

CMH-17 Volume 5

Ceramic Matrix Composites

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Overview

- CMH-17 Mission and Vision
- Format / Content / History Summary
- Volume 5
- Working Groups

CMH-17 Mission

The Composite Materials Handbook (CMH) 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.

- Volunteer organization that creates, publishes, and maintains engineering information and standards to support the use of composite materials and structures
- Statistically analyzed composite data and guidance

Structure of Handbook

- Volume 1 Polymer Matrix Composites: *Guidelines for Characterization of Structural Materials*
- Volume 2 Polymer Matrix Composites: *Material Properties*
- Volume 3 Polymer Matrix Composites: *Materials Usage, Design and Analysis*
- Volume 4 Metal Matrix Composites
- Volume 5 Ceramic Matrix Composites
- Volume 6 Structural Sandwich Composites (Initial Release)

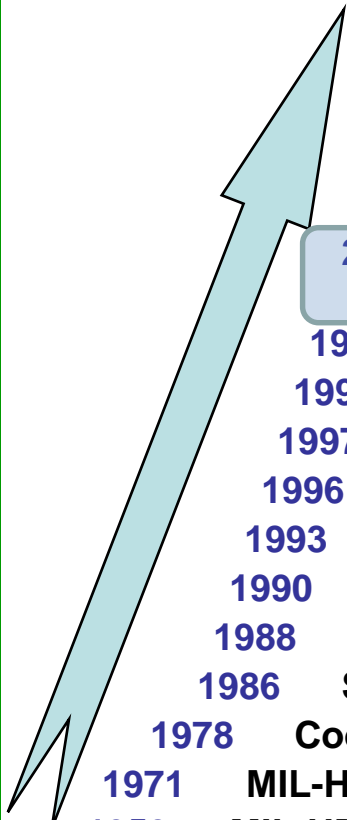
Volume 5 Goals

1. Document “best practices” for CMC design, processing, and operation.
2. Document test and analysis methods that can be used to show compliance to civil and military aviation regulations.
3. Provide information that will help simplify the process of assuring that CMCs are safe for use in aviation.
4. Provide characterization, property, and performance data of current and emerging ceramic matrix composite systems.

Handbook History

CMH-17

COMPOSITE MATERIALS HANDBOOK

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- 2017** Release of Vol. 5A – CMH-17 Handbook
 - 2013** Release of Vol. 6, 4B – CMH-17 Handbooks
 - 2012** Release of Volumes 1-3 Rev G – CMH-17 Handbooks
 - 2006** Transition from Army to FAA as Primary Sponsor
Established Roadmap to New Composite Materials Handbook “Release G”
 - 2004** Joint Meetings with CACRC, SAE-P17
 - 2002** MIL-HDBK-17 Vol. 1F, 2F, 3F, 4A, 5
Commercial Publication through ASTM
 - 1999** MIL-HDBK-17 Vol. 2E, Vol. 4
 - 1998** Joint Meetings with ASTM D-30
 - 1997** MIL-HDBK-17 Vol. 1E, 3E
 - 1996** CMC Coordination Group Formed
 - 1993** MMC Coordination Group Formed
 - 1990** First PMC Data Set Approved
 - 1988** MIL-HDBK-17B Vol. 1 Release
 - 1986** Secretariat Added
 - 1978** Coordination Group Formed
 - 1971** MIL-HDBK-17A Plastics for Aerospace Vehicles
 - 1959** MIL-HDBK-17 Plastics for Air Vehicles
 - 1943** ANC Bulletin 17 Plastics for Aircraft

Last CMC
handbook issued
~15 years ago

PMC: Polymer Matrix Composites
MMC: Metal Matrix Composites
CMC: Ceramic matrix Composites

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The Indispensable Reference Tool
Composite Materials Handbook (CMH-17)

Used by engineers worldwide to design and fabricate products made from composite materials.

