

**The Effect of Long-Term Thermal Cycling on the Microcracking Behavior and
Dimensional Stability of Composite Materials**

Timothy L. Brown

Dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University in
partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Engineering Mechanics

Michael W. Hyer (Chair)

Scott L. Hendricks

John J. Lesko

Brian J. Love

Kenneth L. Reifsnider

December 1, 1997

Blacksburg, Virginia

Keywords: Graphite-Epoxy, Cyanate Ester, Coefficient of Thermal Expansion, Stiffness, Thermal Fatigue, Cryogenic, Fizeau Interferometry, Space, Shear Lag

Copyright 1997. Timothy L. Brown

The Effect of Long-Term Thermal Cycling on the Microcracking Behavior and Dimensional Stability of Composite Materials

Timothy L. Brown

(ABSTRACT)

The effect of thermal-cycling-induced microcracking in fiber-reinforced polymer matrix composites is studied. Specific attention is focused on microcrack density as a function of the number of thermal cycles, and the effect of microcracking on the dimensional stability of composite materials. Changes in laminate coefficient of thermal expansion (CTE) and laminate stiffness are of primary concern. Included in the study are materials containing four different Thornel fiber types: a PAN-based T50 fiber and three pitch-based fibers, P55, P75, and P120. The fiber stiffnesses range from 55 Msi to 120 Msi. The fiber CTE's range from $-0.50 \times 10^{-6}/^{\circ}\text{F}$ to $-0.80 \times 10^{-6}/^{\circ}\text{F}$. Also included are three matrix types: Fiberite's 934 epoxy, Amoco's ERL1962 toughened epoxy, and YLA's RS3 cyanate ester. The lamination sequences of the materials considered include a cross-ply configuration, $[0/90]_{2s}$, and two quasi-isotropic configurations, $[0/+45/-45/90]_s$ and $[0/+45/90/-45]_s$. The layer thickness of the materials range from a nominal 0.001 in. to 0.005 in. In addition to the variety of materials considered, three different thermal cycling temperature ranges are considered. These temperature ranges are $\pm 250^{\circ}\text{F}$, $\pm 150^{\circ}\text{F}$, and $\pm 50^{\circ}\text{F}$. The combination of these material and geometric parameters and temperature ranges, combined with thermal cycling to thousands of cycles, makes this one of the most comprehensive studies of thermal-cycling-induced microcracking to date.

Experimental comparisons are presented by examining the effect of layer thickness, fiber type, matrix type, and thermal cycling temperature range on microcracking and its influence on the laminates. Results regarding layer thickness effects indicate that thin-layer laminates microcrack more severely than identical laminates with thick layers. For some specimens in this study, the number of microcracks in thin-layer specimens exceeds that in thick-layer specimens by more than a factor of two. Despite the higher number of microcracks in the thin-layer specimens, small changes in CTE after thousands of cycles indicate that the thin-layer specimens are relatively unaffected by the presence of these cracks compared to the thick-layer specimens. Results regarding fiber type indicate that the number of microcracks and the change in CTE after thousands of cycles in the specimens containing PAN-based fibers are less than in the specimens containing comparable stiffness pitch-based fibers. Results for specimens containing the different

pitch-based fibers indicate that after thousands of cycles, the number of microcracks in the specimens does not depend on the modulus or CTE of the fiber. The change in *laminar* CTE does, however, depend highly on the stiffness and CTE of the fiber. Fibers with higher stiffness and more negative CTE exhibit the lowest change in laminar CTE as a result of thermal cycling. The overall CTE of these specimens is, however, more negative as a result of the more negative CTE of the fiber. Results regarding matrix type based on the $\pm 250^{\circ}\text{F}$ temperature range indicate that the RS3 cyanate ester resin system exhibits the greatest resistance to microcracking and the least change in CTE, particularly for cycles numbering 3000 and less. Extrapolations to higher numbers of cycles indicate, however, that the margin of increased performance is expected to decrease with additional thermal cycling. Results regarding thermal cycling temperature range depend on the matrix type considered and the layer thickness of the specimens. For the ERL1962 resin system, microcrack saturation is expected to occur in all specimens, regardless of the temperature range to which the specimens are exposed. By contrast, the RS3 resin system demonstrates a threshold effect such that cycled to less severe temperature ranges, microcracking does not occur. For the RS3 specimens with 0.005 in. layer thickness, no microcracking or changes in CTE are observed in specimens cycled between $\pm 150^{\circ}\text{F}$ or $\pm 50^{\circ}\text{F}$. For the RS3 specimens with 0.002 in. layer thickness, no microcracking or changes in CTE are observed in specimens cycled between $\pm 50^{\circ}\text{F}$. Results regarding laminar stiffness indicate negligible change in laminar stiffness due to thermal cycling for the materials and geometries considered in this investigation. The study includes X-ray examination of the specimens, showing that cracks observed at the edge of the specimens penetrate the entire width of the specimen. Glass transition temperatures of the specimens are measured, showing that resin chemistry is not altered as a result of thermal cycling.

