

Polymer Matrix Composites: Guidelines for Characterization of Structural Materials

CMH-17

COMPOSITE MATERIALS HANDBOOK



WICHITA STATE
UNIVERSITY



**NOT MEASUREMENT
SENSITIVE**

CMH-17-1H
Volume 1 of 6
AUGUST 2022

Superseding
CMH-17-1G
MARCH 2012

COMPOSITE MATERIALS HANDBOOK

POLYMER MATRIX COMPOSITES GUIDELINES FOR CHARACTERIZATION OF STRUCTURAL MATERIALS

VOLUME 1. Revision H



Copyright 2022 - Composite Materials Handbook – 17 (CMH-17). All rights reserved. Unauthorized duplication or distribution may violate the Copyright Laws of the United States and of other jurisdictions.

This handbook arises from work funded by the Federal Aviation Administration to Wichita State University under Cooperative Agreement Number 12-C-AM-WISU and is protected by United States copyright law. The handbook may not be reproduced, distributed, transmitted, displayed, published, or broadcast without the prior, express written permission of Wichita State University. You may not alter or remove any copyright or other notice from copies of this content.

The underlying data from the work conducted under Cooperative Agreement Number 12-C-AM-WISU is publicly available and accessible at from the Defense Logistics Agency (DLA) Document Services, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

FOREWORD

The Composite Materials Handbook, CMH-17, provides information and guidance necessary to design and fabricate structural components from composite materials. Its primary purposes are a) the standardization of engineering data development methodologies related to testing, data reduction, and data reporting of property data for current and emerging composite materials, b) guidance on material and process specifications and procedures for utilization of the material data presented in the handbook, and c) methodologies for the design, analysis, certification, manufacture, and field support of composite structures. In support of these objectives, the handbook includes composite materials properties that meet specific data requirements. The handbook therefore constitutes an overview of the field of composites technology and engineering, an area that is advancing and changing to support new applications. As a result, the document will be continually revised as sections are added or modified to reflect advances in best industry practices.

CMH-17 Mission

The Composite Materials Handbook organization creates, publishes, and maintains proven, reliable engineering information and standards, subjected to thorough technical review, to support the development and use of composite materials and structures.

CMH-17 Vision

The Composite Materials Handbook will be the authoritative worldwide focal point for technical information on composite materials and structures.

Goals and Objectives to Support the CMH-17 Mission

- To periodically meet with experts from the field to discuss critical technical issues for composite structural applications, with an emphasis on increasing overall product efficiency, quality, and safety
- To provide comprehensive, practical engineering guidance that has proven reliable for the design, fabrication, characterization, test, and maintenance of composite materials and structures
- To provide reliable data, linked to control of processes and raw materials, thereby being a comprehensive source of material property basis values and design information that can be shared within the industry
- To provide a resource for composite material and structure education with examples, applications and references to supporting engineering work
- To establish guidelines for use of information in the handbook, identifying the limitations of the data and methods
- To provide guidance on references to proven standards and engineering practices
- To provide for periodic updates to maintain the all-inclusive nature of the information
- To provide information in formats best suited for user needs
- To serve the needs of the international composites community through meetings and dialog between member industries, which use teamwork and the diverse member engineering skills to provide information for the handbook

Notes

1. Every effort has been made to reflect the latest information on polymer (organic), metal, and ceramic composites. The handbook is continually reviewed and revised to ensure it is complete and current.
2. CMH-17 provides guidelines and material properties for polymer (organic), metal, and ceramic matrix composite materials. The first three volumes of this handbook currently focus on, but are not limited to, polymeric composites intended for aircraft and aerospace vehicles. Metal matrix composites (MMC), ceramic matrix composites (CMC), and sandwich composites are covered in Volumes 4, 5, and 6, respectively. The organization is also developing a new Volume 7 for non-metallic additive manufacturing.
3. The information contained in this handbook was obtained from materials producers, industry companies and experts, reports on government-sponsored research, the open literature, and by contract with research laboratories and those who participate in the CMH-17 coordination activity. The information in this handbook has undergone vigorous technical review and was subject to membership vote.
4. Beneficial comments (recommendations, additions, and deletions) and any pertinent data which may be of use in improving this document should be addressed to: CMH-17 Secretariat, Wichita State University, 1845 Fairmount, Wichita, KS 67260, by letter or email, info@cmh17.org.

ACKNOWLEDGEMENT

Committee members from government, industry, and academia develop, coordinate, and review all the information provided in this handbook. The time and effort of the members and the support of their respective departments, companies, and universities make it possible to ensure the handbook reflects completeness, accuracy, and industry best practices.

Support necessary for the development and maintenance of the Composite Materials Handbook (CMH-17) is provided by the Handbook Secretariat, Wichita State University. The primary source of funding for the current Secretariat contract is the Federal Aviation Administration.

SUMMARY OF CHANGES

Chapter	Section	Title	Change type / Proceedings
	Cover	Cover	CMH-17 Leadership Committee
	Foreword	Foreword	CMH-17 Leadership Committee
1		<u>Objectives</u>	
	1.4.1	Roadmaps for use of Volumes 1 - 3	Revision / Virtual (7/20)
	1.7.1.2	Laminae and laminates	Revision / Salt Lake City (3/15)
	1.8	Definitions	Revision and New / Salt Lake City (3/15, 3/17), Charleston (7/18), Salt Lake City (3/19)
2		<u>Guidelines for Property Testing of Composites</u>	
	ALL	Complete chapter revision	Revision / Salt Lake City (2/17), Charleston (7/18), Salt Lake City (3/19), virtual (7/20)
3		<u>Evaluation of Reinforcement Fibers</u>	
	ALL	Complete chapter revision	Revision / Salt Lake City (3/19), Wichita (10/19)
4		<u>Matrix Characterization</u>	
	ALL	Complete chapter revision	Revision / Salt Lake City (3/19), Virtual (7/20)
5		<u>Prepreg Material Characterization</u>	
	Chapter 5	Complete chapter revision	Revision / Wichita (11/17), Salt Lake City (3/19)
6		<u>Lamina, Laminate, and Special Form Characterization</u>	
	6.2	Specimen Preparation	Revision / Virtual (7/20)
	6.3	Conditioning and Environmental Exposure	Revision / Wichita (10/19), Virtual (7/20)
	6.4	Instrumentation and Calibration	Revision / Virtual (7/20)
	6.5	Testing Environments	Revision / Virtual (7/20)
	6.6	Thermal/Physical Property Tests	Revision / Wichita (11/17 and 10/19), Virtual (7/20)
	6.8	Static Uniaxial Mechanical Property Tests	Revision / Virtual (7/20)
	6.8.6	Fracture Toughness	revision / Virtual (7/20)
	6.11	Viscoelastic Properties Tests	Revision / Virtual (7/20)

Chapter	Section	Title	Change type / Proceedings
7		<u>Structural Element Characterization</u>	
	ALL	Complete chapter revision	Revision / Salt Lake City (3/19)
	7.6	Bonded joint tests	Revision / Virtual (7/20)
	7.8	High Load Rate and Dynamic Testing	New / Virtual (7/20)
8		<u>Statistical Methods</u>	
	8	References and examples to CMH-17 STATS updated throughout	
	8.3.7	Calculation of basis values for structured data using regression analysis	Revision / Salt Lake City (3/19), Virtual (7/20)
	8.4	Statistical Methods	Revision / Virtual (7/20)
	8.4.1	Methods to set material specification limits or determine equivalency between an existing database and a new dataset for the same material	Revision / Salt Lake City (3/19)
	8.4.2.2	Test method induced variability in comparing two groups	New / Virtual (3/21)
	8.4.7	General linear statistical models	Revision / Salt Lake City (3/19)

Contents

1.1	INTRODUCTION TO THE HANDBOOK.....	2
1.2	OVERVIEW OF HANDBOOK CONTENT	2
1.3	PURPOSE AND SCOPE OF VOLUME 1.....	3
1.4	USE OF THE DOCUMENT AND LIMITATIONS	5
1.4.1	Roadmaps for use of Volumes 1 – 3	5
1.4.2	Source of information.....	16
1.4.3	Use of data and guidelines in applications	17
1.4.4	Strength properties and allowables terminology.....	17
1.4.5	Use of references	17
1.4.6	Use of tradenames and product names	17
1.4.7	Toxicity, health hazards, and safety	18
1.4.8	Ozone depleting chemicals.....	18
1.5	APPROVAL PROCEDURES	18
1.6	MATERIAL ORIENTATION CODES	19
1.6.1	Laminate orientation codes.....	19
1.6.2	Braiding orientation codes	22
1.7	SYMBOLS, ABBREVIATIONS, AND SYSTEMS OF UNITS	22
1.7.1	Symbols and abbreviations.....	22
1.7.2	System of units	32
1.8	DEFINITIONS	33
	REFERENCES.....	61

Polymer Matrix Composites: Materials Properties

CMH-17

COMPOSITE MATERIALS HANDBOOK



WICHITA STATE
UNIVERSITY



**NOT MEASUREMENT
SENSITIVE**

CMH-17-2H
Volume 2 of 6
FEBRUARY 2018

SUPERSEDING
CMH-17-2G
Volume 2 of 6
17 JUNE 2012

COMPOSITE MATERIALS HANDBOOK

POLYMER MATRIX COMPOSITES: MATERIALS PROPERTIES

VOLUME 2. Rev. H/Part A



CMH-17
COMPOSITE MATERIALS HANDBOOK

ISBN-Print 978-0-7680-9481-7

Copyright 2018 - Composite Materials Handbook – 17 (CMH-17). All rights reserved. Unauthorized duplication or distribution may violate the Copyright Laws of the United States and of other jurisdictions

FOREWORD

The Composite Materials Handbook, CMH-17, provides information and guidance necessary to design and fabricate structural components from composite materials. Its primary purposes are a) the standardization of engineering data development methodologies related to testing, data reduction, and data reporting of property data for current and emerging composite materials, b) guidance on material and process specifications and procedures for utilization of the material data presented in the handbook, and c) methodologies for the design, analysis, certification, manufacture, and field support of composite structures. In support of these objectives, the handbook includes composite materials properties that meet specific data requirements. The handbook therefore constitutes an overview of the field of composites technology and engineering, an area that is advancing and changing rapidly. As a result, the document will be continually revised as sections are added or modified to reflect advances in the state of the art.

CMH-17 Mission

The Composite Materials Handbook organization creates, publishes, and maintains proven, reliable engineering information and standards, subjected to thorough technical review, to support the development and use of composite materials and structures.

CMH-17 Vision

The Composite Materials Handbook will be the authoritative worldwide focal point for technical information on composite materials and structures.

Goals and Objectives to Support the CMH-17 Mission

- To periodically meet with experts from the field to discuss critical technical issues for composite structural applications, with an emphasis on increasing overall product efficiency, quality, and safety
- To provide comprehensive, practical engineering guidance that has proven reliable for the design, fabrication, characterization, test, and maintenance of composite materials and structures
- To provide reliable data, linked to control of processes and raw materials, thereby being a comprehensive source of material property basis values and design information that can be shared within the industry
- To provide a resource for composite material and structure education with examples, applications and references to supporting engineering work
- To establish guidelines for use of information in the handbook, identifying the limitations of the data and methods
- To provide guidance on references to proven standards and engineering practices
- To provide for periodic updates to maintain the all-inclusive nature of the information
- To provide information in formats best suited for user needs
- To serve the needs of the international composites community through meetings and dialog between member industries, which use teamwork and the diverse member engineering skills to provide information for the handbook

Notes

1. Every effort has been made to reflect the latest information on polymer (organic), metal, and ceramic composites. The handbook is continually reviewed and revised to ensure it is complete and current.
2. CMH-17 provides guidelines and material properties for polymer (organic), metal, and ceramic matrix composite materials. The first three volumes of this handbook currently focus on, but are not limited to, polymeric composites intended for aircraft and aerospace vehicles. Metal matrix composites (MMC), ceramic matrix composites (CMC) including carbon–carbon composites (C–C), and sandwich composites are covered in Volumes 4, 5, and 6, respectively.
3. The information contained in this handbook was obtained from materials producers, industry companies and experts, reports on government-sponsored research, the open literature, and by contract with research laboratories and those who participate in the CMH-17 coordination activity. The information in this handbook has undergone vigorous technical review and was subject to membership vote.
4. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: CMH-17 Secretariat, Wichita State University, 1845 Fairmount, Wichita, KS 67260, by letter or email, info@cmh17.org.

ACKNOWLEDGEMENT

Volunteer committee members from government, industry, and academia develop, coordinate, and review all the information provided in this handbook. The time and effort of the volunteers and the support of their respective departments, companies, and universities make it possible to insure the handbook reflects completeness, accuracy, and state-of-the-art composite technology.

Support necessary for the development and maintenance of the Composite Materials Handbook (CMH-17) are provided by the Handbook Secretariat, Wichita State University. The primary source of funding for the current Secretariat contract is the Federal Aviation Administration.

TABLE OF CONTENTS

	Page
Foreword	ii
Summary of Changes	viii
 PART A	
Chapter 1 General Information	1-1
Chapter 2A Carbon Fiber Composites	2A-1
Appendix A1. MIL-HDBK-17A Data.....	A1-1
 PART B	
Chapter 2B Carbon Fiber Composites.....	2B-1
Chapter 3 Boron Fiber Composites	3-1
Chapter 4 Glass Fiber Composites.....	4-1
Chapter 5 Quartz Fiber Composites	5-1

	Page
<u>TABLE</u>	
A1.1 U.S. Polymeric E-720E/7781 (ECDE/05-550) Fiberglass Epoxy	.....A1-6
A1.3 Hexcel F-161/7743(550) Fiberglass Epoxy	..... A1-14
A1.4 Hexcel F-161/7781 (ECDE-1/0-550) Fiberglass Epoxy (26% resin)	..... A1-24
A1.5 Hexcel F-161/7781 (ECDE-1/0-550) Fiberglass Epoxy (31% resin)	..... A1-30
A1.6 Hexcel F-161/7781 (ECDE-1/0-550) Fiberglass Epoxy (36% resin)	..... A1-36
A1.8 Narmco N588/7781 (ECDE-1/0-550) Fiberglass Epoxy	..... A1-46
A1.40 Narmco N506/7781 (ECDE-1/0-A1100) Fiberglass Phenolic	..... A1-56
A1.110 Narmco 5505 Boron-Epoxy (100%—0° Direction)	..... A1-64
A1.111 Narmco 5505 Boron-Epoxy (0°-90° Crossply)	..... A1-68
<u>FIGURE</u>	
A1.1.1(a) Tensile stress-strain for E-720E/7781 fiberglass epoxy loaded in the 0° direction	..... A1-7
A1.1.1(b) Tensile stress-strain for E-720E/7781 fiberglass epoxy loaded in the 90° direction	..... A1-8
A1.1.2(a) Compressive stress-strain for E-720E/7781 fiberglass epoxy loaded in the 0° direction	... A1-9
A1.1.2(b) Compressive stress-strain for E-720E/7781 fiberglass epoxy loaded in the 90° direction	..... A1-10
A1.1.3 0°-90° rail shear for E-720E/7781 fiberglass	.....A1-11
A1.1.4 Poisson effects for E-720E/7781 fiberglass epoxy	..... A1-12
A1.3.1(a) Tensile stress-strain for F-161/7743 fiberglass epoxy loaded in the 0° direction	..... A1-15
A1.3.1(b) Tensile stress-strain for F-161/7743 fiberglass epoxy loaded in the 90° direction	..... A1-17
A1.3.2(a) Compressive stress-strain for F-161/7743 fiberglass epoxy loaded in the 0° direction	.... A1-18
A1.3.2(b) Compressive stress-strain F-161/7743 fiberglass epoxy loaded in the 90° direction	..... A1-19
A1.3.3 0°-90° rail shear for F-161/7743 fiberglass epoxy	..... A1-20
A1.3.4 Poisson effects for F-161/7743 fiberglass epoxy	..... A1-21
A1.3.5 Voids vs. resin content and specific gravity for F-161/7743 fiberglass epoxy	..... A1-22
A1.4.1(a) Tensile stress-strain for F-161/7781 fiberglass epoxy loaded in the 0° direction (26% resin)	.....A1-25
A1.4.1(b) Tensile stress-strain for F-161/7781 fiberglass epoxy loaded in the 90° direction (26% resin)	..... A1-26

	Page
A1.4.2(a) Compressive stress-strain for F-161/7781 fiberglass epoxy loaded in the 0° direction (26% resin)	..... A1-27
A1.4.2(b) Compressive stress-strain for F-161/7781 fiberglass epoxy loaded in the 90° direction (26% resin)	..... A1-28
A1.4.4 Poisson effects for F-161/7781 fiberglass epoxy (26% resin)	..... A1-29
A1.5.1(a) Tensile stress-strain for F-161/7781 fiberglass epoxy loaded in the 0° direction (31% resin)	..... A1-31
A1.5.1(b) Tensile stress-strain for F-161/7781 fiberglass epoxy loaded in the 90° direction (31% resin)	..... A1-32
A1.5.2(a) Compressive stress-strain for F-161/7781 fiberglass epoxy loaded in the 0° direction (31% resin)	..... A1-33
A1.5.2(b) Compressive stress-strain for F-161/7781 fiberglass epoxy loaded in the 90° direction (31% resin)	..... A1-34
A1.5.4 Poisson effects for F-161/7781 fiberglass epoxy (31% resin)	..... A1-35
A1.6.1(a) Tensile stress-strain for F-161/7781 fiberglass epoxy loaded in the 0° direction (36% resin)	..... A1-37
A1.6.1(b) Tensile stress-strain for F-161/7781 fiberglass epoxy loaded in the 90° direction (36% resin)	..... A1-38
A1.6.2(a) Compressive stress-strain for F-161/7781 fiberglass epoxy loaded in the 0° direction (36% resin)	..... A1-39
A1.6.2(b) Compressive stress-strain for F-161/7781 fiberglass epoxy loaded in the 90° direction (36% resin)	..... A1-40
A1.6.3 Picture frame shear for F-161/7781 fiberglass epoxy (26%, 31%, 36% resin)	..... A1-41
A1.6.4 Poisson effects for F-161/7781 fiberglass epoxy (36% resin)	..... A1-42
A1.6.5 Voids vs. resin content and specific gravity for F-161/7781 fiberglass epoxy (26%, 31%, 36% resin)	..... A1-43
A1.6.6 Thickness vs. resin content for F-161/7781 fiberglass epoxy	..... A1-44
A1.8.1(a) Tensile stress-strain for N588/7781 fiberglass epoxy loaded in the 0° direction	..... A1-47
A1.8.1(b) Tensile stress-strain for N588/7781 fiberglass epoxy loaded in the 90° direction	..... A1-48
A1.8.2(a) Compressive stress-strain for N588/7781 fiberglass epoxy loaded in the 0° direction.....	A1-49
A1.8.2(b) Compressive stress-strain for N588/7781 fiberglass epoxy loaded in the 90° direction...	A1-51
A1.8.3 Rail shear for N588/7781 fiberglass epoxy	..... A1-52

	Page
A1.8.4 Poisson effects for N588/7781 fiberglass epoxy	A1-53
A1.8.5 Voids vs. resin content and specific gravity for N588/7781 fiberglass epoxy	A1-54
A1.40.1(a) Tensile stress-strain for N506/7781 fiberglass phenolic loaded in the 0° direction.....	A1-57
A1.40.1(b) Tensile stress-strain for N506/7781 fiberglass phenolic loaded in the 90° direction.....	A1-58
A1.40.2(a) Compressive stress-strain for N506/7781 fiberglass phenolic loaded in the 0° direction	A1-59
A1.40.2(b) Compressive stress-strain for N506/7781 fiberglass phenolic loaded in the 90° direction	A1-60
A1.40.3 0°-90° rail shear for N506/7781 fiberglass phenolic	A1-61
A1.40.4 Poisson effects for N506/7781 fiberglass phenolic	A1-62
A1.40.5 Voids vs. resin content and specific gravity for N506/7781 fiberglass phenolic	A1-63
A1.110.1 Tensile stress-strain for AVCO 5505 boron/epoxy (100% - 0° orientation/50.3% to 35% fiber volume) loaded in the 0° and 90° direction	A1-65
A1.110.2 Compressive stress-strain for AVCO 5505 boron/epoxy (100% - 0° orientation loaded in the 0° direction	A1-66
A1.110.3 Poisson effects for AVCO 5505 boron/epoxy (100% - 0° direction)	A1-67
A1.111.1(a) Tensile stress-strain for AVCO 5505 boron/epoxy (0°-90° crossply) loaded in the 0° direction	A1-69
A1.111.1(b) Tensile stress-strain for AVCO 5055 boron/epoxy (0°-90° crossply) loaded in the 45° direction	A1-70
A1.111.3 Poisson effects for AVCO 5055 boron/epoxy (0°-90° crossply)	A1-71
REFERENCES	A1-72

