Materials and Design 94 (2016) 303–313

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

In-situ measurements of fracture toughness properties in composite laminates

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ARTICLE INFO

Article history:
Received 1 November 2015
Received in revised form 30 December 2015
Accepted 4 January 2016
Available online 7 January 2016

Keywords:
Composite laminates
In-situ measurements
Non-destructive evaluation
Fracture toughness
Finite element analysis

ABSTRACT

Prediction of matrix failure in composite laminates can be accomplished using computational methods based on material strength and fracture toughness. Engineering theories and failure criteria, which use such material properties generated by current standard experimental methods, may result in poor accuracy of predicting structural strength and fatigue characteristics due to complexity of deformation and failure mechanisms in composites. In this work the applicability of fracture toughness properties measured using standard test methods is investigated. A customized X-ray Computed Tomography system with a 50 kN axial force capacity integrated load frame, enabling full scanning under load, is utilized for accurate 3D in-situ measurements of crack geometry in composite Double Cantilever Beam specimens and Open Hole Tension specimens. These experiments are used to determine Mode I and Mode II fracture toughness based on finite element analysis of models transferred from the tomographic measurements. While measured interlaminar Mode I fracture toughness is in good agreement with standard tests, intralaminar Mode II fracture toughness is shown to depend on crack length.

1. Introduction

Prediction of matrix failure in composite laminates, including both intra- and interlaminar failure, can be accomplished using computational methods based on material strength and fracture toughness [1–3]. The two approaches are often used separately, and the effects of damage mode interactions are not included in failure predictions. Material property measurements are performed on specimens that localize one failure mode and minimize interactions with the other types of damage [3]. Toughness properties measured in such experiments are used in computational methods that simulate both interlaminar and intralaminar (matrix ply-cracking) failure.

For example, interlaminar fracture toughness properties are measured in composites according to ASTM D5528 standard [4] for Mode I failure and according to ASTM D7905 standard [5] for Mode II failure. No standard exists for Mode III failure although an edge crack torsion test was recommended [6]. In these test methods crack growth initiates from relatively large pre-cracks typically simulated by inserts. Fracture toughness properties obtained from these tests tend to depend on crack length, and properties related to crack initiation and propagation are reported [5]. Intralaminar fracture toughness as well as interlaminar toughness are affected by fiber bridging. Reference [7] suggested that the effect of fiber bridging on intralaminar toughness may be more significant although it reported essentially equivalent interlaminar and intralaminar toughness characteristics.

Computational methods that predict matrix damage development in composite laminates typically use stress-based criteria for damage and crack initiation, and fracture toughness properties for crack propagation. One example is damage simulation methods that use cohesive zone elements [8,9], where crack propagation is based on the traction–separation law that equates the area under the traction–separation curve to fracture toughness in the respective mode or a mixed-mode expression. Most applications used a bi-linear cohesive law that corresponds to a single-parameter fracture criterion; however recent results for cohesive zone modeling of the Double Cantilever Beam and End Notched Flexure tests have shown that crack length and shape of cohesive law can have a significant effect on the post-peak response [10]. On the other hand, damage simulation methods that include interaction between intra- and interlaminar failure modes [2,11] are based on the assumption of multiple crack initiations, arrests and restarts, and use stress-based failure criteria that also depend on fracture toughness material allowables [1]. There is a lack of test methods for determining fracture toughness of small cracks and including the effects of crack front geometry adding to the uncertainty in damage predictions.

Fig. 1 shows an example of structural damage in an 8-ply open-hole $[0_2/90_2]_S$ Carbon/Epoxy laminate subjected to static tensile loading. The Figure shows matrix cracks developing in all laminate plies, delaminations at the 0/90 ply-interfaces between the intersections of matrix cracks and surface of the hole. Delaminations also extend to the opposite quadrants following the development of zero-degree cracks. Even in the case of thin plies, as shown in this example, matrix cracks may have curved fronts leading to variations in crack length through the thickness of the ply and inclined or non-planar crack surface.

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http://dx.doi.org/10.1016/j.matdes.2016.01.008
0264-1275/

Nomenclature

G_I	strain energy release rate, Mode I
G_{IC}	fracture toughness, Mode I
p_c	crack front profile
x	coordinate along DCB specimen width
x_c	curvilinear coordinate along crack front
w	DCB specimen width
a	crack length
z	coordinate through OHT specimen thickness
t	OHT specimen thickness

Damage geometry in this laminate specimen demonstrates patterns that are different from the cracking reproduced in standard tests. These observations motivated the authors to investigate the applicability of fracture toughness properties measured in standard tests, in failure predictions of notched specimens.