Results are also presented based on a one-dimensional shear lag analysis developed in the literature. The analysis requires material property information that is difficult to obtain experimentally. Using limited data from the present investigation, material properties associated with the analysis are modified to obtain reasonable agreement with measured microcrack densities. Based on these derived material properties, the analysis generally overpredicts the change in laminar CTE. Predicted changes in laminar stiffness show reasonable correlation with experimentally measured values.

ACKNOWLEDGEMENTS

The author would like to gratefully acknowledge Professor Michael W. Hyer for his dedication to this project. I have worked with him for over seven years in my graduate education and his unending drive and dedication to the field of composite materials never ceases to amaze me. I am also grateful for the technical support of my Ph.D. committee members, Profs. Scott L. Hendricks, John J. Lesko, Brian J. Love, and Kenneth L. Reifsnider. I would like to thank Profs. Ron G. Kander and Don H. Morris, who served on my committee during the preliminary stages of my degree but had to withdraw in the end due to scheduling conflicts.

The technical support and advice I received during my residency at NASA Langley Research Center is gratefully acknowledged. Specifically, I would like to thank Dr. Stephen Tompkins, Dr. David Bowles, Dr. Wallace Vaughn, Dr. Howard Maahs, Craig Ohlhorst, and James Shen. Additional technical support was provided by Teresa O'Neil, Craig Leggette, Ron Penner, and Sandy Branham, to whom I am also grateful. A special thanks is given to Ashley Predith who helped tremendously with some of the experimental testing phases of this work.

I would also like to acknowledge Prof. Hugh McManus of M.I.T. for his help and advice with the analysis portion of the project. He was very willing to share his analysis code with me, for which I am most grateful.

Finally, I would like to thank my wife, Dr. Nicole L. Breivik, for her support throughout the completion of this degree. The final preparation of this dissertation coincided with the arrival of our son, Patrick Steven Brown, born on Oct. 17, 1997. I would like to thank my parents, Peter and Carol Brown, for their help and support during this momentous time in our lives.

This work was funded by the Environmental Interactions Branch of NASA Langley Research Center through the NASA-Virginia Tech Composites Program, grants NAG-1-343 and NAG-1-1912.

TABLE OF CONTENTS

1. INTRODUCTION.....	1
1.1 BACKGROUND	1
1.2 OVERVIEW	3
1.3 PAST EXPERIMENTAL CHARACTERIZATION	4
1.3.1 Microcrack Density Results.....	4
1.3.1.1 Fiber Modulus Trends	4
1.3.1.2 Matrix Trends	4
1.3.1.3 Ply Thickness Trends	5
1.3.2 Property Degradation Results	6
1.3.2.1 Coefficient of Thermal Expansion Trends	6
1.3.2.2 Stiffness Loss Trends.....	6
1.4 PAST ANALYTICAL CHARACTERIZATION.....	7
1.4.1 Modeling the State of Stress	8
1.4.1.1 Shear Lag Theory	8
1.4.1.2 Variational Approach.....	12
1.4.1.3 Other Methods for Determining the State of Stress	13
1.4.2 Modeling the Development of Microcracks	14
1.4.2.1 Strength Models	14
1.4.2.2 Fracture Mechanics Models.....	17
1.4.3 Modeling Property Variations due to Microcracking	20
1.4.3.1 Shear Lag Models.....	21
1.4.3.2 Fracture Mechanics Models.....	21
1.4.3.3 Continuum Damage Mechanics Models.....	22
1.4.3.4 Internal State Variable Models	23
1.5 REMAINING CHAPTERS.....	23
2. EXPERIMENTAL PROGRAM.....	24
2.1 MATERIAL SPECIFICATIONS	25
2.2 SPECIMEN DESIGNS CONSIDERED	28
2.3 SPECIMEN GEOMETRY AND PREPARATION.....	34
2.4 THERMAL CYCLING PROCEDURE	35
2.5 MICROCRACK CHARACTERIZATION	35
2.6 THERMAL EXPANSION MEASUREMENTS	37

