



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
© Copyright by Aaron Michael Cook (2001)

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 (G_c). 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 be 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

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Mechanical Engineering

MONTANA STATE UNIVERSITY-BOZEMAN
Bozeman, Montana

July 2001

N378
C7711

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.

Dr. Douglas Cairns *Douglas S. Cairns* 7/10/01
(Signature) Date

Approved for the Department of Mechanical & Industrial Engineering

Dr. Vic Cundy *Vic A. Cundy* 7/11/01
(Signature) Date

Approved for the College of Graduate Studies

Dr. Bruce McLeod *Bruce R. McLeod* 7-17-01
(Signature) Date

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University-Bozeman, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Signature Daron Cook
Date 7/10/01

ACKNOWLEDGMENTS

I thank Dr. Douglas Cairns and Dr. John Mandell for their assistance and motivation in this research. I would also like to thank Dr. Ladean McKittrick for serving as a graduate committee member, and for providing guidance in the field of finite element analysis. Additional gratitude is offered to the sponsors involved in this study. Pratt & Whitney, AlliantechSystems, Advanced Composite Group, and the D.O.E. EPSCOR all provided funding and unique research opportunities. A special thanks is also extended to the members of the Composite Technology Research Team. Daniel Samborsky was especially helpful with his knowledge and suggestions for experimental testing. I am additionally thankful to Dr. Cundy and the Industrial and Mechanical Engineering Department's administrative team.

TABLE OF CONTENTS

LIST OF FIGURES	xi
LIST OF TABLES	xvii
ABSTRACT	xix
1. INTRODUCTION	1
Composite Materials	1
Needs	2
Available Technology	2
Goals	3
Case Study Approach	3
Case I Carbon Fiber Aerofan Blades	5
Case II Honeycomb Sandwich Fuel Tanks	6
Case III Low Temperature Cure Composite Structures	7
Case IV Composite to Metal Interfaces	8
Evaluation Methodology	9
2. BACKGROUND	10
Composites	10
Advantages and Disadvantages	10
In-plane and Out of Plane Properties	11
Manufacturing	12
Failure Types and Related Theories	12
Strength of Materials Approach	13
Fracture Mechanics Approach Background and History	14
Interlaminar Fracture	15
Fracture Mechanics Overview	16
Mode I	17
Testing Procedure for DCB Specimen	19
Data Reduction Methods	21
Mode II	22
Testing Procedure for ENF Specimen	23
Data Reduction Methods	26
Finite Element Theory	27
Benefits	27
Models and Modeling Procedure	28
Step 1 Geometry Development	29
Step 2 Element Choice	29
Step 3 Constitutive Properties	31

Step 4 Meshing	31
Step 5 and 6 Application of Constraints and Loads.....	32
Step 7 and 8 Solution and Results	32
Finite Element as Related to Fracture Mechanics	32
Strain Energy Release Rate Methods.....	33
Virtual Crack Closure Techniques.....	33
Crack Extension Techniques.....	36
3. INTERLAMINAR FRACTURE CHARACTERIZATION PROCESS	38
Needs.....	38
Optimization	39
Fracture Toughness Tips and Tradeoffs	39
Resin System.....	40
Fibers.....	40
Inhomogeneities.....	41
Porosity	41
Ply-drops and Dissimilar Material Interface.....	42
Interlaminar Zone and Other Inhomogeneities	43
Prediction and Screening Approach.....	44
Database.....	45
Screening Process	46
Screening Procedure	47
Prediction Approach	49
Composite Design.....	51
4. CASE STUDY I COMPOSITE AEROFAN BLADE EVALUATION.....	54
Project Introduction.....	54
Existing Work	55
Full Scale testing and Need for Screening Process.....	56
Problem Statement.....	57
Design Drivers and Material Limitations	58
Materials Provided and Specimen Description.....	58
Material Property Isolation	60
Test Matrix.....	61
Experimental Procedures.....	63
Basic In-plane and Interlaminar Properties.....	63
Delamination Mode II Testing.....	63
Apparatus	64
Procedure	66
Data Reduction.....	68
Dynamic Flexure Testing.....	74
Apparatus	75