SUMMARY OF CHANGES

Chapter	Section [old section #]	Title	Change type
1		<u>General Information</u>	
	1.7.1.2	Laminae and laminates	Revision/Salt Lake City (3/2015)
	1.8	Definitions	Revision and new/Salt Lake City (3/2015 and 3/2017)
	1.10 [Volume 1, Section 2.4]	Data Reduction and Documentation	Reorganization/Wichita (12/2013)
	1.11 [Volume 1, Section 2.5]	Material Testing for Submission of Data to CMH-17	Reorganization/Wichita (12/2013)
	1.12 [Volume 1, Section 2.3.7]	Data Substantiation for Use of Basis Values from CMH-17 or Other Large Databases	Reorganization/Wichita (12/2013)
2		<u>Carbon Fiber Properties</u>	
	2.2.1.3	AS4 12k/8552 Unidirectional Tape	New/Boston (8/2012)
	2.2.1.4	IM7 12k/8552 Unidirectional Tape	New/Supplemental YPs (3/2015)
	2.2.1.5	T650 6k/5320 Unidirectional Tape	New/Wichita (10/2015)
	2.2.1.6	IM7 12k/MTM45-1 Unidirectional Tape	New/Salt Lake City (3/2015)
	2.2.1.7	HTS40 12k/MTM45-1 Unidirectional Tape	New/Salt Lake City (3/2015)
	2.2.1.8	AS4 12k/MTM45-1 Unidirectional Tape	New/Salt Lake City (3/2015)
	2.2.1.9	IM7 12k/EP2202 Unidirectional Tape	New/Salt Lake City (3/2017)
	2.2.1.10	IM7 GP 12k/BT250E-6 Unidirectional Tape	New/St. Paul (8/2016)
	2.2.2.5	AS4 3k/8552 Plain Weave Fabric	New/Wichita (12/2013)
	2.2.2.6	HTS40 E13 3k/MTM45-1 Plain Weave Fabric	New/Miami (8/2014)
	2.2.2.7	T650 3k/5320-1 Plain Weave Fabric	New/Supplemental YPs (3/2015)
	2.2.2.8	HTS40/TC250 Plain Weave Fabric	New/Salt Lake City (3/2015)
	2.2.2.9	AS4C 3k/BT250-E Plain Weave Fabric	New/St. Paul (8/2016)
	2.2.2.10	T650/EP2202 Plain Weave Fabric	New/Salt Lake City (3/2017)

CHAPTER 1 GENERAL INFORMATION

Table of Contents

1.1	INTRODUCTION TO THE HANDBOOK	1-4
1.2	OVERVIEW OF HANDBOOK CONTENT	1-4
1.3	PURPOSE AND SCOPE OF VOLUME 2.....	1-5
1.4	ORGANIZATION OF DATA IN VOLUME 2	1-6
1.5	PRESENTATION OF DATA.....	1-7
1.5.1	Complete Documentation	1-7
1.5.1.1	Data Set Description	1-7
1.5.1.2	Summary Tables	1-8
1.5.1.3	Individual Data Tables—Normalized Data	1-15
1.5.1.4	Individual Data Tables—Unnormalized Data	1-18
1.5.1.5	Individual Data Tables—Notched Laminate Data	1-19
1.5.1.6	Individual Data Tables—Bearing Data	1-19
1.5.1.7	Individual Data Tables—Bearing/Bypass Data	1-19
1.5.2	Legacy Data	1-23
1.5.3	Appended MIL-HDBK-17 Rev A data.....	1-23
1.6	MATERIALS SYSTEMS	1-24
1.6.1	Materials System Codes	1-24
1.6.2	Index of Materials.....	1-24
1.7	MATERIAL ORIENTATION CODES.....	1-24
1.7.1	Laminate Orientation Codes	1-24
1.7.1.1	Stacking Sequence Notation	1-25
1.7.1.2	Ply Percentage Notation	1-26
1.7.2	Braiding Orientation Codes.....	1-27
1.8	SYMBOLS, ABBREVIATIONS, AND SYSTEMS OF UNITS.....	1-27
1.8.1	Symbols and Abbreviations.....	1-28
1.8.1.1	Constituent Properties	1-33
1.8.1.2	Laminae and Laminates	1-34
1.8.1.3	Subscripts	1-35
1.8.1.4	Superscripts	1-36
1.8.1.5	Acronyms	1-36
1.8.2	System of Units	1-38
1.9	DEFINITIONS.....	1-40
1.10	DATA REDUCTION AND DOCUMENTATION	1-63
1.10.1	Introduction	1-63
1.10.2	Lamina Properties from Laminates.....	1-63

Volume 2, Chapter 1 General Information

1.10.2.1	Methodology	1-64
1.10.2.2	Tension Strength Tests.....	1-65
1.10.2.3	Compression Strength Tests.....	1-66
1.10.2.4	Other Properties.....	1-66
1.10.3	Data Normalization.....	1-67
1.10.3.1	Normalization Theory.....	1-67
1.10.3.2	Normalization Methodology	1-67
1.10.3.3	Practical Application of Normalization.....	1-71
1.10.4	Dispositioning of Outlier Data	1-72
1.10.5	Data Documentation	1-75
1.11	MATERIAL TESTING FOR SUBMISSION OF DATA TO CMH-17.....	1-75
1.11.1	Introduction	1-75
1.11.2	Material and Process Specification Requirements	1-78
1.11.3	Sampling Requirements.....	1-78
1.11.3.1	Additional Requirements for B and A Data Classes	1-78
1.11.3.2	Data Pooling	1-79
1.11.4	Conditioning Requirements.....	1-80
1.11.5	Test Method Requirements	1-80
1.11.6	Data Documentation Requirements.....	1-81
1.11.7	Data Normalization.....	1-86
1.11.8	Statistical Analysis.....	1-86
1.11.9	Mechanical Properties of Laminae and Laminates.....	1-86
1.11.9.1	Unidirectional Properties from Laminates.....	1-87
1.11.9.2	Strength and Strain-to-Failure	1-87
1.11.9.3	Failure Modes and Locations.....	1-87
1.11.9.4	Elastic Moduli, Poisson's Ratios, and Stress-Strain Curves.....	1-87
1.11.10	Chemical Properties.....	1-87
1.11.11	Physical Properties of Laminae and Laminates.....	1-87
1.11.11.1	Density	1-87
1.11.11.2	Composition	1-88
1.11.11.3	Equilibrium Moisture Content.....	1-88
1.11.11.4	Moisture Diffusivity.....	1-88
1.11.11.5	Coefficient of Moisture Expansion	1-88
1.11.11.6	Glass Transition Temperature	1-88
1.11.12	Thermal Properties.....	1-88
1.11.12.1	Coefficient of Thermal Expansion.....	1-89
1.11.12.2	Specific Heat.....	1-89

Volume 2, Chapter 1 General Information

1.11.12.3 Thermal Conductivity	1-89
1.11.12.4 Thermal Diffusivity	1-89
1.11.13 Electrical Properties	1-89
1.11.14 Fatigue	1-89
1.12 DATA SUBSTANTIATION FOR USE OF BASIS VALUES FROM CMH-17 OR OTHER LARGE DATABASES.....	1-91
REFERENCES.....	1-93

Polymer Matrix Composites: Materials Properties

CMH-17

COMPOSITE MATERIALS HANDBOOK



WICHITA STATE
UNIVERSITY



**NOT MEASUREMENT
SENSITIVE**

CMH-17-2H
Volume 2 of 6
FEBRUARY 2018

SUPERSEDING
CMH-17-2G
Volume 2 of 6
17 JUNE 2012

COMPOSITE MATERIALS HANDBOOK

POLYMER MATRIX COMPOSITES: MATERIALS PROPERTIES

VOLUME 2. Rev. H/Part B



CMH-17
COMPOSITE MATERIALS HANDBOOK

ISBN-Print 978-0-7680-9481-7

Copyright 2018 - Composite Materials Handbook – 17 (CMH-17). All rights reserved. Unauthorized duplication or distribution may violate the Copyright Laws of the United States and of other jurisdictions

FOREWORD

The Composite Materials Handbook, CMH-17, provides information and guidance necessary to design and fabricate structural components from composite materials. Its primary purposes are a) the standardization of engineering data development methodologies related to testing, data reduction, and data reporting of property data for current and emerging composite materials, b) guidance on material and process specifications and procedures for utilization of the material data presented in the handbook, and c) methodologies for the design, analysis, certification, manufacture, and field support of composite structures. In support of these objectives, the handbook includes composite materials properties that meet specific data requirements. The handbook therefore constitutes an overview of the field of composites technology and engineering, an area that is advancing and changing rapidly. As a result, the document will be continually revised as sections are added or modified to reflect advances in the state of the art.

CMH-17 Mission

The Composite Materials Handbook organization creates, publishes, and maintains proven, reliable engineering information and standards, subjected to thorough technical review, to support the development and use of composite materials and structures.

CMH-17 Vision

The Composite Materials Handbook will be the authoritative worldwide focal point for technical information on composite materials and structures.

Goals and Objectives to Support the CMH-17 Mission

- To periodically meet with experts from the field to discuss critical technical issues for composite structural applications, with an emphasis on increasing overall product efficiency, quality, and safety
- To provide comprehensive, practical engineering guidance that has proven reliable for the design, fabrication, characterization, test, and maintenance of composite materials and structures
- To provide reliable data, linked to control of processes and raw materials, thereby being a comprehensive source of material property basis values and design information that can be shared within the industry
- To provide a resource for composite material and structure education with examples, applications and references to supporting engineering work
- To establish guidelines for use of information in the handbook, identifying the limitations of the data and methods
- To provide guidance on references to proven standards and engineering practices
- To provide for periodic updates to maintain the all-inclusive nature of the information
- To provide information in formats best suited for user needs
- To serve the needs of the international composites community through meetings and dialog between member industries, which use teamwork and the diverse member engineering skills to provide information for the handbook

Notes

1. Every effort has been made to reflect the latest information on polymer (organic), metal, and ceramic composites. The handbook is continually reviewed and revised to ensure it is complete and current.
2. CMH-17 provides guidelines and material properties for polymer (organic), metal, and ceramic matrix composite materials. The first three volumes of this handbook currently focus on, but are not limited to, polymeric composites intended for aircraft and aerospace vehicles. Metal matrix composites (MMC), ceramic matrix composites (CMC) including carbon-carbon composites (C-C), and sandwich composites are covered in Volumes 4, 5, and 6, respectively.
3. The information contained in this handbook was obtained from materials producers, industry companies and experts, reports on government-sponsored research, the open literature, and by contract with research laboratories and those who participate in the CMH-17 coordination activity. The information in this handbook has undergone vigorous technical review and was subject to membership vote.
4. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: CMH-17 Secretariat, Wichita State University, 1845 Fairmount, Wichita, KS 67260, by letter or email, info@cmh17.org.

ACKNOWLEDGEMENT

Volunteer committee members from government, industry, and academia develop, coordinate, and review all the information provided in this handbook. The time and effort of the volunteers and the support of their respective departments, companies, and universities make it possible to insure the handbook reflects completeness, accuracy, and state-of-the-art composite technology.

Support necessary for the development and maintenance of the Composite Materials Handbook (CMH-17) are provided by the Handbook Secretariat, Wichita State University. The primary source of funding for the current Secretariat contract is the Federal Aviation Administration.

TABLE OF CONTENTS

	Page
Foreword	ii
Summary of Changes	v
 PART A	
Chapter 1 General Information	1-1
Chapter 2A Carbon Fiber Composites	2A-1
Appendix A1. MIL-HDBK-17A Data.....	A1-1
 PART B	
Chapter 2B Carbon Fiber Composites.....	2B-1
Chapter 3 Boron Fiber Composites	3-1
Chapter 4 Glass Fiber Composites.....	4-1
Chapter 5 Quartz Fiber Composites	5-1

SUMMARY OF CHANGES

Chapter	Section [old section #]	Title	Change type
2		<u>Carbon Fiber Properties</u>	
	2.3.2.15 [2.2.2.4]	AS4C 3k/HTM45 8-Harness Satin Fabric	Reorganization
	2.3.2.16 [2.2.2.5]	AS4C 3k/HTM45 Plain Weave Fabric	Reorganization
4		<u>Glass Fiber Composites</u>	
	4.2.1.1	S-2 Glass/BT250E-6 Unidirectional Tape	New/St. Paul (8/2016)
	4.2.2.2	6781 S-2 Glass/MTM45-1 8-Harness Satin Weave Fabric	New/Miami (8/2014)
	4.2.2.3	E-Glass 7781/MTM45-1 8-Harness Satin Weave Fabric	New/Supplemental YPs (3/2015)

CHAPTER 2B CARBON FIBER COMPOSITES

Table of Contents

2.3	LEGACY DATA.....	2B-3
2.3.1	Carbon-Epoxy Prepreg Tape	2B-3
2.3.1.1	T500 12k/976 Unidirectional Tape	2B-3
2.3.1.2	HITEX 33 6k/E7K8 Unidirectional Tape	2B-8
2.3.1.3	AS4 12k/E7K8 Unidirectional Tape.....	2B-17
2.3.1.4	Celion 12k/E7K8 Unidirectional Tape.....	2B-26
2.3.1.5	AS4 12k/938 Unidirectional Tape.....	2B-35
2.3.1.6	Celion 12k/938 Unidirectional Tape	2B-43
2.3.1.7	AS4 12k/3502 Unidirectional Tape.....	2B-53
2.3.1.8	AS4/3501-6 (Bleed) Unidirectional Tape.....	2B-68
2.3.1.9	AS4/3501-6 (No Bleed) Unidirectional Tape	2B-78
2.3.1.10	T300 15k/976 Unidirectional Tape	2B-87
2.3.1.11	IM7 12k/8551-7A Unidirectional Tape	2B-98
2.3.1.12	IM6 12k/3501-6 Unidirectional Tape	2B-104
2.3.1.13	IM7 12k/8552 Unidirectional Tape.....	2B-116
2.3.1.14	IM7 12K/977-2 Unidirectional Tape.....	2B-136
2.3.1.15	AS4 12k/997 Unidirectional Tape.....	2B-148
2.3.1.16	T650-35 12k/976 Unidirectional Tape	2B-160
2.3.1.17	IM7 12k/PR 381 Unidirectional Tape.....	2B-168
2.3.1.18	T800HB 12k/3900-2 Unidirectional Tape	2B-180
2.3.2	Carbon-Epoxy Prepreg Fabric	2B-186
2.3.2.1	T300 3k/934 Plain Weave Fabric.....	2B-186
2.3.2.2	Celion 3000/E7K8 Plain Weave Fabric.....	2B-198
2.3.2.3	HITEX 33 6k/E7K8 Plain Weave Fabric	2B-213
2.3.2.4	AS4 3k/E7K8 Plain Weave Fabric	2B-225
2.3.2.5	AS4 3k/3501-6 Plain Weave Fabric.....	2B-230
2.3.2.6	AS4 3k/3501-6S 5-Harness Satin Weave Fabric.....	2B-239
2.3.2.7	AS4 6k/3502-6S 5-Harness Satin Weave Fabric.....	2B-245
2.3.2.8	AS4 3k/3501-6 (Bleed) 5-Harness Satin Weave Fabric	2B-253
2.3.2.9	AS4 3k/3501-6 (No Bleed) 5-Harness Satin Weave Fabric.....	2B-262
2.3.2.10	T300 3K/977-2 Plain Weave Fabric.....	2B-270
2.3.2.11	T300 3K/977-2 8-Harness Satin Weave Fabric	2B-282
2.3.2.12	T650-35 3k/976 Plain Weave Fabric.....	2B-294

2.3.2.13	T650-35 3k/976 8-Harness Satin Weave Fabric.....	2B-302
2.3.2.14	T700S 12k/3900-2 Plain Weave Fabric	2B-310
2.3.2.15	AS4C 3k/HTM45 8-Harness Satin Weave Fabric.....	2B-316
2.3.2.16	AS4C 3k/HTM45 Plain Weave Fabric.....	2B-334
2.3.3	Carbon-Epoxy Wet-Lay-Up Fabric.....	2B-352
2.3.3.1	T300 3k/EA9396 8-Harness Satin Weave Fabric	2B-352
2.3.4	Carbon-Epoxy Resin-Transfer-Molded Fabric	2B-362
2.3.4.1	AS4 6k/PR500 5-Harness Satin Weave Fabric	2B-362
2.3.4.2	IM7 6k/PR500 4-Harness Satin Weave Fabric	2B-385
2.3.5	Carbon-Bismaleimide Prepreg Tape And Fabric.....	2B-408
2.3.5.1	T300 3k/F650 Unidirectional Tape	2B-408
2.3.5.2	T300 3k/F650 8-Harness Satin Weave Fabric.....	2B-413
2.3.5.3	T300 3k/F652 8-Harness Satin Weave Fabric.....	2B-418
2.3.5.4	AS4/5250-3 Unidirectional Tape	2B-423
2.3.5.5	T650-35 3k/5250-4 8-Harness Satin Weave Fabric	2B-435
2.3.5.6	T650-35 3k/5250-4 Plain Weave Fabric	2B-443
2.3.6	Carbon-Bismaleimide Resin-Transfer-Molded Fabric.....	2B-451
2.3.6.1	IM7 6k/5250-4-RTM 4-Harness Satin Weave Fabric.....	2B-451
2.3.7	Carbon-Polyimide Prepreg Fabric.....	2B-474
2.3.7.1	Celion 3000/F670 8-Harness Satin Weave Fabric	2B-474
2.3.8	Carbon-Thermoplastic Prepreg Tape.....	2B-483
2.3.8.1	IM6 12k/APC-2 Unidirectional Tape.....	2B-483
2.3.9	Carbon-Cyanate Ester Prepreg Tape.....	2B-495
2.3.9.1	M55J 6k/954-3 Unidirectional Tape.....	2B-495
REFERENCES	.....	2B-538

Polymer Matrix Composites: Materials Usage, Design, and Analysis

CMH-17

COMPOSITE MATERIALS HANDBOOK

NIAR[®]

WICHITA STATE UNIVERSITY

SAE
INTERNATIONAL[®]

CMH-17-3H

Volume 3 Polymer Matrix Composites Materials Usage, Design and Analysis

COMPOSITE MATERIALS HANDBOOK

VOLUME 3. POLYMER MATRIX COMPOSITES MATERIALS USAGE, DESIGN AND ANALYSIS



Copyright 2025 - Composite Materials Handbook – 17 (CMH-17). All rights reserved. Unauthorized duplication or distribution may violate the Copyright Laws of the United States and of other jurisdictions.

FOREWORD

The Composite Materials Handbook (CMH-17) provides information and guidelines necessary to design, fabricate, and maintain components from composite and non-metallic additively manufactured (AM) materials. Its primary purposes are to provide:

- a) Rigorously reviewed material property data linked to publicly available material and process specifications,
- b) Guidelines and recommendations for material and process controls and methods for testing, data reduction, and reporting material data, and
- c) Proven methodologies, engineering solutions, best practices, lessons learned, and case studies for the design, analysis, certification, manufacture, and field support of parts and structures made from advanced materials.

In support of these purposes, the handbook is written for aerospace applications, although other applications can benefit as well. This handbook constitutes an overview of the field of advanced materials technology and engineering. It is continually updated to reflect industry advancements.

SUMMARY

CMH-17 covers material characterization, design and analysis, processing, certification, and sustainment of parts and structures made from polymer, ceramic, and metal matrix composites, and non-metallic AM materials, including bonded and bolted joints, and sandwich constructions.

CMH-17 ORGANIZATION

The Composite Materials Handbook organization creates, publishes, and maintains pedigreed material data as well as proven engineering information, subjected to thorough technical review, to support the development and use of advanced materials and structures in aerospace applications.

VISION

The Composite Materials Handbook is the authoritative worldwide focal point for technical information on composite and non-metallic additively manufactured materials and structures in aerospace applications.

GOALS AND OBJECTIVES

- Provide comprehensive, practical engineering guidelines that have proven reliable for the design, fabrication, characterization, test, and maintenance of composites and non-metallic AM in aerospace applications
- Provide reliable data, linked to control of processes and raw materials, thereby being a source of material property basis values and design information that satisfies the needs of the aerospace industry
- Provide content, including examples, on applications, lessons learned, and supporting engineering guidelines that outline limitations, strengths and weaknesses of composites and non-metallic AM materials and structures
- Promote safe use of composites and non-metallic AM in aerospace applications
- Promote efficient methods for design, test, analysis, and quality assurance of composite and non-metallic AM materials and structures
- Provide educational resources through both the handbook content and in-person training/content review
- Establish relationships with other standards organizations and engineering handbooks with similar goals to jointly develop and maintain consistent information

ACKNOWLEDGEMENT

Committee members from government, industry, and academia develop, coordinate, and review all the information provided in this handbook. The time and effort of the members and the support of their respective departments, companies, and universities make it possible to ensure the handbook reflects completeness, accuracy, and industry best practices.

Support necessary for the development and maintenance of the Composite Materials Handbook (CMH-17) is provided by the Handbook Secretariat, Wichita State University. The primary source of funding for the current Secretariat contract is the Federal Aviation Administration.