2.7 LAMINATE STIFFNESS MEASUREMENTS.....	40
2.8 MATERIAL AGING CHARACTERIZATION.....	46
3. EXPERIMENTAL RESULTS.....	48
3.1 EXPERIMENTAL MEASUREMENTS.....	48
3.1.1 Microcrack Density.....	48
3.1.2 Laminate Thermal Expansion Coefficients.....	49
3.1.3 Laminate Stiffness	50
3.1.4 Glass Transition Temperature	50
3.2 EFFECT OF LAYER THICKNESS.....	50
3.2.1 Microcrack Density.....	51
3.2.2 Laminate Thermal Expansion Behavior	62
3.2.3 Laminate Stiffness	65
3.3 EFFECT OF FIBER TYPE.....	66
3.3.1 Effect of Fiber Precursor – PAN-Based versus Pitch-Based Fibers.....	67
3.3.1.1 Microcrack Density	67
3.3.1.2 Thermal Expansion Behavior	76
3.3.1.3 Laminate Stiffness.....	77
3.3.2 Effect of Fiber Modulus and Fiber CTE in Pitch-Based Fibers.....	78
3.3.2.1 Microcrack Density	78
3.3.2.2 Thermal Expansion Behavior	87
3.3.2.3 Laminate Stiffness.....	88
3.4 EFFECT OF MATRIX TYPE.....	89
3.4.1 Microcrack Density.....	90
3.4.2 Laminate Thermal Expansion Behavior	94
3.4.3 Laminate Stiffness	95
3.4.4 Glass Transition Temperature	96
3.5 EFFECT OF THERMAL CYCLING TEMPERATURE RANGE	97
3.5.1 Microcrack Density.....	97
3.5.2 Thermal Expansion Behavior.....	107
3.5.3 Laminate Stiffness	109
3.5.4 Glass Transition Temperature	110
3.6 SUMMARY	111
4. ANALYTICAL PREDICTIONS	112

4.1 SHEAR LAG MODEL FORMULATION.....	112
4.2 SENSITIVITY ANALYSIS.....	116
4.3 ANALYTICAL PREDICTIONS VERSUS EXPERIMENTAL RESULTS.....	122
4.3.1 T50/ERL1962 Material System.....	122
4.3.2 P55/ERL1962 Material System.....	130
4.3.3 P75/ERL1962 Material System.....	133
4.3.4 P120/ERL1962 Material System.....	141
4.3.5 P75/RS3 Material System.....	144
4.3.6 P75/934 Material System.....	148
4.4 SUMMARY OF CRACKOMATIC PARAMETERS.....	150
5. CONCLUSIONS AND RECOMMENDATIONS.....	154
5.1 LAYER THICKNESS.....	154
5.2 FIBER TYPE.....	155
5.2.1 PAN-based versus Pitch-based Fibers.....	155
5.2.2 Fiber Modulus/Fiber CTE.....	155
5.3 MATRIX TYPE.....	155
5.4 THERMAL CYCLING TEMPERATURE RANGE.....	156
5.5 COMPARISONS BETWEEN ANALYSIS AND EXPERIMENT.....	157
5.6 IMPLICATIONS TO OTHER MATERIAL SYSTEMS AND DESIGNS.....	158
5.7 RECOMMENDATIONS FOR FUTURE WORK.....	158
REFERENCES.....	160
APPENDIX A - THERMAL CYCLING SOAK TIME CALCULATION.....	165
APPENDIX B - EXTENSOMETER CALIBRATION.....	168
APPENDIX C - EXPERIMENTALLY MEASURED MICROCRACK DENSITIES.....	171
APPENDIX D - LAMINATE THERMAL EXPANSION DATA.....	182
APPENDIX E - NORMALIZED LAMINATE STIFFNESS CALCULATIONS.....	222
APPENDIX F - LAMINA MATERIAL PROPERTY DERIVATION.....	230
VITA.....	248

