Characterization of interlaminar fracture in composite materials : a case study approach
by Aaron Michael Cook

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

Abstract:
Composite materials are replacing standard engineering metals and alloys for many applications. Their inherent ability to be custom tailored for any application has made fiber reinforced composites a very viable material option. Their superior specific strength and stiffness characteristics have made them very competitive in the aerospace industry.

The primary limitation of fiber reinforced composites is fracture toughness, specifically delamination. Delamination failures are common due to the nature of composite construction. A variety of manufacturing techniques are available to make composites. Generally, all these methods employ a layered stacking of fibers in a primary plane. The interface between these layers is typically not reinforced with fibers and is the source of delamination or interlaminar fracture. Porosity and other manufacturing related defects also introduce nucleation sites for delamination.

Methods exist to evaluate and quantify inter-laminar fracture toughness, both experimentally and analytically. The material property that best represents resistance to delamination is the strain energy release rate (Gc). This can be experimentally obtained and analytically predicted with some success.

The primary focus of this study was the development of a process that would characterize and address interlaminar fracture in composites. This common mode of failure is not easily accounted for or mitigated. The design process developed considered two distinct approaches. Both methods required a database of material properties to compiled. The primary design approach was a “screening” methodology that employed comparative testing to down select composite architectures based on design drivers and applications. Another approach that was also investigated was a “predictive” or analytical approach. This process consisted of using closed form solutions or specifically finite element modeling methods to determine the strain energy release rate for given modes of failure. It was determined that analytically predicting crack growth or damage in complex structures will require research and study beyond this thesis. However, the screening approach provided meaningful results repeatedly.

This screening approach was applied to several case studies. Each case study was a separate project that investigated a unique topic relating to interlaminar fracture of composites. The process was used to satisfy sponsor needs and each project in turn provided a means to validate or improve the process. Each case study was also used to advance and validate the analytical techniques as well. Four case studies will be presented and the technical contributions of each will be discussed.

1. Evaluating composite Aerofan blade material for Pratt&Whitney 2. Investigating composite honeycomb fuel tanks for the X-33 3. Characterizing Aerospace resin systems for ACG 4. Understanding composite to metal bond behavior The four case studies were unique investigations that required interlaminar fracture characterization and analysis. In almost all cases delamination was the source of primary structure failure.

CHARACTERIZATION OF INTERLAMINAR FRACTURE IN COMPOSITE MATERIALS

A CASE STUDY APPROACH

by

Aaron Michael Cook

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APPROVAL

of a thesis submitted by

Aaron Michael Cook

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

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4. Understanding composite to metal bond behavior

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CHAPTER 1

INTRODUCTION

This focus of this study is on the delamination and interlaminar fracture performance of composite materials. General testing methods and procedures were employed to evaluate the fracture performance of sponsor supplied materials. Additionally, various methods of analysis were used for fracture toughness evaluation, including FEA (finite element analysis). Guidelines were generated for improving design with regard to fracture toughness. A general methodology for the characterization of composite laminates was developed employing standard procedures and analysis techniques.

Composite Materials

Fiber reinforced composite materials are replacing standard isotropic materials in many applications. Aerospace vehicles, aircraft, marine equipment, and common items such as civil structures, prosthetic devices, and sports equipment are currently being constructed of such composite materials.

The primary advantage of composite materials is their inherent ability to be custom tailored to a specific design situation. Constituents like fibers and matrix material can be used in different combinations, amounts, and architectures to obtain an optimal material composition.

A major drawback to laminated composite materials stems from the manufacturing process used to construct them. Placing fabric or fibers in strata to obtain a desired architecture allows resin rich layers to form between fabric layers. These regions are without reinforcement and are prone to develop discontinuities such as pores and voids. The performance of the composite material at these locations is dominated by the properties of the resin. Often the failure of a composite structure begins with the separation of these layers or delamination.

Needs

Composite designers and engineers recognize delamination as a primary failure mode. Unfortunately, modeling and predicting this behavior is not easy. In general, designers and engineers have the ability to implement a stress analysis and utilize this in parallel with empirically obtained strength data. In the case of engineering composites, fracture toughness and delamination resistance are not as easily accounted for. A general need exists for an organized approach that designers can use to evaluate and improve interlaminar fracture properties and capabilities. Both database-prediction and screening schemes are viable and will be discussed.

Available Technology

As stated previously, procedures regarding the design of laminated composites are abundant [Jones (1999), Hyer (1998), and Tsai (1988)]. Classical lamination theory can be applied to determine an appropriate composite architecture. However, techniques for designing a delamination resistant material with necessary interlaminar fracture toughness properties for service, are not as well established.

Testing procedures, failure criteria, and finite element analysis techniques are at the engineer's disposal to evaluate and predict interlaminar fracture toughness of composite materials. These available technologies can be combined and expressed in terms of a general methodology for fracture performance evaluation. In turn, this methodology can be employed to enhance the performance of composite structures.