OVERVIEW OF HANDBOOK CONTENT

Composite Materials Handbook 17 is composed of a series of seven volumes.

Volume 1: Polymer Matrix Composites - Guidelines for Characterization of Structural Materials

Volume 1 contains guidelines for determining the properties of polymer matrix composite material systems and their constituents, as well as the properties of generic structural elements, including test planning, test matrices, sampling, conditioning, test procedure selection, data reporting, data reduction, statistical analysis, and other related topics. Special attention is given to the statistical treatment and analysis of data. Volume 1 contains guidelines for general development of material characterization data as well as specific requirements for publication of material data in CMH-17.

Volume 2: Polymer Matrix Composites - Material Properties

Volume 2 contains statistically-based data for polymer matrix composites that meets specific CMH-17 population sampling and data documentation requirements. As of the publication of Revision G, data published in Volume 2 are under the jurisdiction of the Data Review Working Group and are approved by the overall CMH-17 Coordinating Committee. New material systems will be included and additional material data for existing systems will be added as data becomes available and are approved. Selected historical data from

Volume 3 Polymer Matrix Composites Materials Usage, Design and Analysis

previous versions of the handbook that do not meet current data sampling, test methodology, or documentation requirements, but that still are of potential interest to industry are also included in this volume.

Volume 3: Polymer Matrix Composites - Materials Usage, Design, and Analysis

Volume 3 provides proven methodologies and lessons learned for the design, analysis, manufacture, and field support of fiber-reinforced, polymeric-matrix composite structures. It also provides guidelines on material and process specifications and procedures for utilization of the data presented in Volume 2. The information provided is consistent with the guidance provided in Volume 1 and is an extensive compilation of the current knowledge and experiences of the engineers and scientists who are active in composites from industry, government, and academia.

Volume 4: Metal Matrix Composites

Volume 4 publishes properties on metal matrix composite material systems for which data meeting the specific requirements of the handbook are available. In addition, it provides selected guidance on other technical topics related to this class of composites, including material selection, material specification, processing, characterization testing, data reduction, design, analysis, quality control, and repair of typical metal matrix composite materials.

Volume 5: Ceramic Matrix Composites

Volume 5 publishes properties on ceramic matrix composite material systems for which data meeting the specific requirements of the handbook are available. In addition, it provides selected guidance on other technical topics related to this class of composites, including material selection, material specification, processing, characterization testing, data reduction, design, analysis, quality control, and repair of typical ceramic matrix composite materials.

Volume 6: Polymer Matrix Composites - Sandwich Structures

Volume 6 is an update to the cancelled Military Handbook 23, which was prepared for use in the design of structural sandwich polymer composites, primarily for flight vehicles. The information presented includes test methods, material properties, design and analysis techniques, fabrication methods, quality control and inspection procedures, and repair techniques for sandwich structures in both military and commercial vehicles. As of the time of this writing, this volume is undergoing extensive revision to add content on design, material properties, testing, and case studies.

Volume 7: Non-Metallic Additive Manufacturing

Volume 7 provides the best technical guidance available on properties, design, manufacture, and use of non-metallic AM parts. It includes material properties data meeting the specific requirements of the handbook where such data is available and provides practical technical information on the design and manufacture of non-metallic AM parts. The volume focusses on the use of non-metallic AM parts in regulated applications such as civil aviation. At the time of this writing, Volume 7 is in final preparation and publication.

Volume 3 Contents

CHAPTER 1 GENERAL INFORMATION

1.1	Introduction To The Handbook	2
1.1	Introduction To The Handbook	2
1.2	Overview Of Handbook Content	2
1.3	Purpose And Scope Of Volume 3	3
1.4	Material Orientation Codes	4
1.4.1	Laminate Orientation Codes	4
1.4.2	Braiding Orientation Codes	6
1.5	Symbols, Abbreviations, And Systems Of Units	7
1.5.1	Symbols And Abbreviations	7
1.5.2	System Of Units	17
1.6	Definitions	18
	References	46

CHAPTER 2 INTRODUCTION TO COMPOSITE STRUCTURE DEVELOPMENT

2.1	Introduction	2
2.1.1	Why Composites Are Different	2
2.1.2	A Different Development Approach	3
2.1.3	Limitations On This Chapter	4
2.2	Behavior Of Composites – Mechanics	4
2.2.1	Materials Terminology And Coordinate Systems	4
2.2.2	Mechanical Properties At The Material Level	5
2.2.3	Stacking Sequence Issues	6
2.2.4	Environmental Effects	8
2.2.5	Damage Effects	9
2.2.6	Variability Issues	10
2.2.7	Mechanical Properties For Design	10
2.3	Material Selection	12
2.3.1	Structural Materials	12
2.3.2	Ancillary Materials	15
2.3.3	Material Selection Considerations	16
2.4	Manufacturing Process Selection	18
2.4.1	Process Steps And Options	19
2.4.2	Tooling Approaches	22
2.4.3	Quality Assurance Processes	23
2.4.4	Process Selection Considerations	25
2.5	Structural Concepts	25
2.5.1	Basic Construction Types	26
2.5.2	Joint Types	26
2.5.3	Assembly Of Detail Parts	28
2.5.4	Integration Of Large Composite Structures	30
2.5.5	Assembly Into Complete Structure	30
2.6	Defect And Damage Issues	31
2.6.1	General Defect And Damage Considerations	32
2.6.2	Defect And Damage Sources	32
2.6.3	Defect And Damage Characteristics	33
2.6.4	In-Service Inspection For Defects And Damage	34
2.6.5	Addressing Defects And Damage During Design And Development	35
2.7	Lifetime Considerations	37

2.7.1	Environmental Degradation	38
2.7.2	Maintenance Issues	38
2.7.3	Issues Related To Changes In "Mission Spectrum"	38
2.7.4	Environmental Management	38
2.8	Development Program Outline	38
References		40

CHAPTER 3 AIRCRAFT STRUCTURE CERTIFICATION AND COMPLIANCE

3.1	Introduction	2
3.2	Civil Aircraft Certification	2
3.2.1	Types Of Certification And Approvals	3
3.2.2	Certification And The Regulators	12
3.2.3	The Regulations	15
3.2.4	Civil Aviation Guidance Documentation	17
3.2.5	Further Considerations For Civil Aviation Applications	23
3.2.6	Guidance And Reports	27

CHAPTER 4 BUILDING BLOCK APPROACH FOR COMPOSITE STRUCTURES

4.1	Introduction And Philosophy	2
4.2	Rationale And Assumptions	5
4.2.1	Risk And Cost Reduction	6
4.2.2	Failure Modes	6
4.2.3	Analysis	7
4.2.4	Other Considerations	7
4.3	Methodology	8
4.3.1	Aircraft Certification Approaches	9
4.3.2	Building Block Levels	9
4.3.3	Analysis Validation	12
4.4	Considerations For Specific Applications	13
4.4.1	Prototype Aircraft	13
4.4.2	Military Production Aircraft	13
4.4.3	Commercial Aircraft	20
4.4.4	Business And Private Aircraft	37
4.4.5	Rotorcraft	42
4.5	Building Block Methodology And Strategy Examples	50
4.5.1	Aircraft Wing Box Type Structure - Schedule-Linked Methodology Guidance	50
4.5.2	Strategies For Building Block Approach Development And Optimization (Bombardier Aviation)	63
4.6	Statistical Methods For Higher Building Block Levels	72
4.6.1	Method For Estimating Laminate Basis Values From Small Sample Datasets	72
References		77

CHAPTER 5 MATERIALS AND PROCESSES – THE EFFECTS OF VARIABILITY ON COMPOSITE PROPERTIES

5.1	Introduction	3
5.2	Purpose	3
5.3	Scope	3
5.4	Constituent Materials	3

5.4.1	Fibers	3
5.4.2	Resins	31
5.5	Processing Of Product Forms	41
5.5.1	Fabrics And Preforms	41
5.5.2	Preimpregnated Forms	44
5.5.3	Detailed Guidelines For Defining A "Batch" Or "Lot" Of Material For Production Use ...	50
5.6	Shipping And Storage Processes	52
5.6.1	Packaging	52
5.6.2	Shipping	52
5.6.3	Unpackaging And Storage	52
5.6.4	Material Life Stages	52
5.7	Construction Processes	55
5.7.1	Hand Lay-Up	55
5.7.2	Automated Tape Placement/Automated Tape Lamination	57
5.7.3	Automated Tow Placement/Fiber Placement	58
5.7.4	Braiding	63
5.7.5	Filament Winding	64
5.7.6	Pultrusion	65
5.7.7	Sandwich Construction	65
5.7.8	Adhesive Bonding	66
5.7.9	Prebond Moisture	67
5.7.10	Adhesive Bond Quality	68
5.8	Cure And Consolidation Processes	72
5.8.1	Vacuum Bag Molding	72
5.8.2	Oven Cure	72
5.8.3	Autoclave Curing Processing	73
5.8.4	Press Molding	74
5.8.5	Integrally Heated Tooling	74
5.8.6	Pultrusion Die Cure And Consolidation	74
5.8.7	Resin Transfer Molding (RTM)	75
5.8.8	Thermoforming	78
5.9	Assembly Processes For Bonded Joints	78
5.9.1	General Considerations For Structural Adhesive Bonding Materials And Processes ...	79
5.9.2	Adhesive And Substrate Selection	113
5.9.3	Surface Preparation	119
5.9.4	Application And Assembly Processes For Secondary Bonding	153
5.9.5	Cocuring	167
5.9.6	Cobonding	173
5.9.7	Multistage Bonding	174
5.9.8	Bond Quality Assurance	178
5.9.9	Considerations For A Bonding Process Specification	185
5.9.10	Considerations For Bonded Joint Substantiation	189
5.10	Process Control	197
5.10.1	Common Process Control Schemes	197
5.10.2	Example - Autoclave Cure Of A Thermoset Composite	199
5.11	Manufacturing Process Simulation And Control	202
5.11.1	Common Process Control Schemes	202
5.11.2	Background	203
5.11.3	Systems Approach To Processing Simulation	204
5.11.4	Process Simulation	206
5.11.5	Construction (Materials Deposition) Simulation	207
5.11.6	Consolidation And Flow Simulation	208
5.11.7	Thermochemical Cure Simulation	211
5.11.8	Residual Stress And Process-Induced Distortion (PID) Simulation	225
5.11.9	Understanding And Simulating Material Behavior	244
5.12	Determining Sources Of Variability During A Composite Material Qualification	262

5.12.1	Introduction	262
5.12.2	Development And Application Of The Nested Qualification Approach	265
5.12.3	Example Of Nested Qualification Data Allowables Calculation	
	Results Using Regression	281
5.12.4	Qualification Of Vendor C Manufacturing Vendor A Material	285
5.12.5	Design Allowables Using Nested Approach	302
5.12.6	Nested Qualification Cost Issues	310
5.12.7	Summary	311
5.13	Generic Basis Values And Equivalence Criteria	312
5.13.1	Background And Overview	312
5.13.2	Null Hypothesis	314
5.13.3	Multivariate Approach And The Assumption Of Independence	315
5.13.4	Generic Approach For Basis Values And Equivalence	317
5.13.5	Computing The Generic Acceptance Region	319
5.13.6	The Null Hypothesis For Generic Equivalence	319
5.13.7	Computing Generic Basis Values	320
5.13.8	Example: Compression Strength Data For MTM45-1 6781 S-1 Glass Fabric	322
References		326

CHAPTER 6 QUALITY CONTROL OF PRODUCTION MATERIALS AND PROCESSES

6.1	Introduction	2
6.2	Material Procurement Quality Assurance Procedures	2
6.2.1	Specifications And Documentation	2
6.2.2	Material Control At The Supplier Level	2
6.2.3	Material Control At The User Level	4
6.3	Part Fabrication Verification	6
6.3.1	Process Verification	6
6.3.2	Nondestructive Inspection (NDI)	7
6.3.3	Destructive Tests (DT)	8
6.4	Managing Change In Materials And Processes	11
6.4.1	Introduction	11
6.4.2	Qualification Of New Materials Or Processes	11
6.4.3	Divergence And Risk	14
6.4.4	Production Readiness	18
6.5	Statistical Tools For Improving Processes	19
6.5.1	Process Feedback Adjustment	19
6.5.2	Design Of Experiments	21
6.5.3	Taguchi	29
References		30

CHAPTER 7 DESIGN OF COMPOSITE STRUCTURES

7.1	Overview Of Unique Issues Associated With Composite Structural Design	2
7.1.1	Design Requirements, Criteria And Constraints	4
7.1.2	Typical Aircraft Composite Structural Design Requirements And Criteria	8
7.1.3	Other Typical Aerospace Design Constraints	17
7.2	Structural Design Process	21
7.2.1	Product And Process Development: 5 Phases And Objectives	26
7.2.2	Technology Development And Product Implementation	32
7.2.3	Design Process Examples (To Be Developed)	63

7.2.4	Integrated Product Teams (To Be Developed).....	63
7.2.5	IPT Case Studies (To Be Developed)	64
7.3	Material And Process Selection	64
7.3.1	Materials Selection	64
7.3.2	Manufacturing Process Selection	65
7.3.3	Quality Control.....	65
7.3.4	Producibility.....	65
7.3.5	Tooling	65
7.3.6	Environmental Effects.....	65
7.4	Structural Concepts.....	65
7.4.1	Solid Laminate Vs. Sandwich Vs. Stiffened Structure (To Be Developed).....	66
7.4.2	Layup Selection.....	66
7.4.3	Tailored Properties.....	66
7.4.4	Hybrid Structure Design	67
7.5	Detailed Part Design	70
7.5.1	Elastic Properties	70
7.5.2	Laminate Design Considerations.....	70
7.5.3	Thermal Compatibility/Low CTE	71
7.5.4	Composite/Metal Interfaces	72
7.5.5	Design For Supportability.....	72
7.5.6	Design Of Joints	72
7.5.7	Damage Resistance/Tolerance.....	74
7.5.8	Durability	74
7.5.9	Lightning Strike (To Be Developed).....	74
7.6	Optimization	74
7.7	Lessons Learned.....	75
	References.....	96

CHAPTER 8 ANALYSIS OF LAMINATES

8.1	Introduction	3
8.2	Lamina Properties And Micromechanics.....	3
8.2.1	Assumptions.....	3
8.2.2	Fiber Composites: Stress-Strain Properties	4
8.2.3	Fiber Composites: Physical Properties	5
8.2.4	Thick Composite 3-D Lamina Properties	6
8.2.5	Determining Lamina Moduli From Laminate Moduli Test Data	6
8.3	Laminate Stiffness Analysis	9
8.3.1	Lamination Theory	9
8.3.2	Laminate Properties.....	10
8.3.3	Usage Of Moduli Values For Analysis.....	17
8.3.4	Thermal And Hygroscopic Analysis.....	18
8.3.5	Thick Composite 3-D Laminate Analysis	19
8.4	Laminate In-Plane Stress Analysis	19
8.4.1	Stresses And Strains Due To Mechanical Loads	19
8.4.2	Stresses And Strains Due To Temperature And Moisture	21
8.4.3	Netting Analysis.....	23
8.4.4	Nonlinear Stress Analysis	26
8.5	General Laminate Strength Considerations.....	26
8.5.1	Lamina Strength And Failure Modes.....	27
8.5.2	Laminate Level Failure Modes.....	35
8.5.3	Effects Of Transverse Tensile Properties In Unidirectional Tape	39
8.5.4	Effect Of Stacking Sequence On Strength.....	39

8.5.5	Lamina Versus Laminate Strength	40
8.6	Laminate In-Plane Strength Prediction	41
8.6.1	Lamina To Laminate Analysis Approach	43
8.6.2	Fiber Failure Approach (Laminate Level Failure).....	47
8.6.3	Laminate Strength Prediction At Stress Concentrations	52
8.7	Intra- And Inter-Laminar Stress And Failure Analysis	55
8.7.1	Out-Of-Plane Loads	55
8.7.2	Interlaminar Stresses	56
8.7.3	Delamination	58
8.7.4	Calculation Of Strain Energy Release Rate Interlaminar Fracture Mechanics.....	64
8.7.5	Other Linear Elastic Fracture Mechanics Based Methods.....	75
8.7.6	Simulation Of Delamination Failure Using Cohesive Zone Models	79
8.8	Composite Progressive Damage And Failure Analysis: Overview	95
8.8.1	Motivation For PDFA Approaches And Outline Of Chapter Content.....	95
8.8.2	Progressive Damage And Failure Analysis For Quasi-Static Events.....	98
8.8.3	Progressive Damage And Failure Analysis For Dynamic Events	110
8.9	Composite Progressive Damage And Failure Analysis: Verification And Validation	130
8.9.1	The Verification And Validation Process	131
8.9.2	Experimental Data For Method Validation	141
8.9.3	Existing Challenges And Future Improvements	147
8.10	Composite Progressive Damage And Failure Analysis: Quasi-Static And Dynamic	148
	Applications.....	148
8.10.1	Progressive Damage And Failure Analysis: Quasi-Static Best Practices And	148
	Examples	
8.10.2	Progressive Damage And Failure Analysis – Dynamic Best Practices And	163
	Examples	
8.11	Composite Progressive Damage And Failure Analysis: Supplementary Information	173
8.11.1	Supplementary Information For PDFA Quasi-Static Methods	173
8.11.2	Supplementary Information For PDFA Dynamic Methods	182
References	.....	190

CHAPTER 9 STRUCTURAL STABILITY ANALYSIS

9.1	Introduction	2
9.1.1	Local Buckling And Crippling	2
9.2	Compressive Plate Buckling	3
9.2.1	Introduction	3
9.2.2	Uniaxial Loading - Long Plate With All Sides Simply Supported	4
9.2.3	Uniaxial Loading - Long Plate With All Sides Fixed	6
9.2.4	Uniaxial Loading - Long Plate With Three Sides Simply Supported And One	7
	Unloaded Edge Free	
9.2.5	Uniaxial Loading - Long Plate With Three Sides Simply Supported And One	7
	Unloaded Edge Rotationally Restrained	
9.2.6	Uniaxial And Biaxial Loading - Plate With All Sides Simply Supported	10
9.2.7	Uniaxial Loading - Plate With Loaded Edges Simply Supported And Unloaded	11
	Edges Fixed	
9.2.8	Stacking Sequence Effects In Buckling	11
9.2.9	Empirical Compressively Loaded Narrow Plate Local Buckling	14
9.3	Shear Plate Buckling.....	17
9.3.1	Shear Loading - Long Plate With All Sides Simply Supported	17
9.4	Compressive Post-Buckling And Crippling.....	17
9.4.1	Introduction	17
9.4.2	Empirical Compressively Loaded Narrow Plate Crippling	21

9.4.3	Normalized Empirical Compressively Loaded Narrow Plate Crippling	22
9.4.4	Non-Dimensional Empirical Compressively Loaded Narrow Plate Crippling.....	24
9.4.5	Stiffener Crippling Strength Determination	26
9.4.6	Effects Of Corner Radii And Tee-Joint Fillets.....	27
9.4.7	Slenderness Correction	28
9.4.8	Fatigue Effects	28
References.....		29

CHAPTER 10 DESIGN AND ANALYSIS OF BONDED JOINTS

10.2	Introduction	3
10.3	Design Of Bonded Joints	5
10.3.1	Design Of Specific Bonded Joint Types.....	5
10.3.2	General Joint Design Issues	9
10.3.3	Adherend Design.....	12
10.3.4	Adhesive-Type Selection.....	13
10.4	Analysis Of Bonded Joints.....	14
10.4.1	Metallic Adherend Bonded Joint Analysis	14
10.4.2	Composite Adherend Bonded Joint Analysis	27
10.4.3	Bonded Joint Durability Analysis	39
10.5	Bonded Joint Certification Issues - Aircraft.....	42
10.5.1	Process Quality Assurance	43
10.5.2	Static Strength	45
10.5.3	Durability.....	48
10.5.4	Damage Tolerance	50
10.5.5	Bonded Repair.....	52
10.6	Bonded Joint Certification / Qualification Issues – Non-Aircraft.....	52
10.7	Derivation Of Elastic-Perfectly-Plastic Lap-Shear Bondline Stress.....	53
10.7.1	Governing Equations.....	53
10.7.2	Joint Conditions	58
10.7.3	Boundary Conditions	60
10.7.4	Application Of Boundary Conditions	62
10.7.5	Scarf Joint Analysis	76
10.7.6	Analysis Summary And Solving For Load With A Given Strain Value.....	79
References.....		80

CHAPTER 11 DESIGN AND ANALYSIS OF BOLTED JOINTS

11.1	Introduction	2
11.1.1	Definitions.....	3
11.1.2	Nomenclature	3
11.1.3	Overall Joint Design And Analysis Process.....	4
11.1.4	Configurations	5
11.2	Bolted Joint Failure Modes And Response.....	6
11.2.1	Static Loading.....	7
11.2.2	Fatigue Loading.....	18
11.3	Joint Design Guidelines	21
11.3.1	Geometry – Spacing, End And Edge Distances	21
11.3.2	Geometry – Fastener Patterns	23
11.3.3	Layups And Thicknesses	25