Procedure	75
Data Reduction.....	75
Static Flexure Testing	78
Apparatus	78
Procedure	79
Data Reduction.....	80
Tensile Test.....	81
Apparatus	81
Procedure	81
Experimental Results.....	83
Mode II Delamination Resistance Results	83
Dynamic Flexure Results	86
Static Flexure Results	89
Tensile Test Results	91
Summary of Experimental Results	92
Numerical Analysis for Case Study I.....	94
Static Flexure Approach	94
Static Flexure Model.....	94
Static Flexure Numerical Results.....	96
End Notch Flexure Approach	98
End Notch Flexure Model.....	99
End Notch Flexure Results	101
Comparison.....	102
Test Specimen Validation.....	104
Summary for Case Study I	105
5. CASE STUDY II HONEYCOMB FUEL TANK INVESTIGATION.....	108
Project Introduction.....	108
Case Study Goal.....	109
Experimental Procedures.....	110
Flatwise Tension Testing	111
Specimen Preparation	113
Testing Procedure	114
Data Reduction Methods.....	115
Mode I Testing.....	118
Testing Procedure	119
Data Reduction Methods.....	119
Mode II Testing.....	121
Testing Procedure	122
Data Reduction Methods.....	122
Flatwise Compression Testing.....	125
Specimen Preparation	125
Testing Procedure	125

Data Reduction Methods.....	126
Experimental Results.....	127
Flatwise Tension Results	128
Discussion of Flatwise Tension Results	130
Mode I Results	131
Mode II Results.....	137
Discussion of Mode II Results.....	138
Flatwise Compression Results	140
Discussion of Flatwise Compression Results	140
Numerical Analysis of Honeycomb Fuel Tank Investigation	142
Motivation.....	142
Flatwise Tension	142
Approach.....	143
Model	143
Results.....	144
Solution and Mesh Convergence	145
Mode I.....	149
Approach.....	149
Model.....	150
Solution and Convergence	151
Comparison.....	152
Mode II.....	154
Summary for Case Study II.....	155
Epilogue	156
6. CASE STUDY III AEROSPACE RESIN EVALUATION.....	157
Project Introduction.....	157
Problem Statement.....	158
Material and Specimen Description.....	159
Test Matrix.....	160
Experimental Methods	161
Static Flexure	161
Static Flexure Apparatus.....	161
Static Flexure Testing Procedure	162
Static Flexure Data Reduction	163
Fracture Toughness Testing.....	163
DCB Testing Procedure	163
DCB Data Reduction Methods	165
Mode II.....	165
ENF Testing Procedure.....	165
ENF Data Reduction Methods	166
Dynamic Mode II Testing.....	167
Dynamic ENF Apparatus.....	167

Dynamic ENF Testing Procedure	167
Dynamic ENF Data Reduction	168
Scanning Electron Microscopy Evaluations	171
SEM Apparatus	171
SEM Testing Procedure	171
Experimental Results	173
Static Flexure Test Results	173
Mode I Results from DCB Testing	174
Mode II Results from Static ENF Testing	177
Mode II Results from Dynamic ENF Testing	179
SEM Results for Selected Systems	182
Summary for Case Study III	186
7. CASE STUDY IV METAL INTERFACE	188
Bond Characteristics	188
Chemical Bond	189
Structural Interlock	189
Need for Simpler Structure and Methodology	189
Lap Shear	190
Single Lap Shear	190
Shear Lap Construction	191
Shear Lap Configuration	191
Test Procedure	192
Data Reduction	192
Double Lap Shear	193
Double Lap Shear Configuration	193
Double Lap Shear Construction	194
Double Lap Shear Test Procedure and Data Reduction	194
Miniroot	195
Miniroot Construction	195
Miniroot Configuration	196
Testing Procedure	197
Data Reduction	198
Sample Results	198
Debonding	199
Pullout	200
Metal Interface Experimental Results	200
Parametric Study	200
Surface Treatment	201
Elastic Properties	201
Chemical Bond Characteristics	201
Mechanical Bond Characteristics	202
Knurling	202