LIST OF TABLES

Table 2.1 Axial Direction Fiber Properties	25
Table 2.2 Room Temperature Neat Resin Properties.....	26
Table 2.3 Average Room Temperature Composite Lamina Properties	27
Table 2.4 Materials and Testing Parameters.....	29
Table 2.5 Specimen Designations and Testing History	30
Table 2.6 Tensile Stiffness Testing Loading Parameters.....	40
Table 2.7 Dimensions of Specimens Used for Stiffness Measurements	43
Table 3.1 Dimensional Microcrack Densities (in cracks/in.) for P75/ERL1962.X.*.G Specimens.....	54
Table 3.2 Dimensional Microcrack Densities (in cracks/in.) for P75/RS3.Q2.*.G Specimens	59
Table 3.3 Axial Direction Fiber Properties for PAN-Based and Pitch-Based Fibers	67
Table 3.4 Dimensional Microcrack Densities (in cracks/in.) for T50 and P55/ERL1962.X.5.G Specimens	68
Table 3.5 Dimensional Microcrack Densities (in cracks/in.) for T50 and P55/ERL1962.Q1.5.G Specimens	74
Table 3.6 Axial Direction Fiber Properties for Pitch-Based Fibers.....	78
Table 3.7 Dimensional Microcrack Densities (in cracks/in.) for P55, P75, and P120/ERL1962.X.5.G Specimens.....	81
Table 3.8 Dimensional Microcrack Densities (in cracks/in.) for P55, P75, and P120/ERL1962.Q1.5.G Specimens.....	85
Table 3.9 Room Temperature Neat Resin Properties.....	90
Table 3.10 Dimensional Microcrack Densities (in cracks/in.) for P75/*..Q2.5.G Specimens.....	92
Table 3.11 Glass Transition Temperatures for the 934, ERL1962, and RS3 Resin Systems Before and After Thermal Cycling.....	97
Table 3.12 Dimensional Microcrack Densities (in cracks/in.) for P75/ERL1962.Q2.5.* Specimens.....	100
Table 3.13 Dimensional Microcrack Densities (in cracks/in.) for P75/RS3.Q2.5.G Specimens	103
Table 3.14 Dimensional Microcrack Densities (in cracks/in.) for P75/RS3.Q2.2.* Specimens	105
Table 3.15 Glass Transition Temperatures for the ERL1962 and RS3 Resin Systems Before and After Thermal Cycling.....	111
Table 4.1 Critical Strain Energy Release Rate as a Function of the Number of Thermal Cycles	119
Table 4.2 Room Temperature Lamina Properties for T50/ERL1962.X.5.G Specimens	123
Table 4.3 Room Temperature Lamina Properties for T50/ERL1962.Q1.5.G Specimens.....	127
Table 4.4 Room Temperature Lamina Properties for P55/ERL1962.X.5.G Specimens.....	130
Table 4.5 Room Temperature Lamina Properties for P55/ERL1962.Q1.5.G Specimens.....	131
Table 4.6 Room Temperature Lamina Properties for P75/ERL1962.X.5.G Specimens.....	133
Table 4.7 Room Temperature Lamina Properties for P75/ERL1962.Q1.5.G Specimens.....	134

Table 4.8 Room Temperature Lamina Properties for P75/ERL1962.Q2.5.* Specimens.....	135
Table 4.9 Room Temperature Lamina Properties for P75/ERL1962.X.1.G Specimens.....	138
Table 4.10 Room Temperature Lamina Properties for P75/ERL1962.Q2.1.G Specimens.....	139
Table 4.11 Room Temperature Lamina Properties for P120/ERL1962.X.5.G Specimens.....	141
Table 4.12 Room Temperature Lamina Properties for P120/ERL1962.Q1.5.G Specimens.....	142
Table 4.13 Room Temperature Lamina Properties for P75/RS3.Q2.5.* Specimens.....	144
Table 4.14 Room Temperature Lamina Properties for P75/RS3.Q2.2.* Specimens.....	145
Table 4.15 Room Temperature Lamina Properties for P75/934.Q2.5.G Specimens.....	148
Table 4.16 Summary of Crackomatic Parameters.....	151
Table 4.17 Comparison of $G_{IC}(0)$ Values from Previous and Current Analyses.....	152
Table B.1 Experimental Tensile Stiffness Measurements for Extensometer Calibration Specimens.....	169
Table B.2 Comparisons of Average Tensile Stiffness Calculated by Strain Gage vs. Extensometer.....	170
Table B.3 Repeatability Characteristics of Average Tensile Stiffness Measurements.....	170
Table E.1 Average Measured Stiffness and Fiber Volume Fractions for Series 6762 Baseline Specimens.....	223
Table E.2 Normalized Laminate Stiffness for Series 6762 Baseline Specimens.....	225
Table E.3 Normalized Laminate Stiffness for All Specimens.....	225
Table F.1 Room Temperature Lamina Properties Measured from Unidirectional Specimens.....	230
Table F.2 Measured and Predicted Laminate Stiffness.....	231
Table F.3 Measured and Revised Predicted Laminate Stiffness Based on Fiber Volume Fraction Measurements.....	234
Table F.4 Measured and Predicted Laminate CTE.....	236
Table F.5 Fixed Micromechanical Material Properties.....	240
Table F.6 Derived Micromechanical Material Properties.....	240
Table F.7 Derived Lamina Material Properties for Thermal Expansion Specimens.....	241
Table F.8 Measured and Predicted Laminate Thermal Expansion.....	242
Table F.9 Measured and Predicted Laminate Stiffness.....	246