11.3.4	Fasteners And Holes	26
11.3.5	Joint Gapping And Shims	36
11.3.6	Joints With Dissimilar Materials	37
11.3.7	Bonded / Bolted Joints	38
11.3.8	Fuel Tank Issues	39
11.3.9	Design Accommodation For Repair	40
11.3.10	Z-Pinning.....	40
11.4	Joint Analysis	41
11.4.1	Overall Analysis Approach	41
11.4.2	Joint Modeling In Finite Element Models	42
11.4.3	Fastener Load Distribution Analysis.....	53
11.4.4	Joint Detail Loads.....	64
11.4.5	Static Analysis	69
11.4.6	Fatigue Analysis	99
11.4.7	Mrb Analyses.....	100
11.5	Test Verification And Certification.....	100
11.5.1	Bolted Joint Property Databases.....	100
11.5.2	Test Verification.....	100
11.5.3	Bolted Joint Certification Issues	102
11.5.4	Publically Available Bolted Joint Test Data	103
11.5.5	Additional References	103
References.....		104

CHAPTER 12 DAMAGE RESISTANCE, DURABILITY, AND DAMAGE TOLERANCE

12.1	Introduction	2
12.1.1	Principles.....	2
12.1.2	Composite-Related Issues.....	3
12.1.3	Aircraft Damage Tolerance.....	4
12.1.4	General Guidelines	5
12.2	Rules, Requirements And Compliance For Aircraft	6
12.2.1	Civil Aviation Regulations And Guidance	7
12.2.2	Categories Of Damage	15
12.2.3	Load And Damage Relationships.....	18
12.2.4	Compliance Approaches	21
12.3	Design Development And Substantiation.....	30
12.3.1	Damage Threat Assessment.....	31
12.3.2	Damage Design Criteria.....	52
12.3.3	Substantiation	59
12.3.4	Addressing Category 5 Damage	69
12.3.5	Additional Design Development Guidance	72
12.4	Inspection For Defects And Damage	72
12.4.1	Aircraft In-Service Inspection Programs	73
12.4.2	Development Of Damage Inspection Data	74
12.4.3	Development Of Inspection Programs	76
12.4.4	Environmental Deterioration And Accidental Damage Rating Systems.....	80
12.4.5	Fleet Leader Programs	85
12.4.6	Probability Of Detection Studies	85
12.5	Damage Resistance.....	87
12.5.1	Influencing Factors.....	88
12.5.2	Design Issues And Guidelines	102
12.5.3	Test Issues	113
12.5.4	Analysis Methods	113

12.6 Durability And Damage Growth Under Cyclic Loading	114
12.6.1 Influencing Factors.....	114
12.6.2 Design Issues And Guidelines	122
12.6.3 Test Issues	142
12.6.4 Analysis Methods	181
12.7 Residual Strength.....	197
12.7.1 Influencing Factors.....	197
12.7.2 Design Issues And Guidelines	220
12.7.3 Test Issues	220
12.7.4 Analysis Methods – Residual Strength	221
12.8 Applications/Examples	256
12.8.1 Rotorcraft (Sikorsky)	256
12.8.2 Commercial Aircraft (Boeing 777 Empennage Torque Boxes)	258
12.8.3 General Aviation (Beech Starship).....	262
12.8.4 Thermal Loads in a Business Jet Horizontal Stabilizer (Designed by Fokker).....	270
12.8.5 General Aviation (KC-100, KAI)	276
12.8.6 A Feasible Analysis Flow For Primary Components (Embraer).....	285
12.8.7 Cirrus SR20 Life Extension	297
12.8.8 ILX-34 Wing Box Technology Demonstrator (Warsaw Institute Of Aviation)....	309
12.9 Supporting Discussions.....	325
12.9.1 Compliance	325
12.9.2 Damage Resistance	328
12.9.3 Durability And Damage Growth.....	329
12.9.4 Residual Strength.....	335
References.....	354

CHAPTER 13 DEFECTS, DAMAGE AND INSPECTION

13.1 Defects and Damage	2
13.1.1 Defect and damage sources	2
13.1.2 Damage types	4
13.2 Inspection Methods	7
13.2.1 Nondestructive inspection	7
13.2.2 Destructive Inspection.....	20
13.2.3 Examples of impact damage inspections.....	21
References.....	36

CHAPTER 14 SUPPORTABILITY, MAINTENANCE, AND REPAIR

14.1 Introduction	3
14.2 Important Considerations	4
14.3 Service Experience	5
14.4 Inspection And Repair Quality Assurance.....	9
14.5 Damage Assessment	12
14.5.1 Mandate Of The Assessor.....	13
14.5.2 Qualification Of The Assessor.....	13
14.5.3 Information For Damage Assessment.....	13
14.5.4 Repair Site Considerations	14
14.6 Repair	16
14.6.1 Introduction	16

14.6.2	Repair Prerequisites.....	19
14.6.3	Design Criteria	32
14.6.4	Bolted Repair Design And Processing.....	40
14.6.5	Bonded Repair Design And Processing.....	45
14.6.6	Composite And Metal Bond Structural Repair Substantiation	69
14.7	Repair Analysis	91
14.7.1	Introduction	91
14.7.2	Analysis Of A Bolted Repair For Composite Structure.....	91
14.7.3	Analysis Of A Bonded Repair For Composite Structure	101
14.8	Composite Repair Of Metallic Structure (CRMS)	119
14.8.1	Introduction	119
14.9	Maintenance Documentation	119
14.9.1	Determining Allowable Damage Limits	120
14.9.2	Repair Limitations	121
14.10	Design For Supportability	121
14.10.1	Introduction	121
14.10.2	Original Design Inspectability And Repairability	123
14.10.3	Original Design Material Selection.....	128
14.10.4	Original Design Damage Resistance, Damage Tolerance, And Durability	131
14.10.5	Original Design Environmental Compliance	135
14.10.6	Original Design Reliability And Maintainability.....	137
14.10.7	Original Design Interchangeability And Replaceability	137
14.10.8	Repair Design And Implementation	138
14.10.9	Specific Repair Design Issues	147
14.11	Logistics Requirements	150
14.11.1	Training	150
14.11.2	Spares.....	151
14.11.3	Materials.....	152
14.11.4	Facilities	153
14.11.5	Technical Data.....	154
14.11.6	Support Equipment	155
14.12	Repair Substantiation Case Studies	157
14.12.1	Introduction	157
14.12.2	Case Study #1 – Substantiation Of Metal Bond Process Changes.....	160
14.12.3	Case Study #2 – Fuselage Skin, Bonded Repair	165
14.12.4	Case Study #3 – Fuselage Skin, Bolted Repair.....	165
14.12.5	Case Study #4 – Horizontal Stabilizer, Family Of Wet Layup Repairs	174
14.12.6	Case Study #5 – Horizontal Stabilizer Lower Skin (Skin Damage With No Stringer Bondline Damage), Bonded Repair	182
14.12.7	Case Study #6 – Horizontal Stabilizer Lower Skin (Skin Damage With Stringer Bondline Damage), Bonded/Bolted Repair.....	192
14.12.8	Case Study #7 – Fan Cowl, VID Damage, Bonded Repair	204
14.12.9	Case Study #8 – Wing Box, Fuel Tank, Bonded Repair	210
14.12.10	Case Study #9 – Normal Category Airplane Bonded Wing Skin Damage.....	214
14.13	Supporting Data – Double Vacuum Debulk (DVD) Process.....	240
	References.....	246

CHAPTER 15 THICK-SECTION COMPOSITES

15.1 Introduction And Definition Of Thick-Section Composites 2
 15.2 Mechanical Properties Required For Thick-Section Composite Three-Dimensional Analysis 3
 15.2.1 Two-Dimensional Composite Analysis 4
 15.2.2 Three-Dimensional Composite Analysis 5
 15.2.3 Theoretical Property Determination 7
 References 15

CHAPTER 16 CRASHWORTHINESS AND ENERGY MANAGEMENT

16.1 Overview And General Guidelines 2
 16.1.1 Section Organization 2
 16.1.2 Principles Of Crashworthiness 2
 16.1.3 Composite-Related Considerations 3
 16.1.4 Terminology 5
 16.1.5 Existing Research And Development 8
 16.1.6 Overview Of Regulating Bodies And Safety Standards 9
 16.2 Design For Crashworthiness 10
 16.2.1 Overview 10
 16.2.2 Impact Conditions 11
 16.2.3 Coupon/Element Testing 14
 16.2.4 Designs For Energy Absorption 15
 16.2.5 Trigger Mechanisms To Initiate Crush 17
 16.3 Aircraft Crashworthiness 20
 16.3.1 Regulatory Requirements 20
 16.3.2 Crashworthiness Roadmap And Building Block Approach 23
 16.3.3 Crashworthiness Modeling Challenges 26
 16.4 Rotorcraft Crashworthiness 29
 16.4.1 Regulations For Rotorcraft Crashworthiness 29
 16.5 Advanced Air Mobility Vehicles Crashworthiness 31
 16.5.1 Overview 31
 16.6 Modeling And Simulation For Crashworthiness - Progressive Damage And Failure Analysis 32
 16.6.1 Simulation Repeatability And Consistency For Model Validation 33
 16.6.2 Current State Of The Art Of The Analysis Methods And Tools 35
 16.6.3 Crashworthiness Models Used In Numerical Round Robin 36
 16.6.4 Current Studies To Evaluate Pdfa Methods For Crash Modeling 37
 16.6.5 Metrics For Model Validation Assessment 37
 16.6.6 Description Of Computational Methods 38
 16.6.7 Modeling Features And Implications For Impact Analysis 50
 16.6.8 Examples Of Calibration For Composite Material – Energy Absorption 74
 16.6.9 Modeling Capabilities And Limitations 77
 16.6.1 Modeling Strategies And Guidelines 78
 References 81

CHAPTER 17 STRUCTURAL SAFETY MANAGEMENT

17.1 Introduction 1
 17.1.1 Background 1

17.1.2	Purpose And Scope	2
17.2	Safety Risk Management Overview	3
17.2.1	Definitions	3
17.2.2	Process Of Safety Risk Management	3
17.2.3	Hazard Identification And Initial Safety Assessment	4
17.2.4	Risk Analysis And Strategies	4
17.2.5	Risk Assessment And Mitigation Actions	4
17.3	Structural Safety And Regulations	5
17.3.1	Sources Of Information	5
17.3.2	Regulations	5
17.3.3	Guidance Documents	6
17.4	Structural Safety Assessment Considerations	6
17.4.1	Design	7
17.4.2	Manufacturing	7
17.4.3	Maintenance	8
17.4.4	Operations	8
17.4.5	Airworthiness Requirements	8
17.4.6	Structural Integrity	8
17.4.7	Illustration	11
17.5	Structural Safety Management Procedure	11
17.5.1	Describe Structure	11
17.5.2	Identify Unsafe Conditions And Damage Threats	12
17.5.3	Analyze Risk	12
17.5.4	Assess Risk	13
17.5.5	Mitigate Risk	14
17.6	Structural Safety Management Applications	14
17.6.1	Application: Implications Of Less Reliance On OEMs For Repaired Parts	15
17.6.2	Application: Nonconforming Extensive Repair Involving Metal Bonding	15
17.6.3	Application: Nonconforming Extensive Repair Involving Composite Repair	17
17.7	Structural Safety Awareness Course Structure	20
17.7.1	Composite Applications	23
17.7.2	Material, Processing, And Fabrication Development	26
17.7.3	Design Development	30
17.7.4	Structural Substantiation	39
17.7.5	Manufacturing Interface	51
17.7.6	Maintenance Interface	54
17.7.7	Additional Topics	60
	References	66

CHAPTER 18 ENVIRONMENTAL MANAGEMENT

18.1	Introduction	1
18.1.1	Scope	1
18.1.2	Glossary Of Recycling Terms	1
18.2	Recycling Infrastructure	4
18.2.1	Recycling Infrastructure Development Models	4
18.2.2	Infrastructure Needs	4
18.2.3	Recycling Education	5
18.3	Economics Of Composite Recycling	5
18.4	Composite Waste Streams	6
18.4.1	Process Waste	7
18.4.2	Post-Consumer Composite Waste	7
18.5	Composite Waste Stream Source Reduction	8
18.5.1	Just-In-Time And Just Enough Material Delivery	8

18.5.2	Electronic Commerce Acquisition Management	8
18.5.3	Waste Minimization Guidelines	9
18.5.4	Lightweighting	9
18.6	Reuse Of Composite Components And Materials	9
18.6.1	Reuse Of Composite Components	9
18.6.2	Machining To Smaller Components	10
18.7	Materials Exchange.....	10
18.7.1	Reallocation Of Precursors	10
18.7.2	Composite Materials Exchange Services	10
18.8	Recycling Of Composite Materials	11
18.8.1	Design For Disassembly And Recycling	11
18.8.2	Recycling Logistics.....	12
18.8.3	Processing Of Composite Recyclate	13
18.8.4	Recycling Of Waste Prepreg.....	15
References.....		16

CHAPTER 19 LAUNCH VEHICLES AND SPACECRAFT

19.1	Life Cycle Considerations.....	2
19.1.1	Preflight and Processing	2
19.1.	Ascent	3
19.1.3	Space	3
19.1.4	Descent.....	4
19.1.5	Pressurization	4
19.2	Material Selection.....	5
19.3	Durability & Damage Tolerance.....	6
19.3.1	Spaceflight Hardware Design Approaches.....	6
19.3.2	Damage Threat Environment.....	7
19.3.3	Impact Damage Protection Plan	8
19.3.4	Damage Tolerance Substantiation	13
19.4	Spacecraft Sandwich Structure Unique Design Considerations.....	14
19.4.1	Requirements and Policies	14
19.4.2	Managing Moisture and Internal Pressure in Spacecraft Sandwich Structure	15
19.4.3	Cryogenic Sandwich Structural Design Complexities.....	18
19.4.4	Design and Validation Considerations for Honeycomb Core	
	Construction for Space Structures	19
19.5	Electromagnetic Environmental Effects.....	24
19.5.1	Space Environment Effects	25
19.5.2	Terrestrial Environment Effects	26
19.5.3	Electrical Shielding of Composite Structures.....	28
19.5.4	Long-Term EMC	29
19.5.5	Design Guidelines.....	29
19.6	Structural Substantiation.....	30
19.6.1	Unique Launch Vehicle and Spacecraft Terminology	30
19.6.2	Design Value Development	31
19.6.3	Qualification Approaches.....	33
19.6.4	Considerations for Launch Vehicle and Spacecraft Qualification.....	34
19.6.5	Workmanship Verification	35
19.7	Composite Overwrapped Pressure Vessels.....	37
19.7.1	COPV Design and Fabrication.....	37
19.7.2	Material Allowables Development.....	38
References.....		39

CHAPTER 20 ENGINE APPLICATIONS

20.1 Introduction.....	2
20.1.1 Scope.....	4
20.1.2 Historical Development.....	4
20.1.3 Special Characteristics of Engine Components	5
20.1.4 Regulations	9
20.2 Design Considerations	11
20.2.1 Thermal.....	11
20.2.2 Fatigue and Vibration.....	13
20.2.3 Blade Containment and Rotor Imbalance (To be developed)	15
20.2.4 Impact Considerations	15
20.2.5 Erosion.....	19
20.2.6 Wear	20
20.2.7 Fire.....	22
20.2.8 Lightning (To be developed).....	26
20.3 Typical Materials and Manufacturing Processes	26
20.3.1 Material selection and uses	26
20.3.2 CMCs.....	27
20.3.3 PMCs	28
20.3.4 Non-Prepreg Systems	29
20.3.5 Advanced Fiber Architectures	29
20.3.6 Thermoplastics	31
20.3.7 Coatings: Erosion, Environmental Barrier	35
20.3.8 Hybrid composite-metal designs (To be developed).....	37
20.4 Specialized Testing	37
20.4.1 Aging.....	37
20.4.2 Fire	40
20.4.3 Impact and High Strain Rate (To be developed)	44
20.4.4 Vibration (To be developed)	45
20.5 Analysis (To be developed).....	45
20.5.1 Role of Analysis in Certification and Continued Airworthiness (To be developed)	45
20.5.2 Types of Analysis Having Special Usage for Engines (To be developed)	45
20.5.3 Components and Design Examples (To be developed)	45
20.5.4 Analysis Validation (To be developed)	46
20.6 Defects and Damage Tolerance (To be developed).....	46
20.6.1 General Considerations (To be developed)	46
20.6.2 Manufacturing Defects & Damage (To be developed).....	46
20.6.3 Service Induced Damage (To be developed)	46
20.6.4 Threat Assessment & Typical Engine Threats (To be developed)	46
20.6.5 Inspections and Engine Diagnostics (To be developed).....	46
References.....	48

Contents

1.1	Introduction To The Handbook	2
1.2	Overview Of Handbook Content	2
1.3	Purpose And Scope Of Volume 3	3
1.4	Material Orientation Codes	4
1.4.1	Laminate Orientation Codes	4
1.4.2	Braiding Orientation Codes	6
1.5	Symbols, Abbreviations, And Systems Of Units	7
1.5.1	Symbols And Abbreviations	7
1.5.2	System Of Units	17
1.6	Definitions	18
	References	46

Metal Matrix
Composites

CMH-17
COMPOSITE MATERIALS HANDBOOK



WICHITA STATE
UNIVERSITY
NATIONAL INSTITUTE
FOR AVIATION RESEARCH



**NOT MEASUREMENT
SENSITIVE**

CMH-17-4B
Volume 4 of 6
JULY 2013

Superseding
MIL-HDBK-17-4A
17 JUNE 2002

COMPOSITE MATERIALS HANDBOOK

VOLUME 4. METAL MATRIX COMPOSITES



CMH-17
COMPOSITE MATERIALS HANDBOOK



Copyright 2013 - Composite Materials Handbook – 17 (CMH-17). All rights reserved. Unauthorized duplication or distribution may violate the Copyright Laws of the United States and of other jurisdictions

Published by SAE International on behalf of CMH-17,
a division of Wichita State University.

FOREWORD

The Composite Materials Handbook, CMH-17, provides information and guidance necessary to design and fabricate structural components from composite materials. Its primary purposes are a) the standardization of engineering data development methodologies related to testing, data reduction, and data reporting of property data for current and emerging composite materials, b) guidance on material and process specifications and procedures for utilization of the material data presented in the handbook, and c) methodologies for the design, analysis, certification, manufacture, and field support of composite structures. In support of these objectives, the handbook includes composite materials properties that meet specific data requirements. The Handbook therefore constitutes an overview of the field of composites technology and engineering, an area that is advancing and changing rapidly. As a result, the document will be continually revised as sections are added or modified to reflect advances in the state-of-the-art.

CMH-17 Mission

The Composite Materials Handbook organization creates, publishes and maintains proven, reliable engineering information and standards, subjected to thorough technical review, to support the development and use of composite materials and structures.

CMH-17 Vision

The Composite Materials Handbook will be the authoritative worldwide focal point for technical information on composite materials and structures.

Goals and Objectives to Support CMH-17 Mission

- To periodically meet with experts from the field to discuss critical technical issues for composite structural applications, with an emphasis on increasing overall product efficiency, quality and safety.
- To provide comprehensive, practical engineering guidance that has proven reliable for the design, fabrication, characterization, test and maintenance of composite materials and structures.
- To provide reliable data, linked to control of processes and raw materials, thereby being a comprehensive source of material property basis values and design information that can be shared within the industry.
- To provide a resource for composite material and structure education with examples, applications and references to supporting engineering work.
- To establish guidelines for use of information in the Handbook, identifying the limitations of the data and methods.
- To provide guidance on references to proven standards and engineering practices.
- To provide for periodic updates to maintain the all-inclusive nature of the information.
- To provide information in formats best-suited for user needs.
- To serve the needs of the international composites community through meetings and dialogue between member industries, which use teamwork and the diverse member engineering skills to provide information for the handbook.

Notes

1. Every effort has been made to reflect the latest information on polymer (organic), metal, and ceramic composites. The handbook is continually reviewed and revised to ensure it is complete and current.
2. CMH-17 provides guidelines and material properties for polymer (organic), metal, and ceramic matrix composite materials. The first three volumes of this handbook currently focus on, but are not limited to, polymeric composites intended for aircraft and aerospace vehicles. Metal matrix composites (MMC), ceramic matrix composites (CMC) including carbon-carbon composites (C-C), and sandwich composites are covered in Volumes 4, 5, and 6, respectively.
3. The information contained in this handbook was obtained from materials producers, industry companies and experts, reports on Government sponsored research, the open literature, and by contract with research laboratories and those who participate in the CMH-17 coordination activity. The information in this handbook has undergone vigorous technical review and was subject to membership vote.
4. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: CMH-17 Secretariat, Materials Sciences Corporation, 135 Rock Road, Horsham, PA 19044, by letter or email, handbook@materials-sciences.com.