Print eBook Multi-User Enterprise

Volume 4: Metal Matrix Composites
Just Released!
Includes properties on metal matrix composite material systems and provides selected guidance on material selection, material specification processing, characterization testing, data reduction, design, analysis, quality control, and repair.
Product Code: R-425; List Price \$109.95

Volume 6: Structural Sandwich Composites
Just Released!
This volume is an update to the cancelled Military Handbook 23, for use in the design of structural sandwich polymer composites, primarily for flight vehicles.
Product Code: R-427; List Price \$119.95

Polymer Matrix Composites

Volume 1: Guidelines for Characterization of Structural Materials
Provides guidelines for determining the properties of polymer matrix composite material systems and their constituents, as well as the properties of generic structural elements, test planning, test matrices, sampling, conditioning, test procedure selection, data reporting, data reduction, statistical analysis, and related topics.
Product Code: R-422; List Price \$219.95

Volume 2: Materials Properties
The second volume of this six-volume compendium contains statistically-based data for polymer matrix composites that meets specific CMH-17 population sampling and data documentation requirements, covering material systems of general interest.
Product Code: R-423; List Price \$279.95

Volume 3: Materials Usage, Design, and Analysis
The third volume of this six-volume compendium provides methodologies and lessons learned for the design, analysis, manufacture, and field support of fiber-reinforced, polymeric-matrix composite structures.
Product Code: R-424; List Price \$279.95

What is the Importance of CMH-17 Volume 5— Ceramic Matrix Composites ?

CMH-17
COMPOSITE MATERIALS HANDBOOK

Ceramic Matrix Composite (CMC) Components For Commercial Aircraft Require Certification

- CMC components have begun to enter service in commercial aircraft.
- A wide range of issues must be addressed prior to certification of this hardware.
- The FAA is working with the CMC community to identify and document best practices for means of compliance to the regulations



**Federal Aviation
Administration**

What is the Importance of CMH-17 Volume 5— Ceramic Matrix Composites? *(continued)*