LIST OF FIGURES

Figure 1.1. Microcracks present in a $[0/+45/90/-45]_s$ quasi-isotropic laminate.	2
Figure 1.2. Shear lag concept in a cross-ply $[0/90/0]$ composite laminate.	9
Figure 2.1. Specimen geometry.	34
Figure 2.2. Microcrack characterization specimen.	36
Figure 2.3. Photograph of the disassembled Priest interferometer.	38
Figure 2.4. Priest interferometer measurement principles.	39
Figure 2.5. Tensile specimen gripping elements.	42
Figure 3.1. Definition of lineal microcrack density.	49
Figure 3.2. Effect of layer thickness on microcrack density in the c90 layer in P75/ERL1962.X.*.G specimens.	53
Figure 3.3. Edge-view photographs of P75/ERL1962.X.*.G specimens containing microcracks.	55
Figure 3.4. X-ray photographs of P75/ERL1962.X.*.G specimens containing microcracks.	56
Figure 3.5. Effect of layer thickness on microcrack density in P75/RS3.Q2.*.G specimens.	58
Figure 3.6. Edge-view photographs of P75/RS3.Q2.*.G specimens containing microcracks.	60
Figure 3.7. X-ray photographs of P75/RS3.Q2.*.G specimens containing microcracks.	61
Figure 3.8. Nondimensional lineal microcrack densities in the c90 layer in P75/ERL1962.X.*.G specimens.	62
Figure 3.9. Effect of layer thickness on room temperature CTE in P75/ERL1962.X.*.G specimens.	63
Figure 3.10. Effect of layer thickness on room temperature CTE in P75/ERL1962.Q2.*.G specimens.	64
Figure 3.11. Effect of layer thickness on room temperature CTE in P75/RS3.Q2.*.G specimens.	64
Figure 3.12. Effect of layer thickness on normalized laminate stiffness in P75/ERL1962.X.*.G specimens.	65
Figure 3.13. Effect of layer thickness on normalized laminate stiffness in P75/ERL1962.Q2.*.G specimens.	66
Figure 3.14. Effect of layer thickness on normalized laminate stiffness in P75/RS3.Q2.*.G specimens.	66
Figure 3.15. Effect of fiber precursor on microcrack density in T50 and P55/ERL1962.X.5.G specimens.	68
Figure 3.16. Edge-view photographs of T50 and P55/ERL1962.X.5.G specimens containing microcracks.	69
Figure 3.17. X-ray photographs of T50 and P55/ERL1962.X.5.G specimens containing microcracks.	70
Figure 3.18. Edge-view photographs at high magnification of 90° layer in T50 and P55/ERL1962.X.5.G specimens containing microcracks.	71
Figure 3.19. Effect of fiber precursor on microcrack density in T50 and P55/ERL1962.Q1.5.G specimens.	73
Figure 3.20. Edge-view photographs of T50 and P55/ERL1962.Q1.5.G specimens containing microcracks.	75
Figure 3.21. X-ray photographs of T50 and P55/ERL1962.Q1.5.G specimens containing microcracks.	76
Figure 3.22. Effect of fiber precursor on room temperature CTE in T50 and P55/ERL1962.X.5.G specimens.	77
Figure 3.23. Effect of fiber precursor on room temperature CTE in T50 and P55/ERL1962.Q1.5.G specimens.	77
Figure 3.24. Effect of fiber precursor on normalized laminate stiffness in T50 and P55/ERL1962.X.5.G and T50 and P55/ERL1962.Q1.5.G specimens.	78

Figure 3.25. Effect of fiber type on microcrack density in P55, P75, and P120/ERL1962.X.5.G specimens.....	80
Figure 3.26. Edge-view photographs of P55, P75, and P120/ERL1962.X.5.G specimens containing microcracks	82
Figure 3.27. Effect of fiber type on microcrack density in P55, P75, and P120/ERL1962.Q1.5.G specimens.....	84
Figure 3.28. Edge-view photographs of P55, P75, and P120/ERL1962.Q1.5.G specimens containing microcracks	87
Figure 3.29. Effect of fiber type on room temperature CTE in P55, P75, and P120/ERL1962.X.5.G specimens...	88
Figure 3.30. Effect of fiber type on room temperature CTE in P55, P75, and P120/ERL1962.Q1.5.G specimens.	88
Figure 3.31. Effect of fiber type on normalized laminate stiffness in P55, P75, and P120/ERL1962.X.5.G and P55, P75, and P120/ERL1962.Q1.5.G specimens.....	89
Figure 3.32. Effect of matrix type on microcrack density in P75/*Q2.5.G specimens.....	91
Figure 3.33. Edge-view photographs of P75/*Q2.5.G specimens containing microcracks.	94
Figure 3.34. Effect of matrix type on room temperature CTE in P75/*Q2.5.G specimens.	95
Figure 3.35. Effect of matrix type on normalized laminate stiffness in P75/*Q2.5.G specimens.....	96
Figure 3.36. Effect of thermal cycling temperature range on microcrack density in P75/ERL1962.Q2.5.* specimens	99
Figure 3.37. Edge-view photographs of P75/ERL1962.Q2.5.* specimens containing microcracks.	101
Figure 3.38. X-ray photographs of P75/ERL1962.Q2.5.G and C specimens containing microcracks.....	102
Figure 3.39. Effect of thermal cycling temperature range on microcrack density in P75/RS3.Q2.2.* specimens..	104
Figure 3.40. Edge-view photographs of P75/RS3.Q2.2.* specimens containing microcracks.	106
Figure 3.41. Effect of thermal cycling temperature range on room temperature CTE in P75/ERL1962.Q2.5.* specimens	108
Figure 3.42. Effect of thermal cycling temperature range on room temperature CTE in P75/RS3.Q2.5.* specimens.	108
Figure 3.43. Effect of thermal cycling temperature range on room temperature CTE in P75/RS3.Q2.2.* specimens.	109
Figure 3.44. Effect of thermal cycling temperature range on normalized laminate stiffness in P75/ERL1962.Q2.5.*, P75/RS3.Q2.5.*, and P75/RS3.Q2.2.* specimens.....	110
Figure 4.1. One-dimensional shear lag model geometry.	113
Figure 4.2. Effect of various material parameters on microcrack density predictions from Crackomatic II. ([0/+45/90/-45] _s 0.005 in. ply thickness)	120
Figure 4.3. Effect of various material parameters on microcrack density predictions from Crackomatic II. ([0/+45/90/-45] _s 0.005 in. ply thickness)	121

