



Mixed mode delamination of glass fiber/polymer matrix composite materials
by Pancasatya Agastra

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Chemical Engineering
Montana State University
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Abstract:

Delamination between layers in composite materials is a major source of structural failure. Delamination resistance, is quantified by the critical strain energy release rate, G . The strain energy release rate in the opening mode (mode I) is symbolized by G_I and in the shearing mode (mode II) by G_{II} . In service, most failures occur by mixed mode delamination cracks. The Mixed-Mode Bending test has been developed to produce a wide range of mixed-mode conditions for composite materials specimens.

Unidirectional stitched fabric E-glass composites with three different resins, isophthalic polyester, vinyl ester and epoxy, were tested for their delamination resistance. The resins represent the types of resins commonly used for the wind turbine blades. Seven G_I/G_{II} ratios were tested. In descending order, the toughest composite materials used: epoxy, vinyl ester, and isophthalic polyester resins.

Finite element models of the three different test geometries, each with three different resins, were also created to validate the data reduction and experimental methods. The G -values were calculated using the one-step virtual crack closure method (VCCT1). The first validation was a comparison between the experimental deflection and that from modified beam theory and finite element models. The second validation was a comparison between the modified beam theory and finite element G -values.

The final step was to explore mixed-mode delamination criteria. All three resin systems produced a maximum in the G_I component at failure, for some intermediate G_I/G_{II} ratio. Several different types of failure criteria, implicit and explicit forms, were fitted to the mixed mode test results. The power interaction criterion, an explicit form, fit the data best according to the R^2 value. The updated failure criterion is now available for implementation in finite element models of complex structures.

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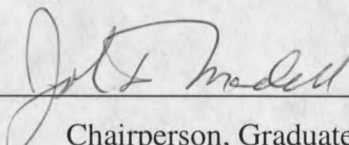
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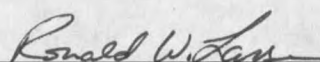
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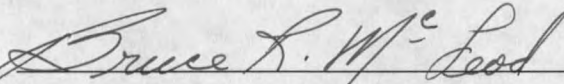
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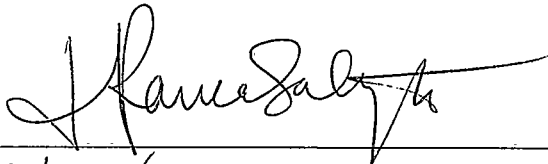
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ABSTRACT

Delamination between layers in composite materials is a major source of structural failure. Delamination resistance is quantified by the critical strain energy release rate, G . The strain energy release rate in the opening mode (mode I) is symbolized by G_I and in the shearing mode (mode II) by G_{II} . In service, most failures occur by mixed mode delamination cracks. The Mixed-Mode Bending test has been developed to produce a wide range of mixed-mode conditions for composite materials specimens.

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INTRODUCTION

Demands for Megawatt Wind Turbine Blades

Renewable energy will gain importance as the fossil fuel is depleted, and people have to find other sources of renewable energy. Wind energy is one of many options for renewable energy. In the world, the US is the second largest producer of wind power after Germany. A lot of the technology originates from Denmark. The leading energy company, GE, is currently testing a prototype of a 3.6 MW wind turbine blade, with a colossal rotor diameter of 104 m. The largest operating wind turbine in North America is operating in Big Spring, Texas, Vestas 1.65 MW V-66 spanning 66 meters in rotor diameter, owned by York Research Corporation.

In relation to the growing size of wind turbine blades, the fundamentals of understanding the constitutive materials must also grow. Montana State University has done extensive research on the behavior of materials used in wind turbine blades [1,2]. The most common materials for wind turbine blades are fiberglass composites. Composites are superior because their strength can be tailored to meet the required application, lightweight, and the specific strength (strength per weight) is high.

One major drawback of composite materials is delamination—separation of a laminate into layers. One major US Company, Kenetech, failed partly because of delamination failure at the trailing edge [3]. The size of the wind turbine blades, without the proper understanding of the material behavior, is likely to produce failure due to delamination.

Many ways have been found to resist delamination, for example weaving the fibers increases the toughness, but introduces micro-buckling modes, which is detrimental to the compressive strength; toughening the resin suppresses delamination but often decreases the modulus, an inherent trade-off in increasing toughness in the resins. Toughened resins are commonly used in aerospace prepregged materials, to resist delamination [4]. However, the cost of using prepreg materials in wind turbine manufacture can be high. Hence, low cost composite materials are sought for building wind turbine blades, such as fiberglass, where delamination has not been studied in detail.

There are three fundamental ways delamination can happen: opening mode, shearing or sliding mode, and tearing mode. More often than not, delamination occurs under mixed opening and shearing modes, which is the subject of this study.

This study is the extension of researches by Darrin Haugen [5] and Robert Morehead [6], who studied delamination of the skin-stiffener intersection geometry which is common in composite materials structures like wind turbine blades. This work combines, adds to, and revises their earlier work.