Recent advances in high-resolution non-destructive evaluation methods such as 3D X-ray Computed Tomography (CT) led to a fundamental change in defect analysis methods by allowing high-fidelity detection of defects in composites and automatic transition of the defect information to structural analysis models [12]. Since X-ray CT uses spatial density contrast to detect boundaries between different media, successful crack detection depends on the crack opening being comparable to the resolution (voxel size) of the scan. Crack surface closure that results from unloading, may lead to inaccurate crack detection. In this work, in-situ measurements by the customized X-ray CT facility are used to provide accurate subsurface geometry detection of structural defects. We used an X5000 X-ray CT system manufactured by North Star Imaging that was customized with the internal installation of a 50 kN axial force capacity electromechanical load frame [13]. In the customized system, two rotational stages are automatically controlled with precise angular positioning required for the in-situ CT scans. The micro-focus CT system used in this work is able to detect structural defects of less than 10 μm in thickness for coupon-sized articles. According to the review of existing in-situ X-ray CT devices [14], this system is unique in its load capacity, specimen size and resolution. The unparalleled high fidelity of measurements by X-ray micro-CT allows transition of measurements to structural models by means of feature analysis of CT reconstructions and automatic scripting available in modern Finite Element (FE) simulation software.

In this work, performance of the in-situ X-ray CT facility is validated by measurements of the advancing crack front in Carbon/Epoxy composite Double Cantilever Beam (DCB) specimens used as standard test for interlaminar Mode I fracture toughness. Fracture toughness measurements obtained per ASTM standard are compared with the FE-based calculations that use high fidelity subsurface measurements of curved crack fronts. Virtual Crack Closure Technique (VCCT) [15] is used to calculate strain energy release rates along the crack front measured in X-ray CT scans of the specimens under the load. In the second part, the in-situ X-ray CT facility is used for high precision measurements of crack geometry and locations, including curved crack fronts and crack plane angles, to determine the intralaminar Mode II fracture toughness in unidirectional Carbon/Epoxy composite Open Hole Tension (OHT) specimens. Technical challenges of this analysis are the ability to accurately measure structural defects in three dimensions and subsequent accurate modeling of the subsurface defect geometry in structural models. FE models that include highly detailed modeling of structural defects are used to calculate strain energy release rates for the in-situ measured structural defect geometry.

The objective of this work is to investigate the in-situ development of structural damage in composite laminates and to measure critical values of strain energy release rates that correspond to the subcritical crack development in composite laminates. As complex geometry of structural defects is uncovered by high fidelity three-dimensional X-ray CT measurements and used in FE modeling to calculate strain energy release rates corresponding to subcritical crack growth, the applicability of analysis methods that use single-parameter fracture toughness property for damage predictions is questioned. Accurate calculation of mode mixity and critical strain energy release rates provides new insights in fracture mechanics-based predictions of damage in composite laminates.

2. X-ray CT facility with an integrated load frame

A concept for load frame installation in X5000 X-ray Computed Tomography system manufactured by North Star Imaging was developed in Ref. [13] and further validated in Ref. [14]. A conceptual drawing of the load frame used in X-ray CT is shown in Fig. 2. The specimen is suspended between the grips that are mounted on two rotating stages moving synchronously to perform X-ray CT scan in the current loading state. Also, since the actuations of each rotating stage are independent,

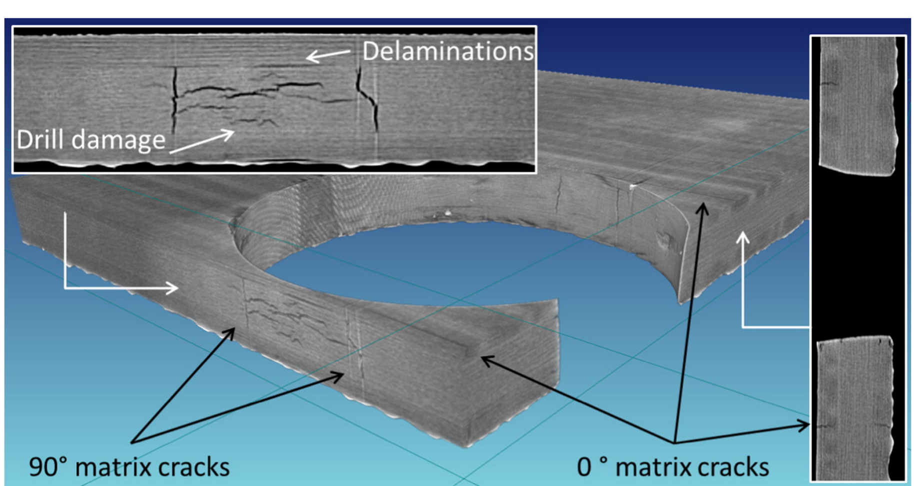

Fig. 1. Complex interaction and geometry of damage in an open-hole composite laminate under tensile load.