ACKNOWLEDGEMENT

Volunteer committee members from government, industry, and academia develop, coordinate and review all the information provided in this handbook. The time and effort of the volunteers and the support of their respective departments, companies, and universities make it possible to insure the handbook reflects completeness, accuracy, and state-of-the-art composite technology.

Support necessary for the development and maintenance of the Composite Materials Handbook (CMH-17) are provided by the handbook Secretariat, Materials Sciences Corporation. The primary source of funding for the current Secretariat contract is the Federal Aviation Administration.

TABLE OF CONTENTS

FOREWORD.....ii

SUMMARY OF CHANGES xiii

1. GUIDELINES 1

 1.1 GENERAL INFORMATION 1

 1.1.1 INTRODUCTION..... 1

 1.1.2 PURPOSE..... 1

 1.1.3 SCOPE..... 1

 1.1.3.1 Section 1: Guidelines 2

 1.1.3.2 Section 2: Design Guidelines for Metal Matrix Materials 3

 1.1.3.3 Section 3: Material property data 3

 1.1.4 USE OF THE DOCUMENT AND LIMITATIONS 3

 1.1.4.1 Source of information 3

 1.1.4.2 Use of data and guidelines in applications 3

 1.1.4.3 Strength properties and allowables terminology 4

 1.1.4.4 Use of references 4

 1.1.4.5 Use of tradenames and product names 4

 1.1.4.6 Toxicity, health hazards, and safety 4

 1.1.4.7 Ozone depleting chemicals..... 4

 1.1.5 APPROVAL PROCEDURES 5

 1.1.6 SYMBOLS, ABBREVIATIONS, AND SYSTEMS OF UNITS 5

 1.1.6.1 Symbols and abbreviations..... 5

 1.1.6.1.1 Constituent properties 11

 1.1.6.1.2 Laminae and laminates 11

 1.1.6.1.3 Subscripts..... 12

 1.1.6.1.4 Superscripts..... 13

 1.1.6.1.5 Acronyms..... 13

 1.1.6.2 Material system codes 15

 1.1.6.3 System of units 15

 1.1.7 DEFINITIONS 17

 REFERENCES..... 31

 1.2 INTRODUCTION TO MMC MATERIALS 32

 1.2.1 INTRODUCTION..... 32

 1.2.2 MMC SYSTEMS..... 32

 1.2.2.1 Systems definitions..... 32

 1.2.2.2 Distinction from other materials/composites..... 32

 1.2.3 MATRIX MATERIALS..... 32

 1.2.3.1 Role of matrix materials 33

 1.2.3.2 Forms of matrix materials 33

 1.2.3.3 Types of matrix materials..... 34

 1.2.3.3.1 Aluminum..... 34

 1.2.3.3.2 Copper 36

 1.2.3.3.3 Iron 36

 1.2.3.3.4 Magnesium 36

 1.2.3.3.5 Nickel 36

 1.2.3.3.6 Titanium 36

 1.2.4 REINFORCEMENT MATERIALS..... 36

 1.2.4.1 Types of reinforcement 37

<u>PARAGRAPH</u>	<u>PAGE</u>
1.2.4.2 Role of reinforcement	37
1.2.4.3 Composition of reinforcement.....	37
1.2.5 REINFORCEMENT COATINGS	37
1.2.5.1 Role of coatings	37
1.2.5.2 Types of coatings.....	38
1.2.6 MANUFACTURING PROCESSES	38
1.2.6.1 Overview and general information	38
1.2.6.2 Assembly and consolidation	38
1.2.6.2.1 Powder blending and consolidation.....	38
1.2.6.2.2 Consolidation diffusion bonding.....	39
1.2.6.2.3 Vapor deposition.....	39
1.2.6.2.4 Squeeze casting and squeeze infiltration	39
1.2.6.2.5 Spray deposition	39
1.2.6.2.6 Slurry casting (compocasting)	40
1.2.6.2.7 Reactive processing (in-situ composites).....	40
1.2.6.3 Thermomechanical processing.....	40
1.2.6.4 Near net shape manufacturing processes.....	40
1.2.7 PRODUCT FORMS	40
1.2.7.1 Intermediate.....	40
1.2.7.2 Standard	40
1.2.7.3 Selectively reinforced components	40
1.2.8 SECONDARY MANUFACTURING PROCESSES.....	40
1.2.8.1 Overview and general information	40
1.2.8.2 Forming.....	40
1.2.8.3 Machining	41
1.2.8.4 Joining	41
1.2.8.4.1 Qualitative assessment for MMC joining methods	41
1.2.8.4.1.1 Qualitative performance assessment.....	41
1.2.8.4.1.2 Joint adaptability, applications and selection.....	41
1.2.8.4.2 Potential issues in joining MMCs	42
1.2.8.4.2.1 Solidification effects	43
1.2.8.4.2.2 Chemical reactions.....	43
1.2.8.4.2.3 Joint preparation	43
1.2.8.4.2.4 Post-joining heat treatment	43
1.2.8.4.3 Classification and discussion of selected joining methods.....	43
1.2.8.4.3.1 Inertia friction (IF) welding.....	43
1.2.8.4.3.2 Friction stir (FS) welding	44
1.2.8.4.3.3 Ultrasonic (US) welding.....	44
1.2.8.4.3.4 Diffusion bonding (DFB).....	45
1.2.8.4.3.5 Laser beam (LB) welding	45
1.2.8.4.3.6 Electron beam (EB) welding.....	45
1.2.8.4.3.7 Gas-tungsten arc (GTA) welding.....	45
1.2.8.4.3.8 Gas-metal arc (GMA) welding.....	46
1.2.8.4.3.9 Resistance spot (RS) welding	46
1.2.8.4.3.10 Capacitor discharge (CD) welding	46
1.2.8.4.3.11 Brazing (BZ)	46
1.2.8.4.3.12 Soldering (SD).....	47
1.2.8.4.3.13 Adhesive bonding (AB)	47
1.2.8.4.3.14 Mechanical fastening (MF).....	47
1.2.8.4.3.15 Cast-insert joining (CI)	47
1.2.8.4.3.16 Transient liquid phase (TLP) bonding	47
1.2.8.4.3.17 Rapid infrared (RI) joining	48
1.2.8.5 Thermal treatment.....	48
1.2.8.6 Coatings and surface treatments.....	48
1.2.9 QUALITY ASSURANCE	48

<u>PARAGRAPH</u>	<u>PAGE</u>
1.2.9.1 Constituents	48
1.2.9.2 Preform	48
1.2.9.3 Final product	48
1.2.9.4 Statistical process control	48
1.2.10 REPAIR	48
1.2.10.1 In-process	48
1.2.10.2 In-service	48
REFERENCES	49
1.3 TEST PLANS FOR MATERIALS CHARACTERIZATION	51
1.3.1 INTRODUCTION	51
1.3.1.1 Objective	51
1.3.1.2 Classes of data	51
1.3.2 REQUIREMENTS	51
1.3.2.1 Test method selection	51
1.3.2.2 Test conditions selection	52
1.3.2.3 Specimen number and sampling	52
1.3.2.4 Specimen preparation	53
1.3.2.5 Data documentation Requirements Checklist	58
1.3.3 MATERIALS PEDIGREE	64
1.3.3.1 Reinforcement	64
1.3.3.2 Reinforcement sizing	64
1.3.3.3 Reinforcement coatings	64
1.3.3.4 Matrix	64
1.3.3.5 Intermediate forms characterization	64
1.3.3.5.1 Metallized fibers	64
1.3.3.5.2 Monotapes	64
1.3.3.5.3 Lamina other than monotapes	64
1.3.3.5.4 Specialized forms	64
1.3.3.6 Composite materials	64
1.3.4 CONTINUOUS FIBER REINFORCED MMC CONSTITUENT MATERIAL PROPERTIES	65
1.3.4.1 Static property data classes	65
1.3.4.1.1 Screening data	65
1.3.4.1.2 Mean data	65
1.3.4.1.3 Fully approved data	65
1.3.4.2 Composite fatigue properties tests	67
1.3.4.3 Composite thermal mechanical tests	67
1.3.4.4 Composite physical properties tests	68
1.3.4.5 Intermediate forms characterization	68
1.3.4.5.1 Metallized fibers	69
1.3.4.5.2 Monotapes	69
1.3.4.5.3 Lamina other than monotapes	69
1.3.4.5.4 Specialized forms	69
1.3.4.6 Constituent characterization	69
1.3.4.6.1 Fiber properties tests	69
1.3.4.6.2 Matrix	70
1.3.5 DISCONTINUOUS REINFORCED MMC & CONSTITUENT MATERIAL PROPERTIES	71
1.3.5.1 Screening	71
1.3.5.2 Testing requirements for fully approved data	71
1.3.5.2.1 Composite static properties tests	71
1.3.5.2.2 Composite fatigue properties tests	71
1.3.5.2.3 Composite thermal mechanical tests	71
1.3.5.2.4 Composite physical properties tests	71

<u>PARAGRAPH</u>	<u>PAGE</u>
1.3.5.2.5 Composite corrosion properties tests	71
REFERENCES.....	72
1.4 COMPOSITE TESTING AND ANALYTICAL METHODS	73
1.4.1 INTRODUCTION.....	73
1.4.2 CONTINUOUS FIBER REINFORCED MMC MECHANICAL PROPERTY TEST METHODS	73
1.4.2.1 Tension	73
1.4.2.2 Compression.....	73
1.4.2.3 Shear (in-plane)	74
1.4.2.4 Fatigue.....	74
1.4.2.4.1 Scope	74
1.4.2.4.2 Specimen design	74
1.4.2.4.3 Waveforms	74
1.4.2.4.4 Control mode	75
1.4.2.4.5 Compressive loading	75
1.4.2.4.6 Failure.....	75
1.4.2.4.7 Data reporting	75
1.4.2.5 Fatigue crack growth rate	75
1.4.2.6 Creep/stress rupture	80
1.4.2.7 Pin bearing tension	81
1.4.2.8 Pin bearing compression	81
1.4.2.9 Filled hole tension	81
1.4.2.10 Open hole tension/notch sensitivity	81
1.4.2.11 Flexure (three-point bend)	81
1.4.2.12 Filled hole compression.....	81
1.4.2.13 Fiber pushout tests	81
1.4.2.13.1 Background	81
1.4.2.13.2 General.....	82
1.4.2.13.3 Description of the method	82
1.4.2.13.4 Significance and use	83
1.4.2.13.5 Apparatus	83
1.4.2.13.6 Indenter	85
1.4.2.13.7 Support plate	85
1.4.2.13.8 Acoustic emission sensor.....	86
1.4.2.13.9 Displacement sensor	86
1.4.2.13.10 Remote viewing using a microscope/camera	87
1.4.2.13.11 Test specimen preparation.....	87
1.4.2.13.12 Test procedure	88
1.4.2.13.13 Effects of environment.....	89
1.4.2.13.14 Analysis of results	89
1.4.2.14 Microhardness	92
1.4.2.15 Thermomechanical fatigue (TMF) (in-phase/out-of-phase).....	92
1.4.2.15.1 Scope	92
1.4.2.15.2 Specimen design	93
1.4.2.15.3 Temperature control and measurement	93
1.4.2.15.4 Waveforms	93
1.4.2.15.5 Phasing.....	94
1.4.2.15.6 Pre-test measurements	94
1.4.2.15.7 Starting the test.....	95
1.4.2.15.8 Data reporting	96
1.4.2.16 Residual strength and stiffness	96
1.4.2.17 Bearing fatigue	96
1.4.2.18 Open hole fatigue	96
1.4.2.19 Filled hole fatigue.....	96

<u>PARAGRAPH</u>	<u>PAGE</u>
1.4.2.20 Corrosion fatigue	96
1.4.2.21 Stress corrosion cracking	96
1.4.2.22 Wear	96
1.4.2.23 Impact	97
1.4.2.24 Damping	97
1.4.3 DISCONTINUOUS REINFORCED MMC MECHANICAL PROPERTY TEST METHODS	97
1.4.3.1 Tension	97
1.4.3.2 Compression.....	97
1.4.3.3 Shear (in-plane)	97
1.4.3.4 Fracture toughness.....	97
1.4.3.5 Fatigue	97
1.4.3.6 Fatigue crack growth	97
1.4.3.7 Creep/stress rupture	97
1.4.3.8 Corrosion fatigue	97
1.4.3.9 Stress corrosion cracking	97
1.4.3.10 Wear	97
1.4.3.11 Impact	97
1.4.3.12 Damping	98
1.4.4 PHYSICAL PROPERTY TEST METHODS	98
1.4.4.1 Density	98
1.4.4.2 Fiber volume fraction	98
1.4.5 MICROSTRUCTURAL ANALYSIS TECHNIQUES	98
1.4.5.1 Titanium matrix composites	98
1.4.6 CHEMICAL ANALYSIS TECHNIQUES	100
1.4.6.1 Analysis of carbon and sulfur.....	100
1.4.6.2 Analysis for oxygen and nitrogen by inert gas fusion.....	101
1.4.7 NONDESTRUCTIVE EVALUATION TEST METHODS	102
1.4.8 ENVIRONMENTAL EFFECTS TEST METHODS	102
1.4.8.1 Corrosion and corrosion test methods.....	102
1.4.8.1.1 Neutral salt spray (fog)	104
1.4.8.1.2 Corrosion testing, cyclic.....	105
1.4.9 INTERPHASES AND INTERFACES TEST METHODS.....	106
REFERENCES.....	107
1.5 INTERMEDIATE FORMS TESTING AND ANALYTICAL METHODS	112
1.5.1 INTRODUCTION.....	112
1.5.2 MECHANICAL PROPERTY TEST METHODS.....	112
1.5.3 PHYSICAL PROPERTY TEST METHODS.....	112
1.5.4 MICROSTRUCTURAL ANALYSIS TECHNIQUES	112
1.5.5 CHEMICAL ANALYSIS TECHNIQUES	112
1.5.6 NONDESTRUCTIVE EVALUATION TEST METHODS	112
1.6 FIBER TESTING AND ANALYTICAL METHODS	113
1.6.1 INTRODUCTION.....	113
1.6.2 MECHANICAL PROPERTY TEST METHODS.....	113
1.6.2.1 Tensile tests	113
1.6.2.2 Creep and creep rupture.....	114
1.6.2.3 Bend stress relaxation	114
1.6.3 PHYSICAL PROPERTY TEST METHODS.....	114
1.6.3.1 Density	114
1.6.4 MICROSTRUCTURAL ANALYSIS TECHNIQUES	114
1.6.5 CHEMICAL ANALYSIS TECHNIQUES	114
1.6.6 ENVIRONMENTAL EFFECTS TEST METHODS.....	115
REFERENCES.....	116

<u>PARAGRAPH</u>	<u>PAGE</u>
1.7 FIBER SIZING TESTING AND ANALYTICAL METHODS	117
1.7.1 INTRODUCTION.....	117
1.7.2 PHYSICAL PROPERTY TEST METHODS.....	117
1.7.3 CHEMICAL ANALYSIS TECHNIQUES	117
1.8 FIBER COATINGS, INTERFACES AND INTERPHASES TESTING AND ANALYTICAL METHODS.....	118
1.8.1 INTRODUCTION.....	118
1.8.2 MECHANICAL PROPERTY TEST METHODS.....	118
1.8.3 PHYSICAL PROPERTY TEST METHODS.....	118
1.8.4 MICROSTRUCTURAL ANALYSIS TECHNIQUES	118
1.8.5 CHEMICAL ANALYSIS TECHNIQUES	118
1.9 MATRIX TESTING AND ANALYTICAL METHODS	119
1.9.1 INTRODUCTION.....	119
1.9.2 MECHANICAL TEST METHODS.....	119
1.9.2.1 Tension	119
1.9.2.2 Creep.....	119
1.9.2.3 Stress relaxation	119
1.9.2.4 Fatigue.....	120
1.9.2.5 Fatigue crack growth	120
1.9.3 PHYSICAL TEST METHOD.....	120
1.9.3.1 Density.....	120
1.9.4 MICROSTRUCTURAL ANALYSIS TECHNIQUES	120
1.9.4.1 Microstructural analysis techniques titanium	120
1.9.4.2 Microstructural analysis techniques aluminum	120
1.9.5 CHEMICAL ANALYSIS TECHNIQUES	120
1.9.6 ENVIRONMENTAL EFFECTS TEST METHODS.....	121
REFERENCES.....	122
1.10 STRUCTURE SENSITIVE PROPERTIES CHARACTERIZATION	123
1.10.1 INTRODUCTION.....	123
1.10.2 MECHANICALLY-FASTENED JOINTS.....	123
1.10.3 BONDED, BRAZED, AND WELDED JOINTS	123
1.10.4 CURVED SHAPES.....	123
1.10.5 STRUCTURAL DESIGN DETAILS.....	123
1.10.6 TRANSITION AND OTHER SPECIAL REGIONS.....	123
1.10.7 SIZE EFFECTS.....	123
1.10.8 OTHER TOPICS	123
1.11 ANALYSIS OF DATA.....	124
1.11.1 GENERAL.....	124
1.11.2 PROCEDURES OF CALCULATION OF STATISTICALLY-BASED MATERIAL PROPERTIES	124
1.11.3 SAMPLES OF COMPUTATIONAL PROCEDURES	124
1.11.4 STATISTICAL TABLES.....	124
2. DESIGN GUIDELINES FOR METAL MATRIX MATERIALS	125
2.1 GENERAL INFORMATION	125
2.1.1 INTRODUCTION.....	125
2.1.2 PURPOSE, SCOPE, AND ORGANIZATION OF SECTION 2	125
2.2 USE OF DATA.....	125
2.3 STRUCTURAL DESIGN AND ANALYSIS.....	125
2.3.1 INTRODUCTION.....	125
2.3.1.1 Analysis methodology classifications.....	126

<u>PARAGRAPH</u>	<u>PAGE</u>
2.3.1.2 Basic concepts.....	126
2.3.2 GENERAL DESIGN GUIDELINES.....	128
2.3.3 ANALYSIS APPROACHES (CONTINUOUS FIBER MMC)	129
2.3.3.1 Micromechanics.....	129
2.3.3.1.1 General relationships.....	129
2.3.3.1.2 Effective elastic properties.....	131
2.3.3.1.3 Residual stresses	135
2.3.3.1.4 Fiber-matrix bond strength	138
2.3.3.1.5 Overall inelastic strain	141
2.3.3.2 Viscoplastic constitutive relations	145
2.3.3.2.1 Axial tensile response.....	145
2.3.3.2.2 Axial compressive response.....	145
2.3.3.2.3 Transverse tensile response	145
2.3.3.2.4 Transverse compressive response	145
2.3.3.3 Macromechanics	145
2.3.3.3.1 Effective elastic properties.....	145
2.3.3.3.1.1Types of laminates	150
2.3.3.3.1.1.1Symmetric laminates.....	150
2.3.3.3.1.1.2Specially orthotropic laminates.....	150
2.3.3.3.1.1.3Cross-ply laminates.....	150
2.3.3.3.1.1.4Angle-ply laminates	150
2.3.3.3.1.1.5Balanced laminates.....	151
2.3.3.3.1.1.6Other specially orthotropic laminates	151
2.3.3.3.1.1.7Quasi-isotropic laminates.....	151
2.3.3.3.1.1.8Laminate effective elastic properties.....	151
2.3.3.3.2 Effective strength.....	152
2.3.3.3.2.1Maximum stress criterion	153
2.3.3.3.2.2Maximum strain criterion.....	155
2.3.3.3.2.3Tsai-Hill criterion.....	156
2.3.3.3.2.4Tsai-Wu criterion	158
2.3.3.3.2.5Hashin criterion	160
2.3.3.3.2.6Puck and LaRC03 criteria	161
2.3.3.3.3 Creep.....	163
2.3.3.3.4 Multiaxial effects	166
2.3.3.4 Damage tolerance	166
2.3.3.5 Durability	166
2.3.3.6 Life prediction	166
2.3.4 DESIGN GUIDELINES (DISCONTINUOUS FIBER REINFORCED MMC).....	166
2.3.4.1 Micromechanics.....	166
2.3.4.1.1 General relationships.....	166
2.3.4.1.2 Effective elastic properties.....	166
2.3.4.1.3 Fiber-matrix bond strength	166
2.3.4.1.4 Inelastic mechanisms and damage.....	166
2.3.4.2 Viscoplastic constitutive relations	166
2.3.4.2.1 Tensile response.....	166
2.3.4.2.2 Compressive response.....	166
2.3.4.2.3 Shear response	166
2.3.4.3 Crack growth behavior.....	167
2.3.4.4 Durability	167
2.3.4.5 Life prediction	167
REFERENCES.....	168
2.4 APPLICATIONS AND CASE STUDIES.....	171
2.4.1 COMPONENTS FOR STRUCTURAL APPLICATIONS.....	171
2.4.2 COMPONENTS FOR TRIBOLOGICAL APPLICATIONS	171