Montana State University's Composite Technology Team has routinely investigated delamination type failures [Orozco (1999)]. Standard test procedures have been applied to unidirectional laminated composites to evaluate and quantify fracture toughness. These procedures have been focused at the evaluation of resin performance in composite architectures. Significant effort has been directed at applying finite element analysis and fracture techniques to the evaluation of these baseline composites. Studies have also been extended towards applying these procedures to more complex structures, such as T-sections [Haugen (1998) and Morehead (2000)].

Goals

Ultimately the procedures and techniques used to quantify the fracture toughness performance of composite specimens can be used to predict failure of more complex composite structures. The goal of the current study is to provide a systematic engineering approach to help develop laminated architectures, evaluate interlaminar fracture properties, and improve performance of engineering composites in commercial applications.

Case Study Approach

Several investigations were conducted to address both the strength and fracture toughness characteristics of different composite candidates. Each project possessed individual specific needs imposed by the demands of the commercial sponsor. However, a common theme was implemented to satisfy those needs. A basic methodology was developed to evaluate and improve fracture toughness properties and interlaminar performance.

Four individual case studies were performed where, each case involved a special class of composites. The material evaluated in each case was generally a more complex evolved composite than a standard longitudinal or quasi-isotropic composite. In all cases, steps were taken to improve the strength or stress performance of the material. It was suspected that certain sacrifices in fracture toughness may have been induced by these modifications. Table 1.1 contains descriptions of each case study including the sponsor, material description, use, and mode of failure investigated.

Table 1.1 Case Study Evaluations

	Case I	Case II	Case III	Case IV
Sponsor	Pratt & Whitney	Alliant Techsystems	Advanced Composite Group	Department of Energy
Material Architecture	Through thickness reinforced carbon fiber composites	Honey comb sandwich panels	Unidirectional carbon fiber laminates	metal reinforced composite root structures
Application	High bypass aerofan engine blade	Fuel cells for X-33 space shuttle	Aerospace low temperature cured structures	Root fittings for wind turbine root connections
Failure Mode Investigated	Dynamic GII, dynamic flexure, static flexure and tension	Flatwise tension and compression, GI and GII	GI, GII, dynamic GII, and strength properties	Bond threshold and damage tolerance
Numerical Study	Dynamic GII	Flatwise tension, GI and GII	None (used SEM technology to inspect damage)	Single and double lap shear and miniature root specimen

Each of the case studies focuses on a specific aspect of delamination or interlaminar fracture. The materials in these studies were evaluated for advanced aerospace applications.

Case I Carbon Fiber Aerofan Blades

Architecture variations were the primary focus of this case study. Through the thickness reinforced fabrics were used to reduce the probability of delamination. The degree of reinforcement was varied and appeared to have an effect on strength. These carbon fiber and epoxy laminates were resin transfer molded for high bypass aerofan blades shown in Figure 1.1.

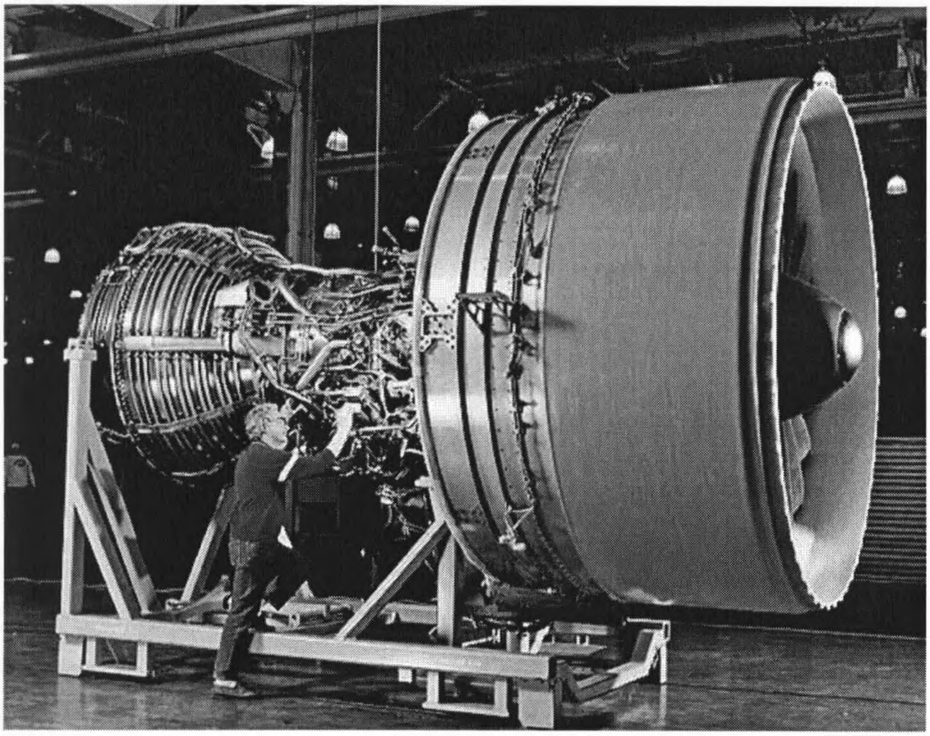

Figure 1.1 PW-4000-112 Aerofan Blade