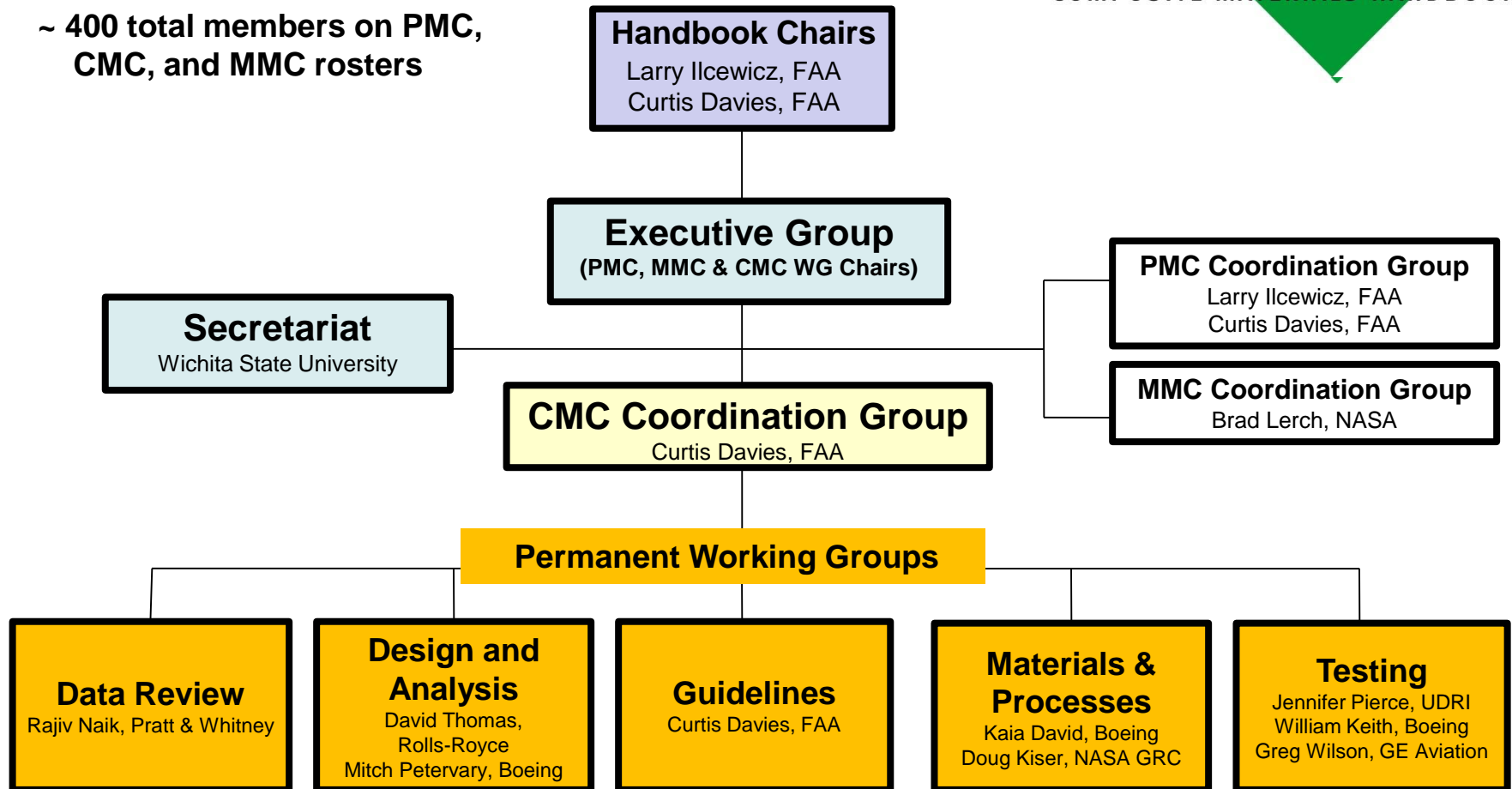
Ceramic Matrix Composite (CMC) Components For Commercial Aircraft Require Certification

- The Composite Materials Handbook-17, Volume 5 on ceramic matrix composites has just been revised to support certification of CMCs for hot structure and other elevated temperature applications.
- The handbook supports the development and use of CMCs through publishing and maintaining proven, reliable engineering information and standards that have been thoroughly reviewed.
- Volume 5 contains detailed sections describing:
 - CMC Materials / Processing
 - Design / Analysis Guidelines
 - Testing Procedures
 - Data Analysis and Acceptance

The CMH-17 Organization



~ 400 total members on PMC, CMC, and MMC rosters



Volume 5 Handbook Outline

- Handbook grouped into 4 sections – each linked to specific working groups
 - *Part A: Introduction and Guidelines*
 - Materials and Processes WG
 - *Part B: Design Supportability*
 - Design & Analysis WG
 - *Part C: Testing*
 - Testing WG
 - *Part D: Data Requirements and Data Sets*
 - Data Review WG

Linking CMH-17 to FAA Certification



Provide standardized data and information for acceptance by authorities by:

- Establishing Active CMC Working Groups
 - Meeting sessions for each WG
 - Regular WG Telecons
 - Continually review WG charters and make necessary changes/edits
 - Work on key tasks identified and review periodically
- Periodically holding coordination meetings to discuss critical issues
 - CLEEN consortium/Cocoa Beach meetings
 - Working group meetings in conjunction with other CMC events

Working Group Activities

- Materials and Processes
- Design and Analysis
- Testing
- Data Review

Goals:

- To provide information on the composition, fabrication, quality control, and characterization of CMC engineering materials and structures.
- To provide a comprehensive overview of ceramic matrix composite (CMC) technology, outlining the types of CMCs, commercial aircraft applications, benefits, methods of fabrication, quality control, and supportability.
- To define the essential elements of information on composition, structure, and processing of CMCs necessary to support design, selection, fabrication, certification, and utilization of CMC structures
- To specify the methods and procedures to be used in the characterization of ceramic matrix composites, their coatings, and their constituents. Efforts will be coordinated with the Testing Working Group.