Threading	202
Resin Systems	202
Layup Variations.....	203
Insert Material.....	203
Insert Coating.....	203
Test Matrix.....	204
Single Lap Shear Results	205
Double Lap Shear Results.....	207
Miniroot Experimental Results	209
Insert Coating Effects	209
Geometry Effects	211
Mechanical Interlock	213
Metal Interface Numerical Study	214
SLS Motivation and Approach	214
Model.....	215
Results.....	216
Miniroot Motivation and Approach.....	218
Model.....	218
Results.....	219
Summary for Case Study IV	221
8. CONCLUSIONS AND FUTURE WORK.....	223
Composite Material Design Process.....	224
Importance of the Screening Process	225
Case Study Review.....	225
Case Study I Composite Aerofan Blade Evaluation.....	226
Case Study II X-33 Fuel Tank Investigation	227
Case Study III Aerospace Composite Resin Characterization.....	228
Case Study IV Metal Interface Evaluation	228
Future Recommendations.....	229
REFERENCES CITED.....	230
APPENDIX A: FINITE ELEMENT CODES	235

LIST OF FIGURES

Figure	Page
1.1 PW-4000-112 Aerofan Blade	5
1.2 Honeycomb Fuel Cell	6
1.3 Composite Applications for Resins Evaluated	7
1.4 Composite Wind Turbine.....	8
2.1 Fiber and Transverse Directions of a Composite.....	11
2.2 Laminate Construction.....	12
2.3 Three Modes of Fracture and Related Loading	17
2.4 DCB Test in Progress.....	18
2.5 DCB Testing Geometry	19
2.6 Mode I Fracture Propagation Behavior of a Composite Specimen	20
2.7 ENF Test in Progress	23
2.8 Mode II Fracture Specimen Geometry	24
2.9 Typical Mode II Crack Behavior	25
2.10 Mode II Crack Behavior with Hysteresis Captured.....	25
2.11 VCCT-1 Schematic with 8 Node Quadrilateral Elements	34
2.12 VCCT-2 Schematic for Mode I Closure	35
3.1 Porosity in a Composite Laminate.....	41
3.2 Sandwich Panel Material with Ply Drops	42
3.3 Resin Rich Region in a Laminated Composite.....	43
3.4 Database Construction Process	46

3.5 Screening Approach.....	48
3.6 Analytical Process for Fracture Modeling.....	50
4.1 Example of Impact and Dynamic Flex Testing Rectangular Specimen	60
4.2 Impact Testing Fixture.....	64
4.3 Data Acquisition Used for Experimental Testing.....	65
4.4 Force vs. Time Output for Series 5 Laminate.....	67
4.5 Acceleration vs. Time for 5 Series Laminate.....	69
4.6 Velocity Profile for 5 Series Laminate	70
4.7 Displacement vs. Time for 5 Series Laminate	72
4.8 Dynamic Load vs. Displacement Trace for Series 5 Laminate	73
4.9 Dynamic Flexure Behavior.....	76
4.10 Static Flexure Test Fixture and Specimen	78
4.11 Static Flexure Behavior.....	79
4.12 Tensile Test Behavior	82
4.13 Delamination Results for 5 Series Material	84
4.14 Force vs. Time for Dynamic Flexure Tests	86
4.15 Force vs. Deflection for Dynamic Flexure Tests.....	87
4.16 Static Flexure Comparison.....	89
4.17 Tensile Test Results	91
4.18 Stress vs. Strain for 5 Series	92
4.19 FEA Static Flexure Model	95
4.20 Comparison of Experimental Static Flexure Results to Numerical.....	96
4.21 Longitudinal Stress Plot from FEA Solution.....	97