This research has explored the delamination of resin transfer molded (RTM) composites under mixed mode conditions, modes I and II, which occurs more commonly in applications than pure modes. The test method used for mixed mode fracture is the Mixed Mode Bending (MMB) Test. At the time this paper is written, the ASTM Standard for MMB had only recently been published [7]. Mixed mode conditions can occur in places where there is a change of geometry, i.e. a ply drop, an inevitable design characteristic of tapered structures. A ply drop is a geometric variation where one or

more plies are discontinued because of design requirements. At the ply drop, a stress concentration is formed at the corner of the dropped ply. The stress concentration generally contains a mixed mode condition; however, the mode components are unknown without a detailed analysis, as by FEA.

In the Double Cantilever Beam (DCB) specimen, a pure mode I test, the End-Notched Flexure (ENF) specimen, a pure mode-II test, and the MMB test geometries, the modal components are known; therefore, the strain energy release rates can easily be calculated. In this study, the test specimens are modeled by finite element analysis and the G 's are calculated using a numerical approach, the Virtual Crack Closure Technique, VCCT [8-11]. These models are the basis for calculating G -values at ply drops.

Once the test specimen models are validated, that is, the experimental values match the numerical values, then a mixed mode failure criterion is established. This criterion can then be used to predict the critical load of a complex structure, i.e., ply drops. The author hopes to establish a new level of analysis of delamination in composite materials structures using finite element analysis.

BACKGROUND

Delamination

Delamination between layers or plies of a composite laminate is a major weakness in composite materials. Delamination may reduce the stiffness of components and cause a catastrophic failure. A source of delamination is a stress concentration, which usually appears at a geometric discontinuity, i.e. edges and ply drops.

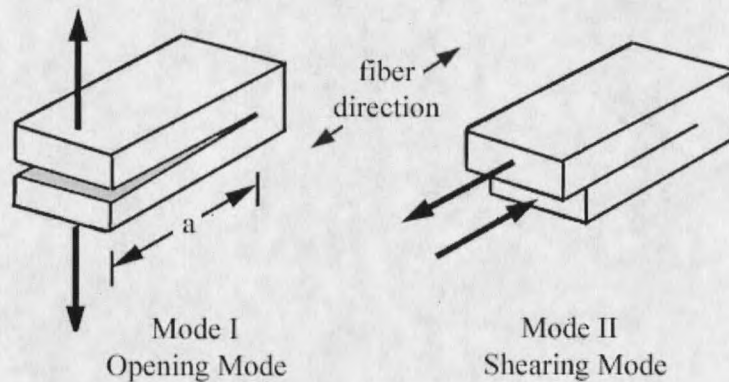


Figure 1 Two modes of crack propagation.

Delamination can occur in three modes:

1. Mode-I, opening mode, referred to as the out-of-plane delamination;
2. Mode-II, shearing mode, in-plane delamination;
3. Mode-II, tearing mode (not illustrated), anti-plane delamination.

Mode I and II are illustrated in Figure 1. The two modes of interest are mode-I and mode-II, as they are the most common modes of composite fracture. The most common approach to delamination analysis is the calculation of the strain energy release rate, SERR, with the symbol G , based on linear elastic fracture mechanics, LEFM. This

method is limited to "brittle matrices"; for tough matrices, another method like elastic-plastic fracture mechanics may be employed, i.e., J-integral [12,13]. G is a measure of how tough the material is in resisting delamination and can be calculated from the load-deflection curve.

The criterion for the critical load used for metals is the 5% offset load from a load-deflection curve as prescribed in ASTM E399 [14]. The five percent method lumps nonlinear effects of small crack extension and material response into a modified linear calculation. Delamination is dominated by the resin property; as the resin gets tougher, the delamination becomes less brittle, which may limit the linear analysis of toughness [12]. In the load-deflection curve, crack extension is sometimes indicated by a sudden drop in load, under displacement controlled testing.¹

The most common criterion for mode-I fracture toughness for metals is the critical stress intensity factor, K_{Ic} , and this value can be related to the corresponding energy based criterion G_{Ic} . The two criteria are not independent, but are related through the elastic constants [12]. The choice of criteria is generally a matter of convenience for the particular test method, with energy being easily calculated for compliant specimens as used for ply delamination.

¹ If the test were under load control, the load would not drop, instead the displacement would increase. Displacement control is most commonly used for testing.

Crack Interface

The most vulnerable lay-up to delamination is one where the crack is located at the interface between two 0° plies, (0/0) [5]. Tests of coupons with the (+45/-45) lay-up may be complicated because coupling effects, such as bending-twisting, may arise, and due to intra-ply matrix cracking within the plies [5].

