}/{+45^\circ}/90^\circ)_s\ (0^\circ/{+45^\circ}/{-45^\circ}/90^\circ)_s]$
Configuration 2 Interface $+45^\circ/\underline{-45^\circ}$	$[({+45^\circ}/0^\circ/90^\circ/{-45^\circ})_s({+45^\circ}/90^\circ/0^\circ/{-45^\circ})_s\ //(\underline{-45^\circ}/90^\circ/0^\circ/{+45^\circ})_s({-45^\circ}/0^\circ/90^\circ/45^\circ)_s]$
Configuration 3 Interface $-45^\circ/\underline{+45^\circ}$	$[({-45^\circ}/0^\circ/90^\circ/{+45^\circ})_s({-45^\circ}/90^\circ/0^\circ/{+45^\circ})_s\ //(\underline{+45^\circ}/90^\circ/0^\circ/{-45^\circ})_s({+45^\circ}/0^\circ/90^\circ/{-45^\circ})_s]$
Configuration 4 Interface $0^\circ/\underline{90^\circ}$	$[(0^\circ/{-45^\circ}/{+45^\circ}/90^\circ)_s(0^\circ/{-45^\circ}/{+45^\circ}/90^\circ)_s\ //(\underline{90^\circ}/{-45^\circ}/{+45^\circ}/0^\circ)_s(90^\circ/{+45^\circ}/{-45^\circ}/0^\circ)_s]$