4.22 ENF Mesh with Refined Region and Boundary Conditions.....	100
4.23 Friction Effects on Predicted Mode II Fracture Toughness.....	103
5.1 Sampling of Panel 1 From Lobe 1	110
5.2 Sampling of Panel 2 From Lobe 4.....	111
5.3 Mounting (Glue) Fixture Used to Attach Tabs to Specimen.....	112
5.4 Flatwise Tension Specimen Complete with Attached Tabs	114
5.5 Testing Jig with Universal Pivoting Capability (flexible coupler).....	115
5.6 Graphical Presentation of Flatwise Tension Specimen	117
5.7a Mode I Testing Apparatus.....	118
5.7b Test in Progress.....	118
5.8 Three Successive Loading Cases for Lobe 4 Material.....	120
5.9 Mode II Testing Apparatus In Progress.....	121
5.10 Mode II Test Results of Lobe 4 Material.....	123
5.11 Mode II Test Showing Constant Loading During Crack Growth.....	124
5.12 Compression Testing Configuration.....	126
5.13 Typical Compression Test Result for Lobe 4	127
5.14 Graphical Behavior of Lobe 4 Material in Flatwise Tension	129
5.15 Comparison of Failure Modes of Lobe 4 to Lobe 1.....	129
5.16 Peel-off Test Results for Lobe 1 Material L1-DCB-4	131
5.17 Lobe 1 Material Specimen Core Shear Failure.....	134
5.18 Failure Mode of Lobe 4 Material.....	135
5.19 Comparison of Static Flexure and ENF Results for Lobe 4	139

5.20 FWT Flatwise (Transverse) Tension Model	144
5.21 FWT Stress Distribution with Core Close-up	145
5.22 FWT Solution Convergence	146
5.23 Plane Stress vs. Plane Strain	147
5.24 Stress Profile Based on Offset Distance	148
5.25 Stress Profile without Singularities	148
5.26 DCB Model for Sandwich Material	151
6.1 Static Flexure Test Results for 6867 Material	162
6.2 Hysteretic Behavior of 6866 DCB – 3 Specimen	164
6.3 Mode II Crack Behavior with Hysteresis Captured	166
6.4 Force vs. Time Data for 6868 XHTM Material	168
6.5 Acceleration vs. Time for 6868 XHTM Material	169
6.6 Velocity Profile for 6868 XHTM Material	169
6.7 Displacement vs. Time for 6868 XHTM Material	170
6.8 Dynamic Load vs. Displacement Curve for 6868 XHTM Material	170
6.9 SEM Photo	172
6.10 Mode I Results for Varying Post Cure Temperatures	176
6.11 Mode II Fracture Toughness as a Function of Postcure Temperature	179
6.12A 6863 npc at 1500	183
6.12B 6863 npc at 500	183
6.12C 6863 pc177 at 1500	183
6.12D 6863 pc177 at 500	183

6.13A 6865 npc at 1500	184
6.13B 6865 npc at 500	184
6.13C 6865 pc177 at 1500	184
6.13D 6865 pc177 at 500	184
6.14A 6866 npc at 1500	185
6.14B 6866 npc at 500	185
6.14C 6866 pc177 at 1500	185
6.14D 6866 pc177 at 500	185
7.1 Fatigue Specimen, R112 Cross-Section	188
7.2 Single Lap Shear Specimen	191
7.3 Double Lap Shear Specimen (DLS)	194
7.4 Array of Miniroot Variations	196
7.5 Miniroot Anatomy	197
7.6 Lap Shear and Miniroot Test Approach.....	198
7.7 Miniroot Failure Characteristics	199
7.8 Effects of Using Epoxy Coating as an Intermediate Adhesive.....	210
7.9 Debond Behavior of Miniroots with Round Inserts.....	212
7.10 Failure of 45 Degree Diamond Knurled Steel Insert Miniroot.....	213
7.11 Shear Stress Singularity Effects.....	215
7.12 SLS FEA Model and Mesh Detail	216
7.13 Lap Shear Analytical and Numerical Results for Etched Vinylester.....	217
7.14 Miniroot FEA Shear Stress Plot for Vinylester	219