New or Revised M&P Sections

CMH-17

COMPOSITE MATERIALS HANDBOOK

- CMC Systems: Processing, Properties & Applications
- Fiber / Reinforcement Types and Technology
- Interphase / Interface Technology and Approaches
- Fabrication and Forming of Fiber Architectures
- External Protective Coatings for Non-Oxide CMCs
- External Protective Coatings for Oxide CMCs
- Characterization Methods
- NDE Methods for CMCs
- Machining

- Quality Control of Production Materials and Processes

- Applications, Case Histories, and Lessons Learned

Chapter 3

Chapter 4

Chapter 5

New M&P Sections - examples

CMH-17-5A
Volume 5, Part A Introduction and Guidelines

3.1.2 CMC Systems, Processing Methods, and Properties

Several CMC systems have reached or are reaching the commercial stage of development in which processing and properties are defined, and they are available in commercial quantities. In addition, other CMC materials are currently being developed for future use. The different SiC/SiC CMC systems that are most relevant to aircraft turbine engines are shown in Figure 3.1.2 (Reference 3.1.2(a)). Oxide/Oxide CMCs are the other type of CMC system used in advanced aircraft engines. Each of these systems will be discussed in detail in subsequent subsections of this handbook. An overview of different SiC/SiC systems, with the exception of prepreg CMCs, can be found in the literature (for example, Reference 3.1.2(a)).

Processing of Different SiC/SiC CMC Systems of Interest for Turbine Engine Applications

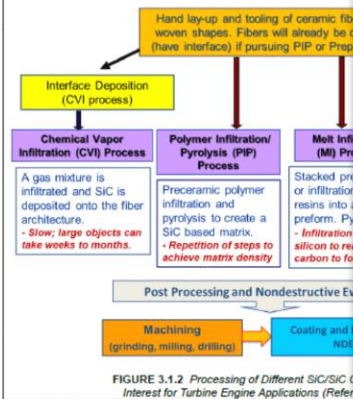


FIGURE 3.1.2 Processing of Different SiC/SiC CMC Systems of Interest for Turbine Engine Applications (Reference 3.1.2(a)).

U.S. companies currently fabricating CMCs are listed in Table 3.1.1 as providers of CMCs (materials suppliers), while others currently only sell CMCs. This situation will continue to evolve, as the CMC industry becomes more widely utilized. In addition, there are companies such as GE Aviation that are suppliers of materials that are used to make the matrix.

Volume 5, Part A Introduction and Guidelines

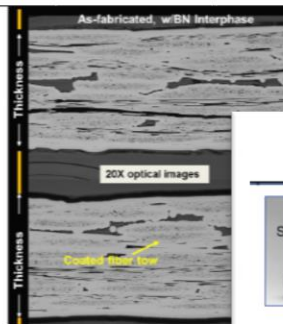


FIGURE 3.1.3.1.2(a) Polished cross section of 2D CVI (chemical vapor infiltration) with Sytramic™-BN SiC fabric (CMC manufactured by Rolls-Royce formerly Hyper-Therm High Temperature Composites). (Reference 3.1.3.1.2(a)).

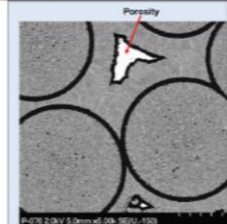


FIGURE 3.1.3.1.2(b) Polished cross section of 2D CVI (chemical vapor infiltration) with Sytramic™-BN SiC fabric (CMC manufactured by Rolls-Royce formerly Hyper-Therm High Temperature Composites). (Reference 3.1.3.1.2(b)).

