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Experimental determination of fracture toughness for adhesively bonded composite joints

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ABSTRACT

The characterization of fracture toughness or critical energy release rate of adhesive joint in composite structures is a key parameter. In the present study, fracture toughness of adhesively bonded composite joints is experimentally investigated for the basic fracture modes. Experiments are conducted on the double cantilever beam, end notched flexure and edge crack torsion specimens to determine the fracture toughness of three modes, namely mode-I, mode-II and mode-III. Specimens are bonded with epoxy adherent and cured at room temperature. The fracture toughness values of mode-II and mode-III are 2.6 and 4.6 times respectively of mode-I. Acoustic emission (AE) technique is also employed to aid in determining the fracture toughness of bonded joints. The results indicate that AE signals have good correlation with load–displacement behavior to determine the fracture initiation stage especially in the mode-II loading.

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1. Introduction

Adhesively bonded joints are playing an ever-increasing role in composite structures for aerospace applications due to its potential advantages over mechanical fastening like low weight, no machining and better stress distribution. Pethrick [1] presented the review on adhesives for structural bonding provides an insight into the factors such as adhesive type, cure time, temperature, surface treatment of the adherend surfaces prior to bonding, thickness of adhesive layer and the type of operating environment which needs to be considered to achieve the durable bonds. The performance and durability of an adhesive bond are critically dependent on the stability of the interface between the adhesive and adherend and is sensitive to the pre-treatment processes used in the creation of the bond. Process induced defects like debonds on the bonded joints is one of the major issues in advanced laminated composite structures. It necessitates the knowledge on damage tolerance of composite joints for establishing design allowable on the design of composite structures. The traditional approach for analyzing failure mechanisms of adhesive joints in the presence of defects, is the use of linear elastic fracture mechanics (LEFM), which is on the basis of an energy parameter, i.e., critical energy release rate (G_C) when material non-linearities can be neglected. In the design phase of bonded composite structures, failure analyses are often employed which require reliable characterization of the material properties. The main focus of this work is to determine the critical energy release rate or fracture toughness values of adhesively bonded CFRP joints under the three basic fracture modes of loading, namely opening, shearing and tearing. Fracture toughness parameters play a vital role in prediction of onset of defect growth, especially in

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Nomenclature

a	crack length
b	width of the specimen
G_{Ic}	critical fracture toughness for mode I
G_{IIc}	critical fracture toughness for mode II
G_{IIIc}	critical fracture toughness for mode III
Δ	correction factor for rotation in DCB
P	load
δ	load point displacement
C	compliance
n	slope

bonded composite structures. Appropriate test methods are reported in the literature to determine the fracture toughness parameters under various modes of loading. Chaves et al. [2] presented a detailed review on the fracture mechanics characterization test for adhesively bonded joints under mode-I, mode-II, mixed-mode I + II and the data reduction techniques. The test techniques for interlaminar fracture toughness in mode-I have been well established. However, standard for mode-II is being evolved and there is no standard test method of mode-III at the present stage. Standard test method ASTM-D5528, for mode-I interlaminar fracture toughness of unidirectional fiber-reinforced polymer matrix composites using double cantilever beam (DCB) specimen are approved by ASTM international body [3]. The significance, specimen configurations, detailed test procedure and data reduction methods to determine mode-I fracture toughness (G_{Ic}) is described. Stevanovic et al. [4] investigated the influence of pre-crack conditions on the fracture behavior of unidirectional vinyl-ester/E-glass composite. Their study revealed that pre-crack conditions had the influence on the initiation values of the G_{Ic} and the propagation values of the strain-energy release rate were unaffected by the pre-crack conditions. de Moura et al. [5] proposed a data reduction scheme based on the crack equivalent concept to obtain fracture toughness, which does not require crack length measurement during its growth and accounts for the energy dissipated at the fracture process zone, which can be non-negligible when ductile adhesive are used. Studies on the fracture behavior of adhesively bonded joints to determine the fracture toughness were investigated by many researchers [6–9].

The early study on the determination of mode-II fracture toughness (G_{IIc}) using end-notched flexure (ENF) specimen under three point bending was reported in the literature [10]. The ENF test is the most commonly used test for determining the mode-II delamination toughness of laminated composites. Schuecker and Davidson [11] investigated experimentally, the four-point bend end-notched flexure (4ENF) test for the mode-II fracture toughness evaluation and reported that if compliance and crack length are measured accurately, then 4ENF and ENF tests will produce essentially the same values for toughness. In the recent decade debond problems have received a growing interest, so many investigations on the determination of mode-II fracture toughness of various materials accounting geometric, loading parameters and data reduction methods were reported in the literature [12,13]. The ENF test for mode-II fracture toughness is currently under review by ASTM as a potential standard test method and the draft ASTM procedure for G_{IIc} was laid [14]. Several test techniques have been examined as ways to measure mode-III fracture toughness (G_{IIIc}) in literature, including a split cantilever beam [15]. Chen et al. [16] investigated the fracture toughness of bulk adhesive in mode-III using circular specimen with a notch under torsion accounting curing effect. The most commonly investigated mode-III fracture test method is the edge crack torsion (ECT) test. Ratcliffe [17] presented the ECT specimen configuration, laminate sequence to attain mode-III fracture toughness by minimizing the mode-II contribution in the ECT specimen and data reduction methods based on the compliance calibration method. The test data reduction schemes are intended to yield initiation values of critical mode-III strain energy release rate (G_{IIIc}). Pennas and Cantwell [18] studied the influence of loading rate on the mode-III fracture toughness of adhesively bonded composites and found that it does not exhibit any significant rate-sensitive fracture behavior. Browning et al. [19] investigated the effect of support length of ECT specimens and their study revealed that specimens with smallest overhang produced the most consistent delamination toughness data. Mehrabadi and Khoshravan [20]; Mehrabadi [21] studied numerically and experimentally the delamination behavior of woven glass fiber reinforced polymer laminates using ECT specimens for pure mode-III and mixed-mode (III + II). Czabaj et al. [22] examined the 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. Currently the accepted standard for the ECT test to characterize the mode-III fracture toughness in not available, which the ASTM is working on to standardize. Determination of fracture toughness and fracture behavior, stable/unstable propagation of delamination under various modes of loading, using finite element analysis are also reported in the literature [23,24].

To achieve the aim of this study, the fracture behavior of carbon/epoxy composite–composite adhesively bonded joint is studied experimentally to characterize the fracture toughness of adhesive by measuring the critical energy release rates of the basic fracture modes using DCB, ENF and ECT specimens. This will serve as reliable material fracture properties of the used adhesive to enable the composite designer to carry out the failure analysis of bonded joints in the presence of defects.

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