Figure 4.4. Measured and predicted microcrack density in T50/ERL1962.X.5.G specimens using parameters from literature.	123
Figure 4.5. Effect of shear lag factor on predicted microcrack density in T50/ERL1962.X.5.G specimens.	124
Figure 4.6. Effect of $G_{IC}(0)$ on predicted microcrack density in T50/ERL1962.X.5.G specimens.	125
Figure 4.7. Effect of μ on predicted microcrack density in T50/ERL1962.X.5.G specimens.	126
Figure 4.8. Measured and predicted microcrack density in T50/ERL1962.Q1.5.G specimens.	127
Figure 4.9. Measured and predicted room temperature CTE for T50/ERL1962.X.5.G and T50/ERL1962.Q1.5.G specimens.	128
Figure 4.10. Measured and predicted laminate stiffness for T50/ERL1962.X.5.G and T50/ERL1962.Q1.5.G specimens.	129
Figure 4.11. Measured and predicted microcrack density in P55/ERL1962.X.5.G specimens.	131
Figure 4.12. Measured and predicted microcrack density in P55/ERL1962.Q1.5.G specimens.	132
Figure 4.13. Measured and predicted laminate CTE for P55/ERL1962.X.5.G and P55/ERL1962.Q1.5.G specimens.	132
Figure 4.14. Measured and predicted microcrack density in P75/ERL1962.X.5.G specimens.	133
Figure 4.15. Measured and predicted microcrack density in P75/ERL1962.Q1.5.G specimens.	134
Figure 4.16. Measured and predicted microcrack density in P75/ERL1962.Q2.5.G specimens.	135
Figure 4.17. Measured and predicted microcrack density in P75/ERL1962.Q2.5.L specimens.	136
Figure 4.18. Measured and predicted microcrack density in P75/ERL1962.Q2.5.C specimens.	137
Figure 4.19. Measured and predicted microcrack density in P75/ERL1962.X.1.G specimens.	138
Figure 4.20. Predicted microcrack density for P75/ERL1962.Q2.1.G.specimens.	139
Figure 4.21. Measured and predicted room temperature laminate CTE in P75/ERL1962 specimens.	141
Figure 4.22. Measured and predicted microcrack density in P120/ERL1962.X.5.G specimens.	142
Figure 4.23. Measured and predicted microcrack density in P120/ERL1962.Q1.5.G specimens.	143
Figure 4.24. Measured and predicted room temperature laminate CTE in P120/ERL1962.X.5.G and P120/ERL1962.Q1.5.G.specimens.	143
Figure 4.25. Measured and predicted microcrack density in P75/RS3.Q2.5.G specimens.	144
Figure 4.26. Measured and predicted microcrack density in P75/RS3.Q2.5.L specimens.	145
Figure 4.27. Measured and predicted microcrack density in P75/RS3.Q2.2.G specimens.	146
Figure 4.28. Measured and predicted microcrack density in P75/RS3.Q2.2.L specimens.	147
Figure 4.29. Measured and predicted room temperature CTE's for P75/RS3 specimens.	148
Figure 4.30. Measured and predicted microcrack density in P75/934.Q2.5.G specimens.	149
Figure 4.31. Measured and predicted room temperature laminate CTE's for P75/934.Q2.5.G specimens.	150
Figure 4.32. Previous [2] and Current $G_{IC}(0)$ values as a function of transverse tensile strength.	152