CMH-17-5A
Volume 5, Part A Introduction and Guidelines

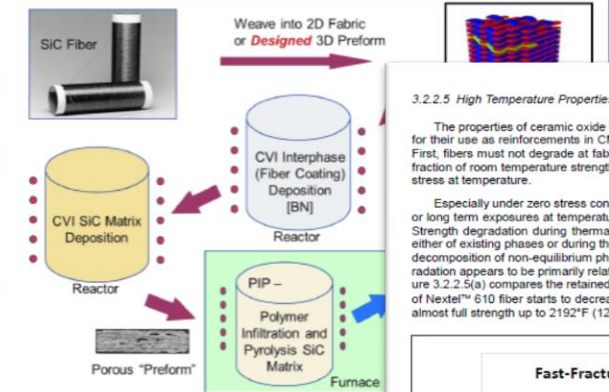


FIGURE 3.1.3.4.3 CVI/PIP Hybrid SiC/SiC Process Schematic (Reference 3.1.3.4.3).

1.4 Oxide/Oxide CMC Systems

1.4.1 Introduction/Applications

Oxide/Oxide composites have seen significant advancement in development and transition to industrial and aerospace applications. These materials (up to 2200°F (1200°C)), coupled with oxidative protective coatings, are used in a variety of applications. Examples of potential applications include turbine engine hot section components, exhaust structures, and thermal protection system (TPS) elements that are put into service in commercial engines. For example, GE Aviation's exhaust mixer, center body and core cowls of the Passport Engine are expected in production by 2018 (Reference 3.1.4.1(a)).

3.2.2.5 High Temperature Properties of Continuous Ceramic Oxide Fibers

The properties of ceramic oxide fibers at high temperature are a primary determinant of their suitability for their use as reinforcements in CMCs. Several distinct phenomena are important at high temperature. First, fibers must not degrade at fabrication and use temperatures. Second, fibers must maintain a large fraction of room temperature strength at high temperature. Third, fibers must not creep excessively under stress at temperature.

Especially under zero stress conditions, fibers should experience no or minimum strength loss for short or long term exposures at temperature (~2192°F (1200°C)), whether during composite fabrication or use. Strength degradation during thermal exposure is related to a number of factors, including grain growth, either of existing phases or during the crystallization of new phases, thermally-activated growth of flaws, or decomposition of non-equilibrium phases in the fiber. For polycrystalline Al₂O₃-based fibers, strength degradation appears to be primarily related to grain growth and defects associated with this grain growth. Figure 3.2.2.5(a) compares the retained strength after 1000 hr. aging in air for two Nextel fibers. The strength of Nextel™ 610 fiber starts to decrease after exposure at 2012°F (1100°C), whereas Nextel™ 720 retains almost full strength up to 2192°F (1200°C) (Reference 3.2.2.5(a)).

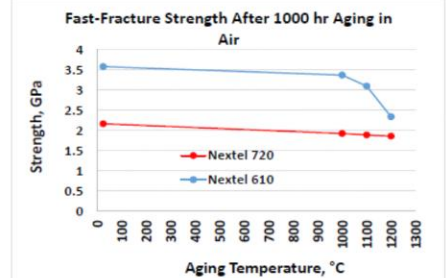


FIGURE 3.2.2.5(a) Strength after high temperature aging for Nextel 610™ and 720™ fibers (Reference 3.2.2.5(a)).

For strength at high temperature ("hot strength"), degradation mechanisms are different than in thermal aging tests. In these short-term tests, there is no time for grain growth to occur, so grain growth is not the cause of strength reduction. Instead, strength drops as stress-induced time-dependent or plastic deformation mechanisms start to occur, leading to crack or flaw growth and fiber necking. As an example, at 2192°F (1200°C), the stress-strain curve for Nextel 610™ becomes non-linear due to creep, with strain to failure significantly reduced.

