

**MECHANICAL PROPERTIES OF MULTIDIRECTIONAL
CARBON-CARBON COMPOSITES**

by

MALLIPUDI VENKATRAO

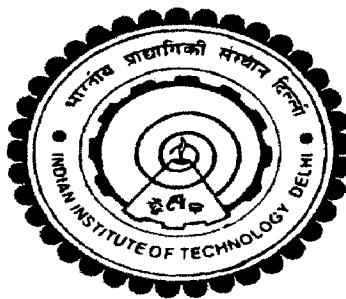
Department of Applied Mechanics

Submitted

In fulfillment of the requirements of the degree of

Doctor of Philosophy

to the



Indian Institute of Technology Delhi

May 2008

I. I. T. DELHI.
LIBRARY
Acc. No. TH-3597



TH
E46.26:620.19
VEN-M

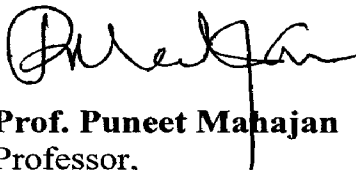
Dedicated

To

My Father

CERTIFICATE

This is to certify that the thesis entitled “**MECHANICAL PROPERTIES OF MULTIDIRECTIONAL CARBON-CARBON COMPOSITES**” being submitted by **MALLIPUDI VENKATRAO** is the report of bonafide research work carried by him under our supervision. This thesis has been prepared in conformity with the rules and regulations of the Indian Institute of Technology Delhi, New Delhi. We further certify that the thesis has attained a standard required for a Ph.D degree of the institute. The research reported and the results presented in the thesis have not been submitted, in part or full to any other institute or university for the award of any other degree or diploma.



Prof. Puneet Mahajan
Professor,
Department of Applied Mechanics,
Indian Institute of Technology Delhi,
New Delhi-110016. INDIA.



Prof. R.K Mittal
Professor,
Department of Applied Mechanics,
Indian Institute of Technology Delhi,
New Delhi-110016. INDIA.

Date: 19-05-2008
Place: New Delhi

ACKNOWLEDGEMENTS

I am very much pleased to express my gratefulness and indebtedness to my esteemed supervisors, Professor **Puneet Mahajan** and Professor **R. K. Mittal**, Applied Mechanics Department, IIT Delhi, for having their outstanding support during the course of this work. It is needless to mention that both of them have been extremely helpful to me in providing quality guidance, valuable time and of course support on various facets of the research work and other situations of life.

I am also extremely grateful to Mr. Atul Bhagat, Scientist-C, Mr. G. Ramaguru, Scientist-F, and Mrs. G. Rohini Devi, Scientist-G, ASL, Hyderabad, for extensive help they have rendered in supplying carbon-carbon samples and shared the knowledge about carbon-carbon composites.

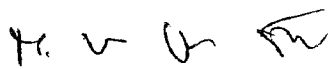
I am also grateful to Mr. Rishi and Mr. Rana, Lab Assistants at Applied Mechanics Deptt., IIT Delhi, who did their best in their capacity to conducting the experiments.

I am thankful to my parents and all family members, who encouraged me to pursue this degree at the cost of physical and mental separation. I am especially grateful to my wife, Satyavani for her long and enduring patience and wait for me without much complain.

I am also thankful to all my friends, co-research students and colleagues at SIEMENS and VESTAS, who helped me with material, moral and intellectual support at the time of need.

I would like to take this opportunity to thank all those who helped me in whatever capacity to see that the present project attains completion.

In the end I thank God, the almighty, for his blessings for whatever I have and giving me inner solace and strength to overcome the ups and downs of life.


(Mallipudi VenkatRao)

ABSTRACT

Multidirectional carbon-carbon composites are specialized group of materials finding varied applications in components operating at high temperature. Commonly used architectures for these composites are 3-directional orthogonal, 3-directional plain-woven, 3-directional 8-harness satin weave and 4-directional in-plane. For these applications a clear understanding of the effect of the architecture on mechanical and thermal behavior of these composites is essential. The macro-mechanical properties of these composites can often be determined from mechanical behavior of the fiber and matrix provided interface behavior between fiber and matrix and the progress of cracking in matrix and fiber bundle is known. In this thesis, 3-dimensional unit cells are established for different architectures and asymptotic homogenization technique is used to determine the equivalent homogeneous material (EHM) properties corresponding to these unit cells. For implementing the homogenization technique periodic boundary conditions are imposed on the unit cells and finite element method (FEM) is used to compute the volume averaged stresses and strains and thereby the EHM properties.

The work has been done at two levels. First, the mechanical properties of a fiber bundle are predicted assuming the fiber bundle to be perfectly bonded uni-directional composite. Next, the predicted properties of fiber bundle are used to predict the mechanical properties of the multidirectional carbon-carbon composites. To understand the effects of fiber-matrix interface bonding, thermal residual stresses and matrix cracking on the mechanical properties four cases are studied: (1) perfect bonding between fiber-bundle and matrix, (2a) interfacial debonding due to mechanical loading i.e. no thermal residual stresses are included, (2b) interfacial debonding due to thermal residual stresses and (2c) interfacial debonding and matrix cracking due to thermal residual stresses. Cohesive zone model

(CZM) has been used to simulate the interfacial debonding. Octahedral shear stress failure criterion is used to predict matrix cracking.