<u>PARAGRAPH</u>	<u>PAGE</u>
2.4.3 COMPONENTS FOR THERMAL MANAGEMENT APPLICATIONS	171
2.4.4 COMPONENTS FOR THERMAL EXPANSION CONTROL	171
2.4.5 OTHER MISCELLANEOUS APPLICATIONS	171
3. MATERIALS PROPERTIES DATA	172
3.1 GENERAL INFORMATION	172
3.1.1 INTRODUCTION.....	172
3.1.2 PURPOSE, SCOPE, AND ORGANIZATION OF SECTION	172
3.1.3 PRESENTATION OF DATA.....	172
3.1.3.1 Properties and definitions	172
3.1.3.1.1 Sign convention	172
3.1.3.2 Table formats	172
3.1.3.3 Fatigue data	183
REFERENCES.....	183
3.2 REINFORCEMENT PROPERTIES.....	184
3.2.1 INTRODUCTION.....	184
3.2.2 ALUMINA FIBERS.....	184
3.2.2.1 Introduction	184
3.2.2.2 Virgin Nextel™ 610 fiber	185
3.2.3 BORON FIBERS	188
3.2.4 BORON CARBIDE FIBERS	188
3.2.5 CARBON AND GRAPHITE FIBERS	188
3.2.6 SILICON CARBIDE FIBERS.....	188
3.2.6.1 Virgin SCS-6 fiber*	189
3.2.6.2 Virgin and extracted SCS-6 fibers	192
3.2.6.3 SCS-6 Fiber	200
3.2.7 STEEL FIBERS	205
3.2.8 TUNGSTEN FIBERS	205
3.2.9 OTHER FIBERS.....	205
3.2.10 OTHER REINFORCEMENTS.....	205
3.3 PROPERTIES OF MATRIX MATERIALS.....	206
3.3.1 INTRODUCTION.....	206
3.3.2 ALUMINUMS.....	206
3.3.3 COPPERS.....	206
3.3.4 MAGNESIUMS.....	206
3.3.5 TITANIUMS	206
3.3.5.1 Ti-15V-3Cr-3Al-3Sn (NASA-GRC)	206
3.3.6 OTHERS	219
3.4 FIBER COATING PROPERTIES	220
3.4.1 INTRODUCTION.....	220
3.4.2 CARBON	220
3.4.3 TITANIUM DIBORIDE	220
3.4.4 YTTRIA	220
3.4.5 OTHERS	220
3.5 ALUMINUM MATRIX COMPOSITE PROPERTIES.....	221
3.5.1 INTRODUCTION.....	221
3.5.2 ALUMINA/ALUMINUM	221
3.5.2.1 Nextel 610/pure Al panel.....	221
3.5.3 BORON/ALUMINUM.....	226

<u>PARAGRAPH</u>	<u>PAGE</u>
3.5.4 BORON CARBIDE/ALUMINUM.....	226
3.5.5 GRAPHITE/ALUMINUM.....	226
3.5.6 SILICON CARBIDE/ALUMINUM.....	226
3.5.7 STEEL/ALUMINUM.....	226
3.5.8 TUNGSTEN/ALUMINUM.....	226
3.5.9 OTHERS/ALUMINUM.....	226
3.6 COPPER MATRIX COMPOSITE PROPERTIES.....	227
3.6.1 INTRODUCTION.....	227
3.6.2 GRAPHITE/COPPER.....	227
3.6.3 OTHERS/COPPER.....	227
3.7 MAGNESIUM MATRIX COMPOSITE PROPERTIES.....	228
3.7.1 INTRODUCTION.....	228
3.7.2 GRAPHITE/MAGNESIUM.....	228
3.7.3 ALUMINA/MAGNESIUM.....	228
3.7.4 OTHER/MAGNESIUM.....	228
3.8 TITANIUM MATRIX COMPOSITE PROPERTIES.....	229
3.8.1 INTRODUCTION.....	229
3.8.2 SILICON CARBIDE/TITANIUM.....	229
3.8.2.1 SCS-6/Ti-15-3.....	229
3.8.2.1.1 SCS-6/Ti-15-3 Tension.....	229
3.8.2.1.2 SCS-6/Ti-15-3 Fatigue.....	253
3.8.2.2 TRIMARC-1/Ti-6Al-2Sn-4Zr-2Mo wire/fiber wound plate*.....	260
3.8.2.3 SCS-6/Ti-6Al-4V fiber/powder.....	279
3.8.2.3.1 Static Properties.....	279
3.8.2.3.2 SCS-6/Ti-6Al-4V fiber/powder*.....	283
3.8.2.3.3 Fatigue.....	314
3.8.2.3.4 Fatigue crack growth.....	320
3.8.3 ALUMINA/TITANIUM.....	326
3.8.4 OTHER/TITANIUM.....	326
3.9 OTHER MATRIX COMPOSITES.....	326
APPENDIX A. TYPICAL PUSHOUT TEST DATA.....	327
A1. FIBER PUSHOUT.....	327
APPENDIX B. RAW DATA TABLES FOR MATRIX MATERIALS.....	330
B1. ALUMINUMS.....	330
B2. COPPERS.....	330
B3. MAGNESIUMS.....	330
B4. TITANIUMS.....	330
B4.1 Ti 15V 3Cr 3Al-3Sn (Section 3.3.5.1).....	331
APPENDIX C. RAW DATA TABLES FOR METAL MATRIX COMPOSITE MATERIALS.....	335
C1. ALUMINUMS.....	335
C1.1 Nextel 610 / SP Al (Section 3.5.2.1).....	336
C2. COPPER.....	346
C3. MAGNESIUMS.....	346
C4. TITANIUMS.....	347
C4.1 SiC/Ti-15-3 (Section 3.8.2.1.1 and 3.8.2.1.2).....	347
C4.2. TRIMARC-1/Ti 6-2-4-2 (Section 3.8.2.2).....	369
C4.3 Titanium Matrix Composite Panels (Section 3.8.2.3).....	383
Index.....	432

COMPOSITE MATERIALS HANDBOOK

Volume

5

Ceramic Matrix Composites

CMH-17

COMPOSITE MATERIALS HANDBOOK



WICHITA STATE
UNIVERSITY

NATIONAL INSTITUTE
FOR AVIATION RESEARCH

SAE
INTERNATIONAL®

**NOT MEASUREMENT
SENSITIVE**

CMH-17-5A
Volume 5 of 6
1 JUNE 2017

Superseding
MIL-HDBK-17-5
17 JUNE 2002

COMPOSITE MATERIALS HANDBOOK

VOLUME 5. CERAMIC MATRIX COMPOSITES



CMH-17
COMPOSITE MATERIALS HANDBOOK



Copyright 2017 - Composite Materials Handbook – 17 (CMH-17). All rights reserved. Unauthorized duplication or distribution may violate the Copyright Laws of the United States and of other jurisdictions

Published by SAE International on behalf of CMH-17,
a division of Wichita State University

FOREWORD

The Composite Materials Handbook, CMH-17, provides information and guidance necessary to design and fabricate structural components from composite materials. Its primary purposes are a) the standardization of engineering data development methodologies related to testing, data reduction, and data reporting of property data for current and emerging composite materials, b) guidance on material and process specifications and procedures for utilization of the material data presented in the handbook, and c) methodologies for the design, analysis, certification, manufacture, and field support of composite structures. In support of these objectives, the handbook includes composite materials properties that meet specific data requirements. The Handbook therefore constitutes an overview of the field of composites technology and engineering, an area that is advancing and changing rapidly. As a result, the document will be continually revised as sections are added or modified to reflect advances in the state-of-the-art.

CMH-17 Mission

The Composite Materials Handbook organization creates, publishes and maintains proven, reliable engineering information and standards, subjected to thorough technical review, to support the development and use of composite materials and structures.

CMH-17 Vision

The Composite Materials Handbook will be the authoritative worldwide focal point for technical information on composite materials and structures.

Goals and Objectives to Support CMH-17 Mission

- To periodically meet with experts from the field to discuss critical technical issues for composite structural applications, with an emphasis on increasing overall product efficiency, quality and safety.
- To provide comprehensive, practical engineering guidance that has proven reliable for the design, fabrication, characterization, test and maintenance of composite materials and structures.
- To provide reliable data, linked to control of processes and raw materials, thereby being a comprehensive source of material property basis values and design information that can be shared within the industry.
- To provide a resource for composite material and structure education with examples, applications and references to supporting engineering work.
- To establish guidelines for use of information in the Handbook, identifying the limitations of the data and methods.
- To provide guidance on references to proven standards and engineering practices.
- To provide for periodic updates to maintain the all-inclusive nature of the information.
- To provide information in formats best-suited for user needs.
- To serve the needs of the international composites community through meetings and dialogue between member industries, which use teamwork and the diverse member engineering skills to provide information for the handbook.

Notes

1. Every effort has been made to reflect the latest information on polymer (organic), metal, and ceramic composites. The handbook is continually reviewed and revised to ensure it is complete and current.
2. CMH-17 provides guidelines and material properties for polymer (organic), metal, and ceramic matrix composite materials. The first three volumes of this handbook currently focus on, but are not limited to, polymeric composites intended for aircraft and aerospace vehicles. Metal matrix composites (MMC), ceramic matrix composites (CMC), and sandwich composites are covered in Volumes 4, 5, and 6, respectively.
3. The information contained in this handbook was obtained from materials producers, industry companies and experts, reports on Government sponsored research, the open literature, and by contract with research laboratories and those who participate in the CMH-17 coordination activity. The information in this handbook has undergone vigorous technical review and was subject to membership vote.
4. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: CMH-17 Secretariat, Wichita State University, 1845 Fairmount, Wichita, KS 67260, by letter or email, info@cmh17.org.

ACKNOWLEDGEMENT

Volunteer committee members from government, industry, and academia develop, coordinate and review all the information provided in this handbook. The time and effort of the volunteers and the support of their respective departments, companies, and universities make it possible to insure the handbook reflects completeness, accuracy, and state-of-the-art composite technology.

Support necessary for the development and maintenance of the Composite Materials Handbook (CMH-17) are provided by the handbook Secretariat, Wichita State University. The primary source of funding for the current Secretariat contract is the Federal Aviation Administration.

CONTENTS

PART A. INTRODUCTION AND GUIDELINES	
PART B. DESIGN AND SUPPORTABILITY	
PART C. TESTING	
PART D. DATA REQUIREMENTS AND DATA SETS	
APPENDIX A. DERIVATION OF THE RESIDUAL STRENGTH REDUCTION EXPRESSIONS FOR LCF AND RUPTURE LOADINGS	

Page

PART A. INTRODUCTION AND GUIDELINES.....	1
1 CMH-17 GUIDELINES AND PROCEDURES	1
1.1 INTRODUCTION TO THE HANDBOOK.....	1
1.2 OVERVIEW OF HANDBOOK CONTENT.....	1
1.3 INTRODUCTION TO VOLUME 5	2
1.3.1 Objectives of Ceramic Matrix Composite (CMC) Working Groups	3
1.3.1.1 Objectives and tasks for Data Review Working Group.....	3
1.3.1.2 Vision, goals and objectives for Materials and Processes Working Group.....	4
1.3.1.3 Vision, goals and objectives for Design and Analysis Working Group	4
1.3.1.4 Vision, goals and objectives for Testing Working Group.....	5
1.4 PURPOSE.....	5
1.5 SCOPE.....	6
1.5.1 Part A: Introduction and Guidelines	7
1.5.2 Part B: Design and Supportability	7
1.5.3 Part C: Testing	7
1.5.4 Part D: Data Requirements and Data Sets	7
1.6 USE OF THE DOCUMENT AND LIMITATIONS	8
1.6.1 Source of information	8
1.6.2 Use of data and guidelines in applications	8
1.6.3 Strength properties and allowables terminology	9
1.6.4 Use of References.....	9
1.6.5 Use of tradenames and product names	9
1.6.6 Toxicity, health hazards, and safety.....	9
1.6.7 Ozone depleting chemicals	9
1.7 APPROVAL PROCEDURES	9
1.8 SYMBOLS, ABBREVIATIONS, AND SYSTEMS OF UNITS	10
1.8.1 Symbols and abbreviations	10
1.8.1.1 Constituent properties.....	15
1.8.1.2 Laminae and laminates.....	16
1.8.1.3 Subscripts	17
1.8.1.4 Superscripts	18
1.8.1.5 Acronyms	18
1.8.2 System of units	23
1.9 DEFINITIONS	24
2 CHAPTER 2 INTRODUCTION, HISTORY AND OVERVIEW	47
2.1 BACKGROUND	47
2.2 CMC STRUCTURAL FUNDAMENTALS.....	48
2.3 HANDBOOK OBJECTIVES	50

3 PROCESSING, CHARACTERIZATION, AND MANUFACTURING	56
3.1 CMC SYSTEMS, PROCESSING, PROPERTIES, AND APPLICATIONS	56
3.1.1 The Application of SiC/SiC and Ox/Ox CMCs in Aircraft Turbine Engine Hot Section and Exhaust Components 56	
3.1.2 CMC Systems, Processing Methods, and Properties	58
3.1.3 SiC/SiC CMCs	59
3.1.3.1 Chemical Vapor Infiltration (CVI) SiC/SiC CMCs	59
3.1.3.1.1 CVI fabrication technique	59
3.1.3.1.2 Typical properties for CVI SiC/SiC CMCs	61
3.1.3.2 Polymer Infiltration & Pyrolysis (PIP) CMCs	63
3.1.3.2.1 Introduction	63
3.1.3.2.2 Fabrication Process	64
3.1.3.3 Melt Infiltrated (MI) SiC/SiC CMCs	67
3.1.3.3.1 MI SiC/SiC Manufacturing Process	68
3.1.3.3.2 Aero Engine Applications	69
3.1.3.3.3 MI SiC/SiC CMC Supply Chain	70
3.1.3.4 Hybrid SiC/SiC Composites	71
3.1.3.4.1 Processing Hybrid MI SiC/SiC Composites	71
3.1.3.4.2 Properties of Hybrid MI SiC/SiC Composites	72
3.1.3.4.3 Processing and Properties of Other Hybrid SiC/SiC Composites	73
3.1.4 Oxide/Oxide CMC Systems	74
3.1.4.1 Introduction/Applications	74
3.1.4.2 Interface Control	75
3.1.4.3 Oxide/Oxide Composite Processing	76
3.1.4.3.1 Slurry Infiltration	76
3.1.4.3.2 Sol-gel processing of 3-D structures	78
3.1.4.3.3 Alternative Processing Techniques	78
3.1.4.4 Properties	78
3.2 FIBER REINFORCEMENT TYPES AND TECHNOLOGY	80
3.2.1 Introduction	80
3.2.2 Oxide-Based Ceramic Fibers	80
3.2.2.1 Overview	80
3.2.2.2 Production Processing	81
3.2.2.3 Composition and Microstructure	82
3.2.2.4 Commercial Fibers	83
3.2.2.5 High Temperature Properties of Continuous Ceramic Oxide Fibers	85
3.2.2.6 Future Directions in Oxide Fibers	87
3.2.3 Si-Based Ceramic Fibers	88
3.2.3.1 Overview	88
3.2.3.2 SiC-Based Fiber Property Requirements for High-Temperature Structural CMCs	89
3.2.3.3 Current SiC-based Fiber Types for High-Temperature CMC	91
3.2.3.4 Status of Commercial SiC Fiber Types for High-Temperature CMC Applications	95
3.2.3.5 Future Directions	96
3.3 INTERPHASE/INTERFACE TECHNOLOGY AND APPROACHES	100
3.3.1 Introduction	100
3.3.1.1 The roles and requirements for interface coatings	102
3.3.1.2 Fabrication of fiber interface coatings	103
3.3.2 Interphase composition	104
3.3.2.1 Carbon	104

CMH-17-5A
Volume 5, Foreword / Table of Contents

3.3.2.2 Boron nitride.....	105
3.3.2.3 Oxide.....	107
3.3.2.3.1 Porous matrices.....	107
3.3.2.3.2 Porous Coatings.....	108
3.3.2.3.3 Fugitive Interfaces.....	108
3.3.2.3.4 Layered Oxides.....	108
3.3.2.3.5 Monazite.....	108
3.3.3 Summary.....	109
3.4 FABRICATION AND FORMING OF FIBER ARCHITECTURES.....	110
3.4.1 Introduction.....	110
3.4.2 Fiber Suppliers.....	110
3.4.3 Fiber Placement Techniques and Equipment.....	110
3.4.3.1 Automated Fiber Placement, Tape Laying and Tension Winding.....	110
3.4.4 Fiber Weaving.....	112
3.4.5 Fiber Architecture Selection.....	115
3.4.5.1 Discontinuous Fiber Preforms.....	116
3.4.5.2 Dry Unidirectional Tow, Sizing and Servicing.....	117
3.4.5.3 Ceramic Prepreg.....	117
3.4.5.4 Unidirectional Weaves.....	117
3.4.5.5 Two Dimensional (2D) Weaves.....	117
3.4.5.6 Plain Weave.....	118
3.4.5.7 Satin Weave.....	118
3.4.5.8 Twill Weave.....	119
3.4.5.9 Polar Weaves.....	120
3.4.5.10 Contour Weaves.....	121
3.4.5.11 Three Dimensional (3D) Weaves.....	121
3.4.5.12 Orthogonal Interlock.....	121
3.4.5.13 Ply-to-Ply Interlock.....	121
3.4.5.14 Angle Interlock (with & without stuffers).....	121
3.4.5.15 4D, 5D Weaves.....	122
3.4.5.16 Specialty – Z-Pinning.....	123
3.4.5.17 Braids.....	123
3.4.5.17.1 Braiding Introduction and Definition.....	123
3.4.5.17.2 Types of Braids.....	124
3.4.5.17.3 Biaxial Braid.....	124
3.4.5.17.4 Triaxial Braid.....	126
3.4.5.17.5 Two-Dimensional (2D) Braiding Machines.....	126
3.4.5.17.6 Three-Dimensional (3D) / Multi-Directional Braid.....	128
3.4.5.18 Needling.....	132
3.4.6 Computer Modeling and Simulation.....	133
3.4.7 Fabric Weave and Braid Manufacturers.....	135
3.5 EXTERNAL PROTECTIVE COATINGS.....	136
3.5.1 External protective coatings for non-oxide CMCs.....	136
3.5.1.1 Introduction.....	136
3.5.1.2 Candidate Non-Oxide CMCs.....	137
3.5.1.3 Environmental Degradation in Gas Turbine Hot Section.....	138
3.5.1.4 Early Coatings Development Work for Silicon-based materials.....	142
3.5.1.5 State-of-the-Art Environmental Barrier Coatings (EBCs) for Gas Turbine Hot Section.....	143
3.5.1.5.1 First Generation EBCs.....	144
3.5.1.5.2 Second Generation EBCs.....	148
3.5.1.6 Degradation of EBC-coated SiC/SiC CMC Components.....	149
3.5.1.6.1 CMAS Resistance of First-Generation EBC.....	150
3.5.1.6.2 CMAS Resistance of Second Generation Rare-Earth EBCs.....	151
3.5.1.7 EBC Field Testing.....	152

CMH-17-5A
Volume 5, Foreword / Table of Contents

3.5.1.7.1 GE 7FA EBC Coated CMC Inner Shroud Tests.....	154
3.5.1.7.2 Solar Turbines Incorporated CMC/EBC Field Testing	156
3.5.1.7.3 Degradation of EBC-coated SiC/SiC CMC Components	158
3.5.1.8 Next Generation EBCs for 2700-300°F (1482-164°C).....	164
3.5.1.9 Summary of EBC Development and Testing	166
3.5.2 External Protective Coatings for Oxide CMCs	167
3.5.2.1 Overview	167
3.5.2.2 Porous Environmental and Thermal Barriers for Oxide CMCs.....	168
3.5.2.2.1 Friable Graded Insulation (FGI) for Oxide CMCs	169
3.5.2.2.2 Mullite and Alumina Thermal Barrier Coatings for Oxide CMCs.....	171
3.5.2.2.3 EBCs/TBCs for WHIPOX™ and Related Oxide CMCs	174
3.5.2.3 Glass Frit Coatings	178
3.5.2.4 High Emissivity Coatings	181
3.6 CHARACTERIZATION METHODS.....	184
3.6.1 Introduction	184
3.6.2 Sample preparation	184
3.6.3 Optical Microscopy	185
3.6.4 Scanning Electron Microscopy	186
3.6.5 Microstructural Characterization.....	187
3.6.5.1 Area/volume fractions (fibers, tows, matrix, pores).....	189
3.6.5.2 Grain size measurement.....	189
3.6.5.3 Fiber size and spacing.....	190
3.6.5.4 Pore size and spatial distribution	190
3.6.5.5 Application of Characterization technique.....	190
3.6.6 3D Microstructural Evaluation.....	191
3.6.7 Microstructural Characterization Using Microfocus X-ray Computed Tomography	192
3.7 NONDESTRUCTIVE EVALUATION METHODS FOR CMC (DEFECT CHARACTERIZATION).....	195
3.7.1 Needs and Requirements.....	196
3.7.2 NDE Methods	197
3.7.2.1 Infrared Thermography	197
3.7.2.2 Ultrasound.....	201
3.7.2.2.1 Ultrasonic theory of operation	202
3.7.2.2.2 Inspection Modes and Defect Detection.....	203
3.7.2.2.3 Calibration	206
3.7.2.2.4 Data interpretation and processing	207
3.7.2.2.5 Implementation Issues.....	207
3.7.2.2.6 Areas of development.....	208
3.7.2.3 Radiography.....	208
3.7.2.3.1 Modes of operation.....	208
3.7.2.3.2 Calibration	209
3.7.2.3.3 Processing and interpretation.....	209
3.7.2.3.4 Areas of development.....	210
3.7.2.4 Microwave	214
3.7.2.5 Other NDE, Emerging NDE, potential NDE methods	215
3.7.2.5.1 Impact acoustic resonance.....	215
3.7.2.5.2 Guided plate waves	216
3.7.2.5.3 Other methods.....	216
3.7.3 Material States and Defects	216
3.7.3.1 Density and bulk porosity.....	217
3.7.3.2 Localized Porosity/Voids and Inclusions	218
3.7.3.3 Delaminations and planar defects	218
3.7.3.4 Thermal Properties (diffusivity/conductivity)	220
3.7.3.5 Missing plies, ply drop off.....	220