Figure A.1. Specimen temperature as a function of time for free and forced convection.....	167
Figure D.1. Thermal strain data for specimens J-2, 3, and 4 at 0 cycles.....	183
Figure D.2. Thermal strain data for specimens J-2, 3, and 4 at 3500 cycles.....	184
Figure D.3. Average thermal expansion data for specimen series J - T50/ERL1962.X.5.G - T50/ERL1962, [0/90/0/90] _S , 5 mil, ±250°F.....	184
Figure D.4. Thermal strain data for specimens O-3 and 4 at 0 cycles.....	185
Figure D.5. Thermal strain data for specimens O-2, 3, and 4 at 3500(3000 for O-2) cycles.....	186
Figure D.6. Average thermal expansion data for specimen series O - P55/ERL1962.X.5.G - P55/ERL1962, [0/90/0/90] _S , 5 mil, ±250°F.....	186
Figure D.7. Thermal strain data for specimens H-2 and H-4 at 0 cycles.....	187
Figure D.8. Thermal strain data for specimens H-2, 3, 4 at 3500 cycles.....	188
Figure D.9. Average thermal expansion data for specimen series H - P75/ERL1962.X.5.G - P75/ERL1962, [0/90/0/90] _S , 5 mil, ±250°F.....	188
Figure D.10. Thermal strain data for specimens Q-1 and 3 at 0 cycles.....	189
Figure D.11. Thermal strain data for specimens Q-1, 2, and 3 at 3500 cycles.....	190
Figure D.12. Average thermal expansion data for specimen series Q - P120/ERL1962.X.5.G - P120/ERL1962, [0/90/0/90] _S , 5 mil, ±250°F.....	190
Figure D.13. Thermal strain data for specimens UT8X-2 and 4 at 0 cycles.....	191
Figure D.14. Thermal strain data for specimens UT8X-2 and 5 at 5020 cycles.....	192
Figure D.15. Average thermal expansion data for specimen series UT8X - P75/ERL1962.X.1.G - P75/ERL1962, [0/90/0/90] _S , 1 mil, ±250°F.....	192
Figure D.16. Thermal strain data for specimens K-3 and 4 at 0 cycles.....	193
Figure D.17. Thermal strain data for specimens K-3 and 4 at 3500 cycles.....	194
Figure D.18. Average thermal expansion data for specimen series K - T50/ERL1962.Q1.5.G - T50/ERL1962, [0/+45/-45/90] _S , 5 mil, ±250°F.....	194
Figure D.19. Thermal strain data for specimens P-1 and 2 at 0 cycles.....	195
Figure D.20. Thermal strain data for specimens P-1, 2, and 3 at 3500 cycles.....	196
Figure D.21. Average thermal expansion data for specimen series P - P55/ERL1962.Q1.5.G - P55/ERL1962, [0/+45/-45/90] _S , 5 mil, ±250°F.....	196
Figure D.22. Thermal strain data for specimens I-1, 2, 3 at 0 cycles.....	197
Figure D.23. Thermal strain data for specimens I-1, 2, 3 at 3500 cycles.....	198
Figure D.24. Average thermal expansion data for specimen series I - P75/ERL1962.Q1.5.G - P75/ERL1962, [0/+45/-45/90] _S , 5 mil, ±250°F.....	198
Figure D.25. Thermal strain data for specimens R-1, 3, and 4 at 0 cycles.....	199

