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Observation of intralaminar cracking in the edge crack torsion specimen

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ABSTRACT

The edge crack torsion (ECT) test is evaluated to determine its suitability for measuring fracture toughness associated with the onset of mode III delamination in laminated composites. ECT specimens with preimplanted midplane inserts of different lengths are tested and examined using nondestructive and destructive techniques. Ultrasonic inspections of all tested specimens reveal that delamination growth occurs one ply interface beneath the midplane. This is confirmed by sectioning and optical microscopy, which also show that macroscopic delamination advance results from a coalescence of angled intralaminar matrix cracks that form in-between and then extend through the midplane plies. The relative orientation of these intralaminar cracks is approximately 45° with respect to the midplane, suggesting that their formation is caused by resolved principal tensile stresses arising due to the global mode III shear loading. Examination of ECT specimens tested to loads below the level corresponding to the onset of delamination growth reveals that initiation of intralaminar cracking occurs prior to or concurrently with the onset of nonlinearity in the specimen's force–displacement response. The existence of intralaminar cracking prior to delamination growth and the resulting delamination extension at an unintended interface render the ECT test, in its current form, unsuitable for characterizing the onset of mode III delamination growth. The broader implications of the mechanisms observed in this study are also discussed with respect to the current understanding of shear-driven delamination in tape-laminate composites.

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1. Introduction

Delamination has long been recognized as a key failure mode for laminated fiber-reinforced polymeric (FRP) composites. In addition to growth under predominantly mode I (opening) loading conditions, delamination may also occur due to loading in mode II (in-plane shear), mode III (anti-plane shear), or some combination of the three. Common procedures for characterizing the onset of delamination growth are generally based on the critical strain-energy release rate, G_c, which is associated with a particular delamination mode or mode mixity. Methods for measuring G_c associated with mode I, mode II, and mixed mode I/II delamination at unidirectional ply interfaces are well established and are available as standardized tests [1–3]. Although many test methods have been proposed for measuring the value of G_c associated with mode III growth

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Nomenclature

G_c	critical strain energy release rate
G_{IIIc}	critical strain energy release rate associated with mode III delamination
a	insert length
b	ECT specimen width
w	distance separating load and support pins along specimen width
L	ECT specimen length
l	distance separating load and support points along ECT specimen length
P	applied force
D_{16}	bend-twist coupling
D_{26}	bend-twist coupling
B_{16}	extension-twist coupling
B_{26}	extension-twist coupling
P_{NL}	force at onset of nonlinearity in the force-displacement response
P_{max}	maximum force achieved
C	specimen compliance
A	constant from relation between compliance and normalized insert length
m	constant from relation between compliance and normalized insert length
K_{III}	mode III stress intensity factor
τ_{xz}	x–z direction shear stress resultant from mode III loading
τ_{zx}	z–x direction shear stress resultant from mode III loading
σ_1	1 direction principal stress resultant from mode III loading
σ_2	2 direction principal stress resultant from mode III loading

(G_{IIIc}), identifying a candidate most suitable for standardization has proven difficult. Although early efforts considered various split beam geometries [4–6], the majority of work in this area has focused on the edge crack torsion (ECT) test [7].

The ECT test geometry is depicted in Fig. 1. The specimen is rectangular and fabricated from composite tape material. It contains a preimplanted insert at its midplane that spans the specimen's length. The specimen is twisted via equal-and-opposite couples resulting in mode III dominated crack-tip stresses acting along the insert's front. The two plies bounding the insert are oriented such that their fiber direction is parallel to the expected direction of delamination advance (90° orientation in Fig. 1) [7]. This is done with the assumption that the delamination growth will be in the direction of the adjacent plies, and is consistent with the mode I, mode II and mixed-mode I/II delamination toughness tests [1–3].

Because delamination advance cannot be visually documented during an ECT test, Lee [7] proposed two data reduction methods for calculating G_{IIIc}. The first method uses a laminated plate theory solution that requires experimental determination of the compliance of the cracked regions of a test specimen. In this method, subsequent to fracture, test specimens are split into two halves about their midplane and the compliance of each half is measured by loading it in the ECT fixture [7,8]. The second data reduction method uses an experimental, multi-specimen compliance calibration procedure [7]. Here, multiple ECT specimens with different insert lengths, a (as defined in Fig. 1), are tested. This yields a direct measurement of specimen compliance versus delamination length and avoids many of the practical difficulties associated with the former method. One disadvantage of this compliance calibration procedure, however, is that the compliance versus delamination length expression for any single specimen is based on test results from several different specimens.

A number of previous investigations into the ECT test have highlighted other issues. For example, Ratcliffe [8] reported that the specimen's force versus deflection response deviated from linearity prior to delamination growth onset, with growth

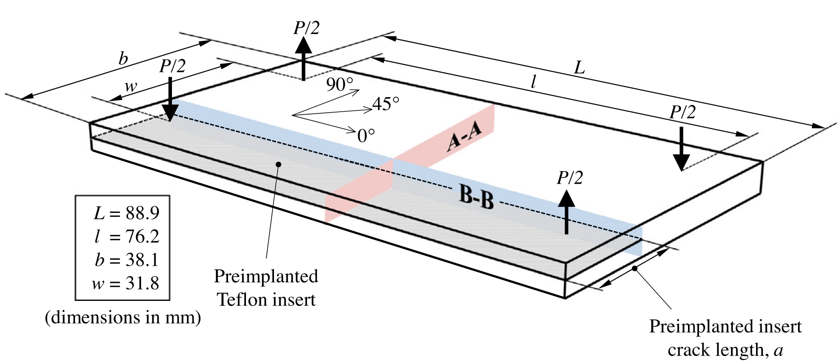

Fig. 1. The ECT test geometry. Planes A–A and B–B define cuts made for optical examinations.