CMH-17-5A
Volume 5, Foreword / Table of Contents

3.7.3.6 Fiber coatings in manufacturing	220
3.7.3.7 In-service NDE	220
3.7.3.8 Repair NDE	221
3.7.4 Transition/implementation Issues	221
3.7.4.1 Costs	221
3.7.4.2 Throughput	222
3.7.4.3 Capability	223
3.7.4.4 Trade-offs	224
3.7.4.5 Calibration Standards	224
3.7.4.6 Procedures and Process standards	225
3.7.4.7 Industry needs	225
3.7.5 Inspection Validation	225
3.8 MACHINING	228
3.8.1 Introduction	228
3.8.2 Conventional Machining	229
3.8.2.1 Conventional Cutting tools	229
3.8.3 Ultrasonic Machining	231
3.8.3.1 Ultrasonic Machining Cutting tools	233
3.8.4 Waterjet Machining	233
3.8.4.1 Waterjet Machining tools	233
3.8.4.2 Waterjet Machining Results	234
3.8.4.3 Waterjet Machining Benefits for CMCs	240
3.8.5 Abrasive Machining	240
3.8.5.1 Abrasive Machining Cutting tools	240
3.8.6 Laser Machining	240
3.8.6.1 Electric Discharge Machining	242
4 QUALITY CONTROL OF PRODUCTION MATERIALS AND PROCESSES	263
4.1 INTRODUCTION	263
4.2 MATERIAL PROCUREMENT QUALITY ASSURANCE PROCEDURES	263
4.2.1 Specifications and documentation	263
4.2.2 Material control at the supplier level	263
4.2.3 Process control documents (PCD)	264
4.2.4 Statistical process control (SPC)	264
4.2.4.1 Lot release testing	265
4.2.5 CMC Material control at the user level	265
4.2.5.1 Lot acceptance/receiving inspection	265
4.2.5.2 Shelf life and out time control	267
4.3 CMC PART FABRICATION VERIFICATION	267
4.3.1 Process verification	267
4.3.2 CMC Nondestructive inspection (NDI)	269
4.3.3 Destructive tests (DT)	270
4.3.3.1 Background	270
4.3.3.2 Usage	270
4.3.3.3 Destructive test approaches	270
4.3.3.4 Implementation guidelines	271
4.3.3.5 Test types	272
4.4 MANAGING CHANGE IN MATERIALS AND PROCESSES	272
4.4.1 Introduction	272
4.4.2 Qualification of new materials or processes	272
4.4.2.1 Problem statement	272
4.4.2.2 Business case	273
4.4.2.3 Divergence and risk	275
4.4.2.4 Technical acceptability	275
4.4.2.5 Allowables development and equivalency validation	275

CMH-17-5A
Volume 5, Foreword / Table of Contents

4.4.2.6 Production readiness	275
4.4.2.7 Lessons learned.....	275
4.4.3 Divergence and risk.....	275
4.4.3.1 Divergence.....	276
4.4.3.2 Risk assessment.....	278
4.4.3.3 Risk analysis	279
4.4.4 Production readiness.....	280
5 APPLICATIONS, CASE HISTORIES AND LESSONS LEARNED	281
5.1 CERCOMP™ CMC DEVELOPMENT AND TESTING BY UNITED TECHNOLOGIES CORPORATION DURING THE 1974 TO 1995 TIME FRAME.....	281
5.1.1 Summary	281
5.1.2 Introduction	281
5.1.3 Fabrication	282
5.1.4 Rig and Engine Testing.....	282
5.1.5 Conclusion.....	286
5.2 SiC/SiC CMC COMBUSTOR LINER DEVELOPMENT AND FIELD TESTING	287
5.2.1 Summary	287
5.2.2 Program Team, Development Strategy and Chronology.....	287
5.2.3 CMC Liner Design	289
5.2.4 CMC Combustor Rig Testing.....	290
5.2.5 Ceramic Engine Field Testing.....	291
5.2.5.1 Field Test Sites.....	291
5.2.5.2 Degradation of Unprotected SiC/SiC CMC Liners.....	291
5.2.5.3 Protection of SiC/SiC CMCs with Environmental Barrier Coatings (EBCs)	292
5.3 OXIDE/OXIDE CMC COMBUSTOR LINER DEVELOPMENT AND FIELD TESTING.....	297
5.3.1 Summary	297
5.3.2 Program Team, Development Strategy and Chronology.....	297
5.3.3 Hybrid Oxide CMC Liner Design and Fabrication	299
5.3.4 Hybrid Oxide CMC Combustor Liner Rig Testing	300
5.3.5 Hybrid Oxide CMC Combustor Liner Engine Testing	302
5.3.6 Post-Test Inspection	305
PART B. DESIGN AND SUPPORTABILITY	312
6 DESIGN AND ANALYSIS.....	313
6.1 INTRODUCTION.....	313
6.2 DEFINITION OF APPLICATION & DESIGN REQUIREMENTS.....	313
6.2.1 Classification of Criticality and Type	313
6.2.2 Establishment of Design Requirements (loads, environment, life cycles, duration, etc).....	313
6.2.3 Substantiation Plan (Validation & Verification Matrix).....	313
6.3 CMC COMPONENT DESIGN AND ANALYSIS CONSIDERATIONS, OPTIONS, METHODS	313
6.3.1 Fiber Types	313
6.3.2 Fiber forms and architecture.....	314
6.3.3 Coatings and interphase.....	314
6.3.4 Matrix types	315
6.3.5 Material Selection Considerations.....	316
6.3.6 Manufacturing Process Selection	316
6.3.7 Definition of Input Properties	316
6.4 VERIFICATION BY ANALYSIS FOR MATERIAL AND COMPONENT	316

CMH-17-5A
Volume 5, Foreword / Table of Contents

6.4.1 Global FEM, local micromechanical models	316
6.4.2 Static, Buckling, and Vibration Analyses	316
6.4.3 Life Prediction or Use of End of Life Properties	316
6.4.4 Impact of environment on structural performance and life	316
6.4.5 Failure Modes & Effects Analysis	317
6.4.6 Impact - Durability and Damage Tolerance	317
6.4.7 Thermal mechanical coupling models	317
6.4.8 Oxidation & mechanical coupling models.....	317
6.4.9 Linear vs Non-linear (damage) analysis.....	318
6.4.10 Deterministic vs stochastic methods	318
6.5 VERIFICATION BY TEST	318
6.5.1 Material qualification and allowables (coupon/subelement test).....	318
6.5.2 Critical design feature (element test).....	318
6.5.3 Critical structure (subcomponent test).....	318
6.5.4 Full-scale structure validation (component test).....	318
7 MAINTAINABILITY AND SUPPORTABILITY.....	320
7.1 INSPECTION ABILITY.....	320
7.2 DAMAGE AND DAMAGE TOLERANCE	320
7.3 REPAIR	320
7.4 LIFE LIMITATIONS AND PLACARDS	320
7.5 SUBSTANTIATION PACKAGE FOR CERTIFICATION	320
PART C. TESTING	322
8 THERMO-MECHANICAL-PHYSICAL TEST METHODS - OVERVIEW	322
8.1 INTRODUCTION.....	322
8.1.1 Building block approach	322
8.1.2 Test level and data uses	322
8.1.2.1 Structural complexity levels	323
8.1.2.2 Data application categories.....	324
8.1.2.3 Screening tests	324
8.1.2.3.1 Material qualification tests	324
8.1.2.3.2 Acceptance tests	324
8.1.2.3.3 Equivalence tests	325
8.2 TEST PROGRAM PLANNING	325
8.2.1 Overview.....	325
8.2.2 Baseline and alternate approaches for statistically-based properties	325
8.2.3 Issues of data equivalence	326
8.2.4 Test method selection	326
8.2.5 Population sampling and sizing	326
8.2.6 Material and processing variation.....	326
8.2.7 Material operating limit	326
8.2.8 Non ambient testing.....	326
8.2.9 Data normalization.....	326
8.2.10 Data documentation	326
8.2.11 Application specific testing needs	326
8.3 RECOMMENDED TEST MATRICES.....	326
8.3.1 Material screening	326
8.3.2 Material qualification.....	327
8.3.3 Material acceptance test matrices.....	327
8.3.4 Alternate material equivalence test matrices.....	327
8.3.5 Generic material/structural element test matrices.....	328

CMH-17-5A
Volume 5, Foreword / Table of Contents

8.3.6 Alternate approaches to basis values.....	328
8.3.7 Data substantiation for use of CMH-17 basis values	328
8.4 DATA REDUCTION AND DOCUMENTATION	329
8.4.1 Introduction	329
8.4.2 Layer properties from composites	329
8.4.3 Data normalization.....	329
8.4.3.1.1 Normalization theory.....	329
8.4.3.2 Normalization methodology	329
8.4.3.3 Practical application of normalization theory	331
8.4.4 Data documentation requirements	331
9 MATERIAL TESTING & CHARACTERIZATION FOR SUBMISSION OF DATA TO CMH-17	332
9.1 INTRODUCTION.....	332
9.2 MATERIAL AND PROCESS SPECIFICATION REQUIREMENTS.....	332
9.3 DATA SAMPLING REQUIREMENTS	332
9.4 TEST METHOD REQUIREMENTS	332
9.4.1 Thermal.....	332
9.4.1.1 Conductivity	332
9.4.1.1.1 Bulk CMC	332
9.4.1.1.2 Matrix	332
9.4.1.1.3 Fiber.....	332
9.4.1.1.4 Interphase.....	332
9.4.1.1.5 Overcoat	332
9.4.1.1.6 Diffusivity	333
9.4.1.1.7 Bulk CMC	333
9.4.1.1.8 Matrix	333
9.4.1.1.9 Fiber.....	333
9.4.1.1.10 Interphase.....	333
9.4.1.1.11 Overcoat	333
9.4.1.1.12 Expansion.....	333
9.4.1.1.13 Bulk CMC	333
9.4.1.1.14 Matrix	336
9.4.1.1.15 Fiber	336
9.4.1.1.16 Interphase.....	336
9.4.1.1.17 Overcoat	336
9.4.1.2 Specific heat	336
9.4.1.2.1 Bulk CMC	336
9.4.1.2.2 Matrix	336
9.4.1.2.3 Fiber.....	336
9.4.1.2.4 Interphase.....	336
9.4.1.2.5 Overcoat	336
9.4.1.3 Thermal shock.....	336
9.4.1.3.1 Bulk CMC	336
9.4.1.3.2 Matrix	336
9.4.1.3.3 Fiber.....	339
9.4.1.3.4 Interphase.....	339
9.4.1.3.5 Overcoat	339
9.4.1.4 Thermal fatigue	339
9.4.1.4.1 Bulk CMC	339
9.4.1.4.2 Matrix	339
9.4.1.4.3 Fiber.....	339
9.4.1.4.4 Interphase.....	339
9.4.1.4.5 Overcoat	339
9.4.2 Mechanical.....	339
9.4.2.1 Tension.....	339

CMH-17-5A
Volume 5, Foreword / Table of Contents

9.4.2.1.1 Bulk CMC	339
9.4.2.1.1.1 In-plane monotonic tensile strength (ambient temperature).....	339
9.4.2.1.1.2 In-plane monotonic tensile strength (elevated temperature).....	340
9.4.2.1.1.3 Trans-thickness monotonic tensile strength (ambient temperature).....	340
9.4.2.1.1.4 Trans-thickness monotonic tensile strength (elevated temperature).....	340
9.4.2.1.1.5 Cyclic fatigue (ambient temperature).....	340
9.4.2.1.1.6 Cyclic fatigue (elevated temperature).....	344
9.4.2.1.1.7 Creep	344
9.4.2.1.2 Matrix.....	344
9.4.2.1.3 Fiber.....	344
9.4.2.1.3.1 Monotonic tensile strength (ambient temperature).....	344
9.4.2.1.3.2 Monotonic tensile strength (elevated temperature).....	347
9.4.2.1.4 Interphase.....	347
9.4.2.1.5 Overcoat	347
9.4.2.2 Compression.....	347
9.4.2.2.1 Bulk CMC	347
9.4.2.2.2 In-plane monotonic compressive strength (ambient temperature).....	347
9.4.2.2.3 Matrix.....	349
9.4.2.2.4 Fiber.....	349
9.4.2.2.5 Interphase.....	349
9.4.2.2.6 Overcoat	349
9.4.2.3 Shear.....	349
9.4.2.3.1 Bulk CMC	349
9.4.2.3.1.1 In-plane monotonic shear strength (ambient temperature).....	349
9.4.2.3.1.2 In-plane monotonic shear strength (elevated temperature).....	351
9.4.2.3.1.3 Interlaminar monotonic shear strength (ambient temperature).....	351
9.4.2.3.1.4 Interlaminar monotonic shear strength (elevated temperature).....	353
9.4.2.3.2 Matrix.....	353
9.4.2.3.3 Fiber.....	353
9.4.2.3.4 Interphase.....	353
9.4.2.3.5 Overcoat	353
9.4.2.4 Flexure	353
9.4.2.4.1 Bulk CMC	353
9.4.2.4.1.1 Monotonic flexural strength (ambient temperature).....	353
9.4.2.4.1.2 Monotonic flexural strength (elevated temperature).....	353
9.4.2.4.1.3 Monotonic shear strength (ambient temperature).....	358
9.4.2.4.2 Matrix.....	358
9.4.2.4.3 Fiber.....	358
9.4.2.4.4 Interphase.....	358
9.4.2.4.5 Overcoat	358
9.4.2.5 Fracture.....	360
9.4.2.5.1 Bulk CMC	360
9.4.2.5.2 Matrix.....	360
9.4.2.5.3 CMC fiber	360
9.4.2.5.4 CMC interphase.....	360
9.4.2.5.5 CMC overcoats.....	360

CMH-17-5A
Volume 5, Foreword / Table of Contents

9.4.3 Physical	360
9.4.3.1 Density	360
9.4.3.1.1 Bulk CMC	360
9.4.3.1.2 Matrix	362
9.4.3.1.3 Fiber.....	362
9.4.3.1.4 Interphase.....	362
9.4.3.1.5 Overcoat	362
9.4.3.2 Electrical.....	362
9.4.3.2.1 Bulk CMC	362
9.4.3.2.2 Matrix	362
9.4.3.2.3 Fiber.....	362
9.4.3.2.4 Interphase.....	362
9.4.3.2.5 Overcoat	362
9.4.3.3 Elastic constants	364
9.4.3.3.1 Bulk CMC	364
9.4.3.3.2 Matrix	364
9.4.3.3.3 Fiber.....	364
9.4.3.3.4 Interphase.....	364
9.4.3.3.5 Overcoat	364
9.4.3.4 Volume fraction	364
9.4.3.4.1 Bulk CMC	364
9.4.3.5 Dimensions	366
9.4.3.5.1 Matrix (grain size).....	366
9.4.3.5.2 Fiber (diameter).....	366
9.4.4 Chemical Properties	366
9.4.5 Electrical Properties.....	366
9.4.6 Environmental Testing	366
10 EVALUATION OF REINFORCEMENTS	368
10.1 INTRODUCTION.....	368
10.2 MECHANICAL PROPERTIES	368
10.2.1 Elastic (Poisson's Ratio, modulus)	368
10.2.2 Strength (FT, RT).....	368
10.2.3 Creep/creep rupture	368
10.2.4 Fatigue.....	368
10.3 THERMAL PROPERTIES	368
10.3.1 Expansion	368
10.3.2 Conductivity	368
10.3.3 Environmental (corrosion, erosion, wear, etc.)	368
10.3.4 Oxidation.....	368
11 EVALUATION OF MATRIX MATERIALS	368
11.1 INTRODUCTION.....	368
11.2 MECHANICAL PROPERTIES.....	369
11.2.1 Elastic (Poisson's Ratio, modulus)	369
11.2.2 Strength (HT, RT).....	369
11.2.3 Creep/creep rupture.....	369
11.2.4 Fatigue	369
11.3 THERMAL PROPERTIES	369
11.3.1 Expansion	369
11.3.2 Conductivity	369
11.3.3 Environmental (corrosion, erosion, wear, etc.)	369
11.3.4 Oxidation.....	369
11.3.5 Other physical (powder or preform char.)	369

12 EVALUATION OF INTERFACE MATERIAL	369
13 EVALUATION OF COMPOSITES	370
13.1 DENSITY.....	370
13.1.1 Applicability.....	370
13.1.2 Test Methods.....	370
13.1.3 Considerations for Density Testing CMCs	372
13.1.3.1 Test Specimen(s) or Components Geometry.....	372
13.1.3.2 Material Condition	373
13.1.3.3 Gripping.....	373
13.1.3.4 Environment Liquid.....	373
13.1.3.5 Material Sample Size	373
13.1.3.6 Operator variability	373
13.1.4 Analysis.....	373
13.1.5 Data Reporting.....	374
13.2 FIBER VOLUME FRACTION.....	374
13.3 CTE	374
13.4 DIFFUSIVITY	374
13.5 SPECIFIC HEAT	374
13.6 TENSILE TESTING.....	374
13.6.1 Applicability.....	374
13.6.2 Test Methods	374
13.6.3 Considerations for In-Plane Tension Testing of CMCs	375
13.6.3.1 Specimen Size & Geometry.....	375
13.6.4 Specimen Preparation	375
13.6.4.1 Use of Tabs Adhesive/Bonding Materials	376
13.6.4.2 Coated Materials	376
13.6.4.3 Alignment	376
13.6.5 Environment	376
13.6.6 Test Sample Size	376
13.7 COMPRESSION TESTING.....	376
13.8 FLEXURE.....	376
13.9 SHEAR.....	376
13.9.1 Applicability.....	376
13.9.2 Test Methods	377
13.9.3 Considerations for Shear Testing	378
13.9.3.1 Double Notched Compression (ASTM C1292 / C1425 / D3846)	378
13.9.3.2 Short Beam Shear (ASTM D2344)	379
13.9.3.3 In-Plane Shear (ASTM D3518).....	380
13.9.3.4 V Notched Shear (Beam ASTM D5379, Rail ASTM 7078).....	380
13.9.4 Specimen Preparation	381
13.9.5 Environment	382
13.9.6 Test Sample Size	382
13.10 INTERLAMINAR TENSION	382
13.11 NOTCHED TESTING	382
13.11.1 Notched Test Methods	382
13.11.2 Considerations for Notch Testing of CMCs.....	382
13.11.2.1 Environments and Life Testing	382
13.11.2.2 Notch and Hole Size Effects	383
13.11.2.3 Notch & Notch Tip Geometry	383
13.12 INTERLAMINAR FRACTURE TOUGHNESS.....	383
13.13 CRACK GROWTH	383
13.14 CREEP TESTING	383
13.15 FATIGUE TESTING	383