To compute the various strength properties of unit cells of different architectures, the maximum stress failure criterion is used to predict fiber or fiber-bundle failure in addition to the interfacial debonding and matrix cracking. To predict the strength properties of the fiber bundle, the unit cell used to predict the stiffness properties of fiber bundle was modified and cohesive zone was incorporated at the fiber/matrix interfaces of the fiber bundle unit cell. For predicting the strength properties of multi-directional composites same unit cells used, that are used predicting the stiffness properties.

The interfacial debonding, matrix cracking and presence of residual stresses have significant effect on mechanical properties of the composite. When there are no residual stresses, debonding causes a significant reduction in properties of the composite. When residual stresses and debonding are already present, (before mechanical loads are applied) the resulting deterioration in the elastic moduli occurs at much lower strains. Debonding along with matrix cracking leads to further deterioration in the properties.

Tensile and shear experiments were carried out on specimens of 3-directional orthogonal, 3-directional 8-harness satin weave, 4-directional in-plane architecture. The experimental results obtained were compared with those predicted by numerical modeling. It was observed that the predicted properties match well with the experimental values, when the debonding and matrix cracking are included in the numerical modeling.

TABLE OF CONTENT

DESCRIPTION OF THE CONTENT	Page No.
CERTIFICATE	ii
ACKNOWLEDGEMENTS	iii
ABSTRACT	iv
TABLE OF CONTENTS	vi
LIST OF FIGURES.....	xi
LIST OF TABLES.....	xviii
NOMENCLATURE	xx
CHAPTER 1 INTRODUCTION	1
1.1 Composite Materials	1
1.2 Classification of Composite Materials	2
1.3 Specific Description of Carbon-Carbon Composites	3
1.3.1 Constituents of Carbon-Carbon Composites	4
1.3.1.1 Carbon Fibers	4
1.3.1.2 Carbon Matrix	4
1.3.2 Fabrication Process of Carbon-Carbon Composites	4
1.3.2.1 Preform Weaving	5
1.3.2.2 Densification of Preform	5
1.3.3 Applications of Carbon-carbon Composites	8
1.4 Motivation	8
1.5 Methods for Determining the Mechanical Properties	9
1.6 Need of Numerical Modeling	10
1.7 Organization of the Thesis	10

CHAPTER 2 LITERATURE REVIEW	12
2.1 Literature Review	12
2.2 Existing Gaps in the Knowledge	21
2.3 Objectives of the Present Work	21
 CHAPTER 3 BASIC CONCEPTS FOR NUMERICAL MODELING	 23
3.1 Introduction	23
3.2 Unit Cells for Different Architectures	24
3.3 Homogenization	28
3.4 Periodic Boundary Conditions	32
3.5 Extraction of the Effective Mechanical Properties of the Composite	37
3.6 Damage Mechanisms	39
3.6.1 Interfacial Debonding	39
3.6.1.1 Cohesive Zone Modeling (CZM).....	40
3.6.2 Matrix Failure	44
3.6.3 Fiber and Fiber bundle Failure	44
 CHAPTER 4 NUMERICAL MODELING FOR DETERMINATION OF	
MECHANICAL PROPERTIES	46
4.1 Introduction	46
4.2 Stiffness Properties	46
4.2.1 Stiffness Properties of a Fiber bundle	47
4.2.2 Stiffness Properties of the Composite for Different Architectures	49
4.2.2.1 Finite element modeling of Multidirectional composite Unit cells	51

4.3 Strength Properties	56
4.3.1 Strength Properties of a Fiber bundle	56
4.3.2 Strength Properties of Multidirectional Carbon-Carbon Composites for Different Architectures.	58
4.4 Results	58
4.4.1 Stiffness Properties	58
4.4.1.1 Fiber bundle Properties	58
4.4.1.2 Composite Properties for Different Architectures	59
4.4.1.2.1 Case 1: Perfect bonding between Fiber bundle and Matrix	59
4.4.1.2.2 Case 2a: Debonding at the Fiber bundle-Matrix Interface, but without the Effect of Cooling from Processing Temperature	61
4.4.1.2.2.1 Effect of Interfacial Strength	74
4.4.1.2.3 Cooling of a Composite from Processing Temperature to Room Temperature, Resulting in the Development of Residual Stresses.	75
4.4.1.2.3.1 Case 2b. Interfacial Debonding between Fiber-bundle/Matrix Interface but Matrix Cracking not Included in Modeling	77
4.4.1.2.3.1.1 Effect of Interfacial Strength..	80
4.4.1.2.3.2 Case 2c. Interfacial Debonding between Fiber bundle-Matrix Interface and Matrix Cracking included in Modeling	81

6.2.1.2 Effect of Fiber Volume Fraction on Stiffness Properties	111
6.2.1.3 Effect of Interfacial Strength on Stiffness Properties	111
6.2.2 Strength Properties of Composites	112
6.3 Discussion on Comparison with Experimental Results	113
6.3.1 Stiffness Properties	113
6.3.2 Strength Properties	120
6.4 Conclusions	120
6.5 Recommendations for Further Study.....	123
REFERENCES	125
APPENDIX-A.....	133
APPENDIX-B.....	136
LIST OF PUBLICATIONS.....	142
AUTHOR'S BIOGRAPHY.....	143