Figure D.26. Thermal strain data for specimens R-1, 3, and 4 at 3500 cycles.	200
Figure D.27. Average thermal expansion data for specimen series R - P120/ERL1962.Q1.5.G - P120/ERL1962, [0/+45/-45/90] _S , 5 mil, ±250°F.....	200
Figure D.28. Thermal strain data for specimens 6762-1, 3, and 5 at 0 cycles.....	201
Figure D.29. Thermal strain data for specimens 6762-1, 3, and 5 at 3000 cycles.....	202
Figure D.30. Average thermal expansion data for specimen series 6762 - P75/ERL1962.Q2.5.G - P75/ERL1962, [0/+45/90/-45] _S , 5 mil, ±250°F.....	202
Figure D.31. Thermal strain data for specimens 6762-02, 04, and 06 at 4000 cycles.....	203
Figure D.32. Average thermal expansion data for specimen series 6762 - P75/ERL1962.Q2.5.L - P75/ERL1962, [0/+45/90/-45] _S , 5 mil, ±150°F.....	203
Figure D.33. Thermal strain data for specimens 6762-07, 08, and 09 at 4000 cycles.....	204
Figure D.34. Average thermal expansion data for specimen series 6762 - P75/ERL1962.Q2.5.C - P75/ERL1962, [0/+45/90/-45] _S , 5 mil, ±50°F.....	204
Figure D.35. Thermal strain data for specimens 75RS3-01, 02, and 03 at 0 cycles.....	205
Figure D.36. Thermal strain data for specimens 75RS3-01, 02, and 03 at 3000 cycles.....	206
Figure D.37. Average thermal expansion data for specimen series 75RS3 - P75/RS3.Q2.5.G - P75/RS3, [0/+45/90/-45] _S , 5 mil, ±250°F.....	206
Figure D.38. Thermal strain data for specimens 75RS3-04, 05, and 06 at 4000 cycles.....	207
Figure D.39. Average thermal expansion data for specimen series 75RS3 - P75/RS3.Q2.5.L - P75/RS3, [0/+45/90/-45] _S , 5 mil, ±150°F.....	207
Figure D.40. Thermal strain data for specimens 75RS3-07, 08, and 09 at 4000 cycles.....	208
Figure D.41. Average thermal expansion data for specimen series 75RS3 - P75/RS3.Q2.5.C - P75/RS3, [0/+45/90/-45] _S , 5 mil, ±50°F.....	208
Figure D.42. Thermal strain data for specimens 75R-A-35 and 43 at 0 cycles.....	209
Figure D.43. Thermal strain data for specimens 75R-A-41, 43, and 44 at 4000, 3500, and 3000 cycles respectively.....	210
Figure D.44. Average thermal expansion data for specimen series 75R-A - P75/RS3.Q2.5.G - P75/RS3, [0/+45/90/-45] _S , 5 mil, ±250°F.....	211
Figure D.45. Thermal strain data for specimens 75R-A-36, 37, and 45 at 4000 cycles.....	212
Figure D.46. Average thermal expansion data for specimen series 75R-A - P75/RS3.Q2.5.L - P75/RS3, [0/+45/90/-45] _S , 5 mil, ±150°F.....	212
Figure D.47. Thermal strain data for specimens 75R-A-38, 39, and 46 at 4000 cycles.....	213
Figure D.48. Average thermal expansion data for specimen series 75RS3 and 75R-A - P75/RS3.Q2.5.C - P75/RS3, [0/+45/90/-45] _S , 5 mil, ±50°F.....	213

Figure D.49. Thermal strain data for specimens P734Q-2, 3, and 4 at 0 cycles.....	214
Figure D.50. Thermal strain data for specimens P734Q-2, 3, and 4 at 3000 cycles.....	215
Figure D.51. Average thermal expansion data for specimen series P734Q - P75/934.Q2.5.G - P75/934, [0/+45/90/-45] _S , 5 mil, ±250°F.....	215
Figure D.52. Thermal strain data for specimens 275RS3-01, 02, and 03 at 0 cycles.....	216
Figure D.53. Thermal strain data for specimens 275RS3-01, 02, and 03 at 3000 cycles.....	217
Figure D.54. Average thermal expansion data for specimen series 275RS3 - P75/RS3.Q2.2.G - P75/RS3, [0/+45/90/-45] _S , 2 mil, ±250°F.....	217
Figure D.55. Thermal strain data for specimens 275RS3-04, 05, and 06 at 4000 cycles.....	218
Figure D.56. Average thermal expansion data for specimen series 275RS3 - P75/RS3.Q2.2.L - P75/RS3, [0/+45/90/-45] _S , 2 mil, ±150°F.....	218
Figure D.57. Thermal strain data for specimens 275RS3-07, 08, and 09 at 4000 cycles.....	219
Figure D.58. Average thermal expansion data for specimen series 275RS3 - P75/RS3.Q2.2.C - P75/RS3, [0/+45/90/-45] _S , 2 mil, ±50°F.....	219
Figure D.59. Thermal strain data for specimens UTQ-1, 2, and 3 at 0 cycles.....	220
Figure D.60. Thermal strain data for specimens UTQ-1, 2, and 3 at 4500 cycles.....	221
Figure D.61. Average thermal expansion data for specimen series UTQ - P75/ERL1962.Q2.1.G - P75/ERL1962, [0/+45/90/-45] _S , 1 mil, ±250°F.....	221
Figure E.1. Experimentally determined laminate stiffness for specimen 6762-13.....	222
Figure E.2. Effect of lamina property variation on laminate stiffness for quasi-isotropic and cross-ply laminates.....	224
Figure F.1. Effect of lamina property variation on laminate stiffness for quasi-isotropic and cross-ply laminates.....	233
Figure F.2. Effect of lamina material property variation on laminate CTE.....	235
Figure F.3. Micromechanical parameter study results.....	239
Figure F.4. Comparison of measured and predicted laminate CTE.....	245