CMH-17-5A
Volume 5, Foreword / Table of Contents

13.16 TMF – THERMO-MECHANICAL FATIGUE	383
13.17 WEAR TESTING	383
13.18 BEARING TESTING	383
13.19 BIAXIAL TESTING	384
14 SUBCOMPONENT TESTING – OVERVIEW OF PROBLEM.....	386
14.1 INTRODUCTION.....	386
14.2 JOINT TESTING	386
14.2.1 Definitions	386
14.2.2 Failure modes	386
14.2.3 Thermal effects	386
14.2.4 Joint configurations.....	386
14.2.5 Design requirements	386
14.2.6 Material bearing strength.....	386
14.2.7 Open-hole tension/compression strength.....	386
14.2.8 Thermal-mechanical fatigue strength	386
14.2.9 Creep and stress rupture.....	386
14.2.10 Fastener qualification tests.....	386
14.3 TUBES	387
15 MACHINING & GRINDING	387
15.1 INTRODUCTION.....	387
15.2 MACHINING CONSIDERATIONS	387
15.3 TOOLING REQUIREMENTS	387
15.4 SPECIMEN PREPARATION	387
PART D. DATA REQUIREMENTS AND DATA SETS	389
16 DATA SUBMISSION, FORMAT AND REQUIREMENTS.....	389
16.1 INTRODUCTION.....	389
16.2 DATA SUBMISSION REQUIREMENTS	391
16.2.1 Material and process specification requirements	391
16.2.2 Sampling requirements.....	391
16.2.2.1 Additional requirements for The Fully Approved data class.....	391
16.2.2.2 Data pooling	391
16.2.3 Test method requirements	392
16.2.4 Data documentation requirements	392
16.3 FORMAT AND UNITS	396
16.4 DESIGN PROPERTIES	396
17 STATISTICAL METHODS	397
17.1 INTRODUCTION.....	397
17.2 BACKGROUND	397
17.2.1 Statistically-based design allowables	397
17.2.2 Basis values for unstructured data	397
17.2.3 Basis values in the presence of batch-to-batch variability (structured data)	398
17.2.4 Computer Software.....	398
17.3 CALCULATION OF STATISTICALLY-BASED MATERIAL PROPERTIES	398
17.3.1 Guide to computational procedures for data from multiple batches and environments	398
17.3.2 Guide to computational procedures using the Single-Point method	401

CMH-17-5A
Volume 5, Foreword / Table of Contents

17.3.3 Material property variability over long periods of time	403
17.4 STATISTICAL METHODS FOR MATERIAL EQUIVALENCE AND MATERIAL ACCEPTANCE	403
17.4.1 Tests for determining equivalency between an existing database and a new data set for the same material	403
17.4.2 Statistical procedures for process control	405
17.4.2.1 Basics of control charts	406
17.4.2.1.1 Purpose of control charts	406
17.4.2.1.2 Two charts are better than one	406
17.4.2.1.3 Types of control charts	407
17.4.2.1.4 Rules for flagging results as being 'out-of-control'	409
18 CMC PROPERTY DATA.....	413
18.1 INTRODUCTION.....	413
18.1.1 Organization of data in the handbook	413
18.1.2 Presentation of data	413
18.1.2.1 Properties and definitions	413
18.1.2.1.1 Sign convention	413
18.1.2.2 Table formats.....	413
18.2 CMC SYSTEMS – PROPERTY DATA.....	424
18.3 CMC SYSTEMS - LEGACY DATA.....	424
18.3.1 9/99 EPM SiC/SiC	425
18.3.2 Enhanced SiC/SiC	430
18.3.3 Carbon/SiC	436
18.3.4 Hi-Nicalon/Mi SiC	443
18.3.5 AS-N720-1	447
18.3.6 Sylramic S-200	453
APPENDIX A. DERIVATION OF THE RESIDUAL STRENGTH REDUCTION EXPRESSIONS FOR LCF AND RUPTURE LOADINGS	460

Structural Sandwich Composites

CMH-17

COMPOSITE MATERIALS HANDBOOK



WICHITA STATE
UNIVERSITY
NATIONAL INSTITUTE
FOR AVIATION RESEARCH



**NOT MEASUREMENT
SENSITIVE**

CMH-17-6
Volume 6 of 6
July 2013

COMPOSITE MATERIALS HANDBOOK

VOLUME 6. STRUCTURAL SANDWICH COMPOSITES



Copyright 2013 - Composite Materials Handbook – 17 (CMH-17). All rights reserved. Unauthorized duplication or distribution may violate the Copyright Laws of the United States and of other jurisdictions.

Published by SAE International on behalf of CMH-17,
a division of Wichita State University.

FOREWORD

The Composite Materials Handbook, CMH-17, provides information and guidance necessary to design and fabricate structural components from composite materials. Its primary purposes are a) the standardization of engineering data development methodologies related to testing, data reduction, and data reporting of property data for current and emerging composite materials, b) guidance on material and process specifications and procedures for utilization of the material data presented in the handbook, and c) methodologies for the design, analysis, certification, manufacture, and field support of composite structures. In support of these objectives, the handbook includes composite materials properties that meet specific data requirements. The Handbook therefore constitutes an overview of the field of composites technology and engineering, an area that is advancing and changing rapidly. As a result, the document will be continually revised as sections are added or modified to reflect advances in the state-of-the-art.

CMH-17 Mission

The Composite Materials Handbook organization creates, publishes and maintains proven, reliable engineering information and standards, subjected to thorough technical review, to support the development and use of composite materials and structures.

CMH-17 Vision

The Composite Materials Handbook will be the authoritative worldwide focal point for technical information on composite materials and structures.

Goals and Objectives to Support CMH-17 Mission

- To periodically meet with experts from the field to discuss critical technical issues for composite structural applications, with an emphasis on increasing overall product efficiency, quality and safety.
- To provide comprehensive, practical engineering guidance that has proven reliable for the design, fabrication, characterization, test and maintenance of composite materials and structures.
- To provide reliable data, linked to control of processes and raw materials, thereby being a comprehensive source of material property basis values and design information that can be shared within the industry.
- To provide a resource for composite material and structure education with examples, applications and references to supporting engineering work.
- To establish guidelines for use of information in the Handbook, identifying the limitations of the data and methods.
- To provide guidance on references to proven standards and engineering practices.
- To provide for periodic updates to maintain the all-inclusive nature of the information.
- To provide information in formats best-suited for user needs.
- To serve the needs of the international composites community through meetings and dialogue between member industries, which use teamwork and the diverse member engineering skills to provide information for the handbook.

Notes

1. Every effort has been made to reflect the latest information on polymer (organic), metal, and ceramic composites. The handbook is continually reviewed and revised to ensure it is complete and current.
2. CMH-17 provides guidelines and material properties for polymer (organic), metal, and ceramic matrix composite materials. The first three volumes of this handbook currently focus on, but are not limited to, polymeric composites intended for aircraft and aerospace vehicles. Metal matrix composites (MMC), ceramic matrix composites (CMC) including carbon-carbon composites (C-C), and sandwich composites are covered in Volumes 4, 5, and 6, respectively.
3. The information contained in this handbook was obtained from materials producers, industry companies and experts, reports on Government sponsored research, the open literature, and by contract with research laboratories and those who participate in the CMH-17 coordination activity. The information in this handbook has undergone vigorous technical review and was subject to membership vote.
4. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: CMH-17 Secretariat, Materials Sciences Corporation, 135 Rock Road, Horsham, PA 19044, by letter or email, handbook@materials-sciences.com.

ACKNOWLEDGEMENT

Volunteer committee members from government, industry, and academia develop, coordinate and review all the information provided in this handbook. The time and effort of the volunteers and the support of their respective departments, companies, and universities make it possible to insure the handbook reflects completeness, accuracy, and state-of-the-art composite technology.

Support necessary for the development and maintenance of the Composite Materials Handbook (CMH-17) are provided by the handbook Secretariat, Materials Sciences Corporation. The primary source of funding for the current Secretariat contract is the Federal Aviation Administration.

TABLE OF CONTENTS

	Page
FOREWORD.....	ii
CHAPTER 1 GENERAL INFORMATION	1
1.1 INTRODUCTION TO THE HANDBOOK.....	1
1.2 OVERVIEW OF HANDBOOK CONTENT.....	1
1.3 INTRODUCTION.....	2
1.4 NOMENCLATURE AND DEFINITIONS.....	3
1.4.1 Loads, geometry, and material properties.....	3
1.4.1.1 Subscripts	7
1.4.1.2 Superscripts.....	8
1.4.1.3 Assumptions and definitions.....	8
1.4.2 System of units.....	9
REFERENCES	10
CHAPTER 2 GUIDELINES FOR PROPERTY TESTING	1
2.1 INTRODUCTION.....	1
2.2 DATA REDUCTION AND PRESENTATION.....	1
2.3 EVALUATION OF CORE MATERIALS	1
2.3.1 Introduction	1
2.3.2 Mechanical properties.....	2
2.3.3 Environmental effects.....	2
2.3.4 Test methods.....	5
2.4 EVALUATION OF CORE-TO-FACE SHEET BONDS.....	6
2.4.1 Introduction	6
2.4.2 Mechanical properties.....	6
2.4.3 Environmental effects.....	6
2.4.4 Test Methods.....	6
2.5 EVALUATION OF FACE SHEET PROPERTIES	7
2.5.1 Introduction	7
2.5.2 Mechanical properties.....	7
2.5.3 Environmental effects.....	8
2.5.4 Test methods.....	8
2.6 EVALUATION OF SANDWICH PANELS	8
2.6.1 Introduction	8
2.6.2 Mechanical properties.....	9
2.6.3 Environmental effects.....	9
2.6.4 Damage resistance	9
2.6.5 Damage tolerance.....	10
2.6.6 Repair.....	10
2.6.7 Test methods.....	10
2.7 EVALUATION OF INSERTS AND FASTENERS	11
2.7.1 Introduction	11
2.7.2 Environmental effects.....	11
2.7.3 Test methods.....	11
2.7.4 Mechanical properties.....	11
2.8 EVALUATION OF OTHER FEATURES	14
2.8.1 Introduction	14
2.8.2 Mechanical properties.....	14
2.8.3 Environmental effects.....	14

2.8.4	Test methods	14
REFERENCES	.....	16
CHAPTER 3	MATERIAL DATA	1
3.1	CORES	1
3.1.1	Description of cores	1
3.1.2	Core specifications	1
3.1.3	Honeycomb Cores	2
3.1.4	Cross-banded core.....	5
3.1.5	Corrugated core	6
3.1.6	Waffle-type core	6
3.1.7	Foam cores	6
3.1.8	Wood cores	7
3.1.9	Core properties	8
3.1.9.1	Estimation of core properties	16
3.2	FACE SHEETS	17
3.2.1	Description of face sheets.....	17
3.2.1.1	Adhesively-bonded pre-fabricated face sheets	17
3.2.1.2	Co-cured or co-bonded face sheets with adhesive	17
3.2.1.3	Self-adhesive face sheets	18
3.2.2	Face sheet properties	18
3.3	ADHESIVES.....	18
3.3.1	Description of adhesives	19
3.3.2	Adhesive specifications.....	19
3.3.3	Adhesive forms/types and uses	20
3.3.3.1	Resins from self-adhesive face sheets.....	20
3.3.3.2	Film adhesives.....	20
3.3.3.3	Paste adhesives	20
3.3.3.4	Liquid resins.....	21
3.3.3.5	Foaming adhesives	21
3.3.4	Adhesive chemistries	21
3.3.4.1	Epoxy	21
3.3.4.2	Bismaleimide	21
3.3.4.3	Phenols	22
3.3.4.4	Polyester	22
3.3.4.5	Polyimide	22
3.3.5	Adhesive properties	23
REFERENCES	.....	24
CHAPTER 4	DESIGN AND ANALYSIS OF SANDWICH STRUCTURES	1
4.1	INTRODUCTION.....	1
4.2	DESIGN AND CERTIFICATION.....	2
4.2.1	Basic design principles	2
4.2.2	Design process	3
4.2.3	Aircraft damage tolerance	4
4.3	CERTIFICATION	8
4.3.1	Introduction to certification issues.....	8
4.3.2	Approach to certification testing.....	9
4.3.3	Analysis validation.....	9
4.3.4	Conformity oversight	9
4.3.5	Nondestructive testing (NDT).....	10
4.3.6	Documentation requirements.....	10
4.3.7	Continued airworthiness	10
4.4	SANDWICH PANEL FAILURE MODES.....	10

4.5	STIFFNESS AND INTERNAL LOADS	13
4.5.1	Beam stiffness analysis.....	13
4.5.2	Plate stiffness analysis.....	16
4.5.3	Combined transverse and in-plane loadings	18
4.5.4	Face sheet internal loads.....	18
4.6	LOCAL STRENGTH ANALYSIS METHODS	19
4.6.1	Face sheet failure.....	19
4.6.2	Core shear	20
4.6.3	Flatwise tension and compression.....	22
4.6.4	Flexural core crushing.....	24
4.6.5	Intracell buckling (dimpling)	24
4.6.5.1	Sandwich having cellular (honeycomb) core.....	25
4.6.5.2	Sandwich having corrugated core	26
4.6.5.3	Shear intracell buckling	40
4.6.5.4	Combined compression and shear intracell buckling	40
4.6.6	Face sheet wrinkling	40
4.6.6.1	Wrinkling of sandwich face sheets under edgewise load	40
4.6.6.2	Sandwich with core supporting face sheets continuously	41
4.6.6.3	Sandwich with honeycomb core	44
4.6.6.4	Shear face sheet wrinkling	45
4.6.6.5	Face sheet wrinkling - combined loads	45
4.6.6.6	Face sheet wrinkling - curved panels	46
4.6.7	Core shear crimping.....	49
4.6.8	Attachments and hard points	49
4.6.8.1	Design of flat circular sandwich panels loaded at an insert	49
4.7	FLAT PANEL INTERNAL LOADS AND STRESSES - PRESSURE LOADING	56
4.7.1	Design of flat rectangular sandwich panels under various normal loadings.....	56
4.7.2	Design of flat sandwich panels under uniformly distributed normal load.....	57
4.7.2.1	Determining face sheet thickness, core thickness, and core shear modulus for simply supported flat rectangular panels under uniform load.....	57
4.7.2.1.1	Use of design charts.....	68
4.7.2.1.2	Determining core shear stress	70
4.7.2.1.3	Checking procedures	74
4.7.2.2	Determining face sheet thickness, core thickness, and core shear modulus for simply supported flat circular panels under uniform load	86
4.7.2.2.1	Use of design charts.....	90
4.7.2.2.2	Determining core shear stress	91
4.7.2.2.3	Checking procedure	92
4.8	CURVED SANDWICH PANEL INTERNAL LOADS AND STRESSES	92
4.8.1	General equations and analysis method.....	92
4.9	FLAT PANEL STABILITY ANALYSIS METHODS	95
4.9.1	Buckling of flat rectangular sandwich columns.....	96
4.9.2	Design of flat rectangular sandwich panels under edgewise compression load	97
4.9.2.1	Determining face sheet thickness.....	97
4.9.2.2	Determining core thickness and core shear modulus	97
4.9.2.2.1	Determining minimum value of d	99
4.9.2.2.2	Determining actual value of d	101
4.9.2.3	Checking procedure for determining buckling stress, F_{cr}	108
4.9.3	Design of flat rectangular sandwich panels under edgewise shear load.....	129
4.9.3.1	Determining face sheet thickness.....	129
4.9.3.2	Determining core thickness and core shear modulus	129
4.9.3.2.1	Determining minimum value of d	131

4.9.3.2.2	Determining actual value of d	138
4.9.3.3	Checking procedure for determining buckling stress, F_{cr}	140
4.9.4	Design of sandwich strips under torsion load	149
4.9.4.1	Determining face sheet thickness, core thickness and core shear modulus for sandwich strips of trapezoidal and rectangular cross section	149
4.9.4.1.1	Determining minimum values of d and t	156
4.9.4.1.2	Determining actual values of d and t	156
4.9.4.1.3	Checking procedure for sandwich strips of trapezoidal and rectangular cross section	157
4.9.4.2	Determining face sheet thickness and core shear modulus for sandwich strips of triangular cross section.....	161
4.9.4.2.1	Determining minimum value of t	163
4.9.4.2.2	Determining actual value of t	166
4.9.4.2.3	Checking procedure for sandwich strips of triangular cross section	166
4.9.5	Design of flat rectangular sandwich panels under edgewise bending moment	168
4.9.5.1	Determining face sheet thickness.....	169
4.9.5.2	Determining core thickness and core shear modulus	171
4.9.5.2.1	Determining minimum value of d	172
4.9.5.2.2	Determining actual value of d	175
4.9.5.3	Checking procedure for determining buckling stress, F_{cr}	178
4.10	DESIGN OF FLAT RECTANGULAR SANDWICH PANELS UNDER COMBINED LOADS	183
4.10.1	Combined load buckling.....	183
4.10.1.1	Biaxial compression	183
4.10.1.2	Bending and compression	183
4.10.1.3	Compression and shear	183
4.10.1.4	Bending and shear	184
4.10.2	Combined in-plane and transverse loads	184
4.11	DESIGN OF SANDWICH CYLINDERS	184
4.11.1	Introduction	184
4.11.2	Sandwich cylinders under external radial pressure	184
4.11.2.1	Determining face sheet thickness, core thickness, and core shear modulus for sandwich cylinders under external radial pressure.....	185
4.11.2.2	Final design.....	188
4.11.3	Sandwich cylinders under torsion	193
4.11.3.1	Determining face sheet thickness for sandwich cylinders under torsion.....	193
4.11.3.2	Determining core thickness and core shear modulus for sandwich cylinders under torsion	194
4.11.3.3	Check to determine whether sideways buckling will occur.....	202
4.11.4	Sandwich cylinders under axial compression or bending	204
4.11.4.1	Determining face sheet thickness, core thickness, and core shear modulus	204
4.11.4.2	Checking procedure for determining cylinder wall buckling stress, F_{cr}	210
4.11.4.3	Check to determine whether column buckling will occur	210
4.11.5	Sandwich cylinders under combined loads.....	210
4.11.5.1	Axial compression and external lateral pressure	211
4.11.5.2	Axial compression and torsion.....	211
4.11.5.3	Torsion and lateral external or internal pressure.....	211
4.12	FINITE ELEMENT MODELING OF SANDWICH STRUCTURE	211
4.12.1	Introduction	211
4.12.2	Global models	212

4.12.3	Layered models.....	213
4.12.4	Solid models.....	214
4.12.5	Sandwich element models.....	215
4.13	OPTIMUM SANDWICH.....	215
4.13.1	Sandwich weight.....	215
4.13.2	Sandwich bending stiffness.....	216
4.13.3	Sandwich bending moment capacity.....	218
4.13.4	Sandwich panel buckling.....	220
	REFERENCES.....	222

CHAPTER 5 FABRICATION OF SANDWICH STRUCTURES (MATERIALS AND PROCESSES).... 1

5.1	INTRODUCTION.....	1
5.2	MATERIALS.....	3
5.2.1	Cores.....	3
5.2.2	Face sheets.....	4
5.2.3	Adhesives.....	6
5.2.4	Surfacing and sealing.....	7
5.3	PROCESSES.....	8
5.3.1	Core.....	8
5.3.1.1	Cleaning.....	8
5.3.1.2	Drying.....	9
5.3.1.3	Forming.....	11
5.3.1.4	Splicing.....	12
5.3.1.5	Potting.....	15
5.3.1.6	Septums.....	15
5.3.1.7	Core stabilization for machining.....	16
5.3.1.8	Machining.....	16
5.3.1.9	Tolerances.....	18
5.3.2	Face sheets - co-cure vs. pre-cure and resin pressure.....	18
5.3.3	Adhesive.....	21
5.3.3.1	Impression check.....	21
5.3.3.2	Bonding.....	23
5.3.3.3	Filleting.....	25
5.4	HONEYCOMB CORE CRUSH.....	28
5.4.1	Core crush during cure.....	28
5.4.2	Core crush - theoretical discussion.....	30
5.4.3	Core crush stabilization for cure.....	31
5.4.4	Core material characteristics and core crush.....	32
5.4.5	Prepreg and adhesive material characteristics and core crush.....	33
5.4.6	Cure cycles and core crush.....	34
5.5	QUALITY ISSUES INCLUDING NONDESTRUCTIVE EVALUATION (NDI).....	35
	REFERENCES.....	39

CHAPTER 6 QUALITY CONTROL..... 1

6.1	INTRODUCTION.....	1
6.2	MATERIAL PROCUREMENT QUALITY ASSURANCE PROCEDURES.....	1
6.2.1	Specifications and documentation.....	1
6.2.2	Receiving inspection.....	1
6.3	PART FABRICATION VERIFICATION.....	3
6.3.1	Process verification.....	3
6.3.2	Nondestructive inspection.....	3
6.3.3	Destructive tests.....	3
6.4	STATISTICAL PROCESS CONTROL.....	4
6.5	MANAGING CHANGE IN MATERIALS AND PROCESSES.....	4

REFERENCES 5

CHAPTER 7 SUPPORTABILITY 1

7.1 INTRODUCTION..... 1

7.2 DESIGN FOR SUPPORTABILITY 1

 7.2.1 In-service experience 1

 7.2.2 Inspectability 2

 7.2.3 Material selection 2

 7.2.4 Damage resistance 2

 7.2.5 Environmental compliance 3

 7.2.6 Reliability and maintainability 3

 7.2.7 Repairability 3

7.3 SUPPORT IMPLEMENTATION 5

 7.3.1 Part inspection 5

 7.3.2 Damage assessment 5

 7.3.3 Repair design criteria 6

 7.3.4 Repair of composite structures 8

 7.3.4.1 Damage removal and site preparation 8

 7.3.4.2 Bonded repairs 8

 7.3.4.3 Repair analysis 10

 7.3.4.4 Repair procedures 10

 7.3.4.5 Repair inspection 12

 7.3.4.6 Repair validation 12

7.4 LOGISTICS REQUIREMENTS 13

REFERENCES 15

Index..... 1