Design and Analysis Working Group



Goals:

- To provide information on design and analysis methods and options, the level of substantiation required, and presentation formats required in validation and certification processes
- To ensure future relevancy of the handbook by maintaining an up to date survey of the current state of the art capabilities within the design, analysis and lifing communities for CMCs

Challenges:

- Creating a document that contains meaningful and valuable content for both industry and government entities while honoring the highly proprietary nature of corporate design practices

New Design & Analysis Sections

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COMPOSITE MATERIALS HANDBOOK

- Definition of Application & Design Requirements
- CMC Component Design and Analysis Considerations
- Verification by Analysis for Material and Component

Testing Working Group

Vision Statement:

- To be the primary and authoritative source for recommended/required methods for testing characterization of CMCs & their constituents

Goals:

- To identify appropriate existing consensus standard test methods (such as ASTM Standards) for CMCs and their constituent materials
- To assist in the identification/development of appropriate standard test methods for CMCs and their constituent materials, where no such standards exist

New Testing Sections

- Density
- Tensile Testing
- Shear Testing
- Notched Testing

New Testing Sections - examples

CMH17

COMPOSITE MATERIALS HANDBOOK

13.6 TENSILE TESTING

13.6.1 Applicability

Tensile properties are important to design as laminated ceramic matrix composites are prone to delamination cracking through the un-reinforced matrix, perpendicular to the plane of the fiber reinforcement. Of interest to designers are the strength, modulus, Poisson's ratio, and strain to failure of the composite.

13.6.2 Test Methods

There are several ASTM and other standards for the measurement of tensile properties of ceramic matrix or other composite materials. Those references are listed in Table 13.6.2.

TABLE 13.6.2 Test Methods

Method	Title
ASTM C1275	Monotonic Tensile Behavior-Reinforced Advanced Solid Rectangular Cross-sections at Ambient Temperature
ASTM C1359	Monotonic Tensile Behavior-Reinforced Advanced Solid Rectangular Cross-sections at Elevated Temperature
HSR-EPM -D-001-93	Monotonic Tensile Testing of Intermetallic Matrix and Matrix Materials
ASTM D3039	Tensile Properties of Polymer Matrix Composite Materials

CMH-17-5A
Volume 5, Part C Testing

13.9.2 Test Methods

There are several ASTM and other standards for the measurement of interlaminar shear properties of ceramic matrix or other composite materials. Those references identified are listed in Table 13.9.2.

TABLE 13.9.2 Applicable test methods for CMC flexure

Method	Title	Materials	Temp
ASTM C1292	Standard Test Method for Shear Strength of Continuous Fiber-Reinforced Advanced Ceramics at Ambient Temperatures ¹	CMC	RT
ASTM C1425	Interlaminar Shear Strength of 1-D and 2-D Continuous Fiber-Reinforced Advanced Ceramics at Elevated Temperatures	CMCs with oxide, SiC, glass (amorphous) matrices	ET
ASTM D3846	Standard Test Method for In-Plane Shear Strength of Reinforced Plastics	Plastics	RT/ET
ASTM D2344	Standard Test method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates	PMCs	RT/ET
ASTM D3518	Standard Test Method for In-Plane Shear Response of a Polymer Matrix Composite Materials by Tensile Test of a ±45° Laminate	PMC	RT/ET
ASTM D5379	Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method	PMCs	RT/ET
ASTM D7078	Standard Test Method for Shear Properties of Composite Materials by V-Notched Rail Shear Method	PMCs	RT/ET

13.11 NOTCHED TESTING

Notched testing of CMCs is often motivated by the desire to develop design strength values that address the presence of damage including manufacturing defects, impact damage, and structural penetrations. Using damaged based strengths can ensure robust designs.

13.11.1 Notched Test Methods

Currently, there are no test methods specifically written for testing CMCs with notches or damage. Yet, the methods written for PMCs can often be adapted for CMCs. Methods for PMCs include tests of laminates with holes and of laminates with damage, typically generated by controlled impacts. Table 13.11.1 provides a list of these test methods. They are frequently adapted for the notch testing of CMCs.