7.15 Shear Stress Data From Peak to Level Stress 220

LIST OF TABLES

Table	Page
1.1 Case Study Evaluations.....	4
2.1 Catastrophies Due to Fracture of Statically Loaded Structures.....	15
4.1 Description of Specimen Architecture.....	59
4.2 Test Matrix of Aircraft Fan Blade Candidates.....	62
4.3 Results for Delamination Mode II Testing	85
4.4 Summary of Dynamic Flexure Data	88
4.4 Comparison of Static Flexure Results.....	90
4.5 Suggested Material Properties for Composite X	93
4.6 ENF Convergence for G_{IIc} cf = 0.35	101
4.7 FEA Results Compared to Analytical Methods.....	102
5.1 Test Development and Test Matrix.....	109
5.2 Comparison of Flatwise Tensile Tests for Lobe 1	128
5.3 Summary of Lobe 4 Transverse or Flatwise Tension Tests.....	130
5.4 Summary of Lobe 1 (L1) Mode I (DCB) Test Results	133
5.5 Mode I Results for Lobe 4 Material.....	136
5.6 Mode II Results for Lobe 4.....	137
5.7 Summary of Compression Test Results for Lobe 1 and Lobe 4.....	141
5.8 Convergence Results for FEA Techniques	152
5.9 Comparison of FEA and Experimental Results for G_c	153
5.10 Shear Effects of G_{II} compared to G_I	154

6.1 Specimen Description	159
6.2 Test Matrix.....	160
6.3 Summary of Static Flexure Results.....	173
6.4 Static Mode I Test Results	175
6.5 Summary of Mode II Test Results	177
6.6 Summary of Dynamic End Notch Flexure Results.....	180
6.7 Rate Dependency Comparison for Mode II Testing.....	181
7.1 Test Matrix for Composite and Metal Interface Investigation.....	204
7.2 Single Lap Shear Test Results for Shear Strength.....	206
7.3 Single Lap Shear Test Results for Load / unit width.....	206
7.4 Double Lap Shear Test Results for Shear Strength	208
7.5 Results of Including Epoxy Coating.....	211
7.6 Comparison of Aluminum and Steel Rod Miniroots	212

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 (G_c). 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 be 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.

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.

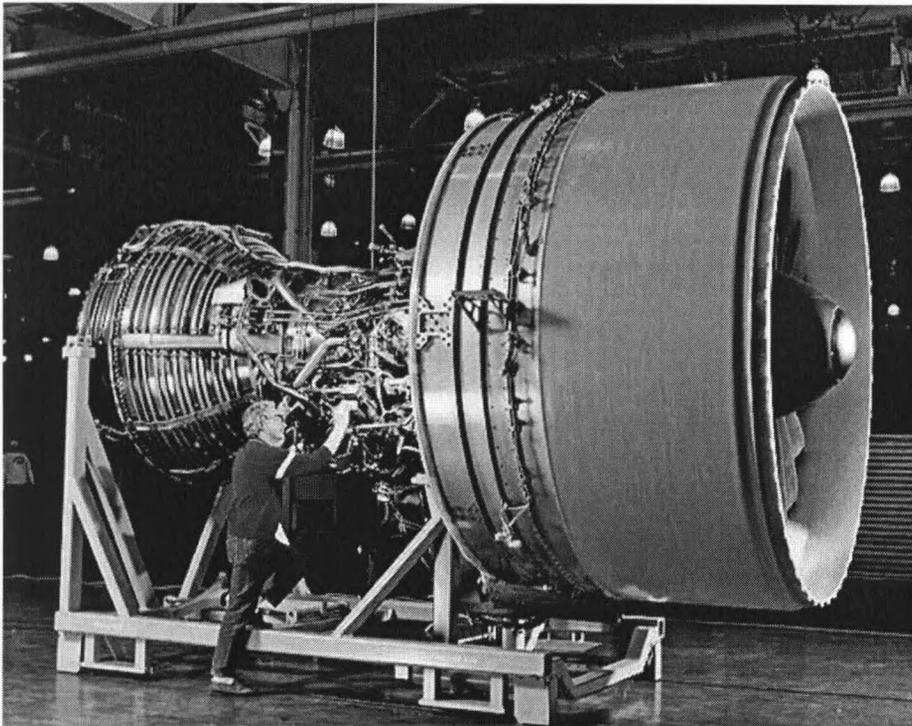


Figure 1.1 PW-4000-112 Aerofan Blade