In addition, fracture at +45/-45 interface is not a simple bi-modal fracture, but tri-modal, because mode-III can be induced at the crack interface where the orientations of the fibers are different [15]. In this study, only unidirectional materials with varying matrices are tested to check the toughness of laminates with these matrices.

When delamination test specimens are prepared, a Nylon starter-strip is incorporated as a crack starter. Originally, the resin rich area that forms at the tip of the Nylon strip was avoided by ignoring the initial step of crack growth [6]. Based on data with materials used in this study, the crack extending from starter crack tip is found to give the lowest G values, and so is the focus of this study.

Strain Energy Release Rate

Strain energy, covered in many mechanics textbooks [16], is the underlying origin of the strain energy release rate. The SERR will be referred to as G ; G_I for SERR in mode I, and G_{II} for mode II. G_{Ic} refers to the critical SERR for crack extension under pure mode-I loading and G_{IIc} , pure mode-II. The G calculations are based on beam theory and, and, because of corrections, the theory is then called modified beam-theory,

MBT. The corrections are discussed in more detail under DCB, ENF, and MMB subheadings.

Delamination in E-glass composites similar to those used in this study has been studied previously by Haugen [5] and Morehead [6]. They both predicted the critical load for delamination in the skin stiffener geometry by using mixed mode failure criteria with G_{Ic} and G_{IIc} values obtained from pure mode-I and -II tests, and finite element results.

In subsequent reports [5,17] based on these results, two methods were presented for predicting mixed mode delamination. Method A used measured G_{Ic} values from the actual (90/45) and (45/45) interfaces involved, and G_{IIc} values from (90/45) interface. Crack extensions corresponding to the observed crack extension in the skin-stiffener experiments were used to determine G_{Ic} and G_{IIc} . Method B used initiation G_{Ic} and G_{IIc} values from (0/0) crack interface in order to simplify the data requirements, since these were the minimum values obtained for various interfaces and crack extensions [5,17].

The MMB results from this study provide mixed mode data, which can be applied to the earlier studies. Available mixed mode failure criteria are empirical in nature, and are the subject of many studies, primarily for prepreg materials [18,24]. Studies reported in the literature [18-31] are based on both linear and nonlinear analysis. A nonlinear relationship between G_I and G_{II} suggests that there may be an interaction between the two [18,21,24,32]; an appropriate model to include this interaction will be sought in this study.

Testing for Pure Modes and Mixed Mode

The most established toughness criterion for mode-I delamination is G_{Ic} , determined using a double cantilever beam (DCB) test, which has been standardized in ASTM 5528 [33]. G_{IIc} is most commonly obtained using an end-notched flexure (ENF) [34-38] test, which is similar to a three-point bending test but with a crack at one end. Figure 2 and Figure 3 illustrate the DCB and ENF test specimens, respectively.

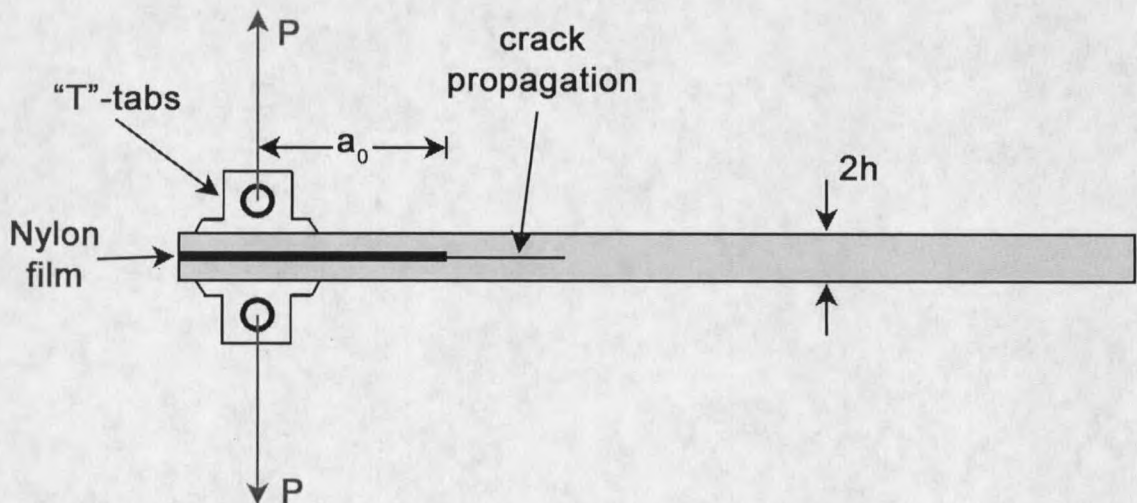


Figure 2 Double Cantilever Beam Test

Several other methods of calculating G_{Ic} from the DCB test, exemplified in ASTM 5528, were not used here because they lack accuracy, i.e. the area method. The compliance calibration method is not applicable because it involves significant crack extension, which causes fiber bridging. This method is also not applicable for G_{II} because the crack is unstable.