TABLE 13.11.1 - Test Methods for Notched and Damaged Composite Laminates

Method	Title
ASTM D5766	Open-Hole Tensile Strength of Polymer Matrix Composite Laminates
ASTM D6484	Open-Hole Compressive Strength of Polymer Matrix Composite Laminates
ASTM D6742	Filled-Hole Tension and Compression Testing of Polymer Matrix Composite Laminates
ASTM D7137	Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates

13.11.2 Considerations for Notch Testing of CMCs

13.11.2.1 Environments and Life Testing

CMCs are used in temperatures and environments much different than standard laboratory conditions. It is often challenging to replicate these environments during testing yet it is important that they are considered. Chemical and physical reactions at the notch tip can significantly affect the performance of CMCs particularly for repeated loading and long duration exposures. Thus, for CMCs that are sensitive to environmental degradation, e.g. non-oxide CMCs in hot oxidizing environments, investigators may need to test notched specimens in fatigue or for long durations in the appropriate environments to establish their service capability.

Data Review Working Group

Vision Statement:

- Formulate guidelines & requirements for submission (batch size, etc.), documentation, analysis, and review for all CMC data that are submitted for inclusion in the handbook.
- Review the data and the analysis of data sets that are submitted for inclusion in the handbook.
- Develop formats for presentation of data in the handbook and for its storage in electronic databases.
- Develop and document statistical methods for pooling and analysis of CMC data.

Key Issues:

- Export classification of data that is submitted to the handbook
- Storage and dissemination of ITAR data
- Appropriate electronic Database choice for data storage and dissemination (with export restricted access as needed)
- Sources of new CMC data

CMC Property Database

Currently not ITAR restricted

Composite Name	Composite Description	Producer
9/99 EPM SiC/SiC	Sylramic™/BN-Si/MI SiC	Ceramic Composite Products
Enhanced SiC/SiC	CG Nicalon™/Carbon/CVI SiC	
Carbon/SiC	T300/Carbon/CVI SiC	
Hi-Nicalon/MI SiC	Hi-Nicalon™/BN/MI SiC	
AS-N720-1	Nextel 720/alumino-silicate	COI Ceramics
Sylramic S-200	CG Nicalon™/BN/PIP Si ₃ N ₄ -SiC	

- New CMC data to be included in future revisions
- Currently working with organizations to obtain data

New Data Review Sections

- Data Submission Requirements
- Calculation of Statistically Based Material Properties
- Statistical Methods for Material Equivalence and Acceptance

New Data Review Sections - examples

CMH-17

COMPOSITE MATERIALS HANDBOOK

17.3.2 Guide to computational procedures using the Single-Point method

The single-point method depicted in Figure 17.3.2 is used when all or portions of the data for multiple batches and environments do not satisfy one or more of the following conditions: (i) at least 3 batches and at least 2 environmental conditions, (ii) the k-sample Anderson-Darling test, (iii) the k-sample Anderson-Darling test is not accepted for all environmental conditions, and (iv) the k-sample Anderson-Darling test is not satisfied. The single-point method also provides a procedure for the calculation of basis values. The procedure (Figure 17.3.2) is performed separately for each environmental condition across environments. The CMH-17 STATS software is associated with the single-point process.

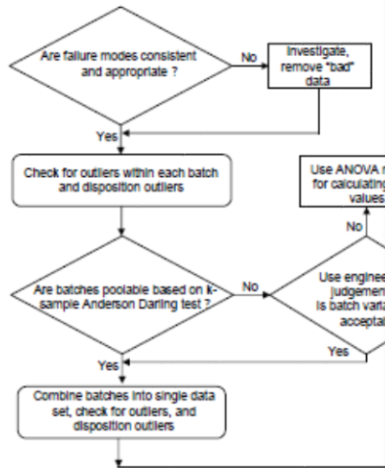


FIGURE 17.3.2 Flowchart for single-point procedure

CMH-17-5A
Volume 5, Part D Data Requirements and Data Sets

TABLE 18.1.3.2(a) Summary Table format, continued on next page.

X.X.X (Fiber) (Filament-Count)/(Interphase)/(Matrix) (Process Description)*

MATERIAL:	(Fiber) (Filament-Count)/(Interphase)/(Matrix) (Process Description)	Ⓢ
FIBER:	(Commercial Name) (Continuous/Discontinuous) (Diameter) (Fabrication Process Manufacturer) (Process)	INTERPHASE: (Commercial Name) MATRIX: (Commercial Name)
MANUFACTURER:	(Fabrication Process Manufacturer)	Ⓢ
PROCESS SEQUENCE:	(Process)	
PROCESSING:	(Type of Process); (Temperature); (Duration); (Pressure)	Source: (Data source)

(Warning)

Date of fiber manufacture	MM/YY	Date of test
Date of matrix manufacture	MM/YY	Date of data
Date of composite manufacture	MM/YY	Date of analysis

LAMINA PROPERTY SUMMARY

Temperature	(RT)			(coldest to hottest)
Environment				
Fiber %/o				(lowest to highest)
Tension, 1-axis				
Tension, 2-axis				
Tension, 3-axis				
Compression, 1-axis				
Compression, 2-axis				
Compression, 3-axis				
Shear, 12-plane				
Shear, 23-plane				
Shear, 31-plane				
(Additional type test/direction)				

Classes of approval at each type test/direction condition/fiber volume

Classes of data: F - Fully approved, I - Interim, S - Screening in order of increasing confidence. Failure/Proportional Limit/0.2-offset-strength.

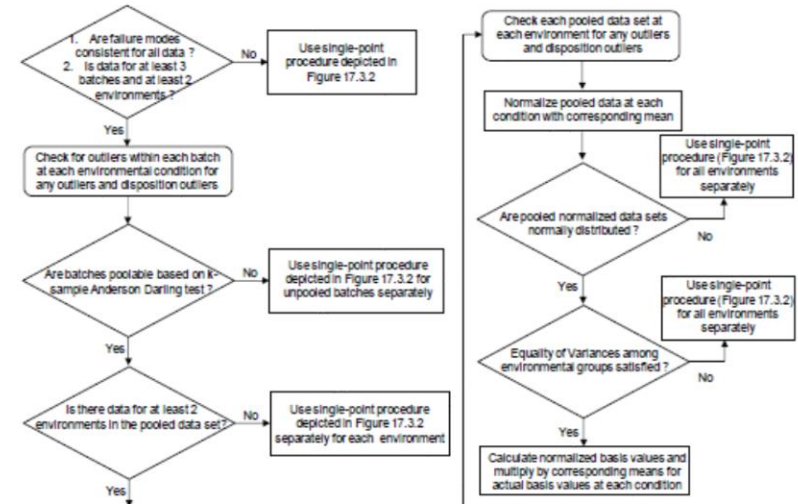


FIGURE 17.3.1 Flowchart for pooled data basis value calculation procedure

Summary

- The Composite Materials Handbook-17, Volume 5 on ceramic matrix composites has just been revised with significant new material useful as a guide for CMCs:
 - CMC Materials / Processing
 - Design / Analysis Guidelines
 - Testing Procedures
 - Data Analysis and Acceptance
- *Developed over a 5 year period with approximately 100 volunteers*
- WGs are currently seeking volunteers
- Input for future revisions
- **Publication – June 2017 through SAE International – VOLUME 5A**

Summary

Individuals interested in contributing to these groups should please forward their contact information to

[Rachael Andrulonis \(rachael@cmh17.org\)](mailto:rachael@cmh17.org)

and/or talk to any Working Group member

Annual Meeting @ USACA – January 2018
Monthly Teleconferences for Working Groups and Coordination