Considerations in the Qualification, Data Capture and Design Allowables Generation for CMC Materials

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Overview

- CMC Considerations
- Material Qualification
- Data Capture
- Design Allowables
CMC Considerations

Thermal Efficiency

Trend continues toward higher OPR cycles

Continued Drive for Higher Temperature Materials
CMC Considerations

Significant Industry Research & Investment in SiC/SiC

**Benefit**
- Higher T capability than superalloy (+300F)
- Lower density (1/3) than superalloy
- Applicable to static and rotating components
- Several % improvement in SFC

**P&W Development Activity**
- Nozzle components
- Turbine Blades & Vanes

**Challenges**
- Oxidation resistance
- CMAS resistant EBC
- Low ductility
- Product Cost
- Industrialization cost

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P&W Development Experience

Increasing Structural, Design and Manufacturing Capability

- 2005 D-Flaps & Seals Engine Test
- 2009 PW206 Combustor Engine Test
- 2011 Vane Demo
- 2013 CMC Blade PT6 Engine Test
- 2000 Nozzle
- 2005 FT8 Combustor
- 1998 Air Seal
- 1999 UEET Vane Rig Test

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CMC Considerations

Constituents

- Fibers – strength, modulus, damage tolerance
- Interface – strength and toughness
- Matrix – strength, porosity, thermal conductivity
CMC Considerations
Fiber Architecture

- Variability in fibers, interface, matrix, fiber architecture, and processing can significantly affect the performance of CMC materials.
CMC Commercial Aviation Application

Certification

- CMC components are being considered for insertion on commercial aircraft.
- A wide range of issues must be addressed prior to certification of this hardware.
- The FAA (Federal Aviation Administration) is working with the CMC Community to identify the tasks required to support these components and to establish a timeframe for certification.
CMC Composite Materials Handbook

CMH-17

• The Composite Materials Handbook, CMH-17 (formerly MIL-HDBK-17) supports the development and use of composites by publishing and maintaining proven, reliable engineering information and standards that have been thoroughly reviewed.

• CMH-17 is also responsible for establishing statistical procedures for composite design allowables and publishing statistically analyzed basis values for composite materials.

• FAA guidance relies heavily upon industry publications such as CMH-17

• CMH-17 Volume 5 (to be released this summer) is devoted to CMC materials and contains detailed sections describing:
  - CMC Materials / Processing
  - Design / Analysis Guidelines
  - Testing Procedures
  - Data Analysis and Acceptance
Material Qualification

Building Block Approach (BBA)

- The “building block approach” is often considered essential to the qualification/certification of composite structures
- Sensitivity of composites to out-of-plane loads
- Multiplicity of composite failure modes
- Lack of standard analytical methods
Material Qualification

Building Block Approach (BBA)

- Major purpose of this approach is to reduce program cost and risk while meeting technical, regulatory and customer requirements.
- Cost-efficiency is achieved by testing greater numbers of less-expensive coupon level tests.
- Each higher level involves fewer test articles than the one below.
- Provides a means to assessing technology risks early in the program.
- Also used to validate analysis methods at each level of the building-block.
Material Qualification

Steps in the BBA

1. Generate material basis values and preliminary design allowables.

2. Based on the design/analysis of the structure, select critical areas for subsequent test verification.

3. Determine the most strength-critical failure mode for each design feature.

4. Select the test environment that will produce the strength-critical failure mode.
Material Qualification

Steps in the BBA – cont.

6. Design and conduct increasingly more complicated tests that evaluate more complicated loading scenarios with the possibility of failure from several potential failure modes.

7. Design and conduct, as required, full-scale component static and fatigue testing for final validation of structural integrity.

8. Compare to analytical predictions and adjust analysis models as necessary at each step.
Material Qualification

Five Levels of Structural Complexity in the BBA

• **Constituent Testing** – properties of fibers, interphases, matrices, and overcoats. Key properties include density, strength, and/or stiffness.

• **Mini-Composite Testing** - properties of the fiber, interphase, and matrix in a single yarn “mini” composite. Key properties include matrix cracking, fiber debonding, environmental effects.

• **Bulk-Composite Testing** - response of the composite material in a given lay-up. Key properties include proportional limit, ultimate strength, and elastic constants.

• **Structural Element Testing** – response at discontinuities. Key properties include open hole tension/compression, notched tension/compression, joint shear/bearing and interlaminar response.

• **Structural Subcomponent (or higher) Testing** - behavior and failure mode of increasingly more complex structural elements.
Material Qualification

BBA Data Application Categories

Material property testing can also be grouped by data application into one or more of the following categories:

- **Screening** – initial evaluation of new material systems under worst case environmental and loading conditions

- **Qualification** – testing for key material properties to establish statistical material acceptance, equivalence, quality control, and design basis values

- **Acceptance** – verifying material consistency through periodic sampling of material product

- **Equivalence** – evaluation of minor constituent, constituent processing or fabrication processing changes for a qualified material system
# Material Qualification

## Material Screening Test Matrix – Strength Properties

<table>
<thead>
<tr>
<th>Test</th>
<th>Number of Test Specimens</th>
<th>Evaluation Emphasis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Room Temp. Ambient</td>
<td>High Temp Environment</td>
</tr>
<tr>
<td>Mini Composite:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tension</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Compression</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Shear</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Bulk Composite:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open Hole Compression</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Compression after Impact</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Notched Tension</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
## Material Qualification

Qualification Test Matrix – Mechanical Properties

<table>
<thead>
<tr>
<th>Mechanical Property</th>
<th>Number of Tests per Batch for each Test Condition</th>
<th>Number of Tests per Batch for each Test Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Room Temp. Ambient</td>
<td>High Temp Environment</td>
</tr>
<tr>
<td>In-plane Tension</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Trans-thickness Tension</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Compression</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>In-plane Shear</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Interlaminar Shear</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>
Material Qualification

Materials and Process Selection

• Need to look at both material and process together
• Material and process maturity
• Material allowables and process reproducibility
• Define material and process specifications
• Develop necessary inspection/QC tools/process
Database for Design Data
Design Data Capture per CMH-17

<table>
<thead>
<tr>
<th>Material identification - required for all composite materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>● material supplier identification</td>
</tr>
<tr>
<td>● material identification</td>
</tr>
<tr>
<td>● material class (e.g., CMC)</td>
</tr>
<tr>
<td>● material and data export classification (e.g., ITAR, EAR, ECCN, etc.)</td>
</tr>
<tr>
<td>+ material procurement specification</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Matrix material - required for all composite materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>● commercial designation and material specification</td>
</tr>
<tr>
<td>● manufacturer</td>
</tr>
<tr>
<td>● date of manufacture, earliest and latest</td>
</tr>
<tr>
<td>● lot number for each lot</td>
</tr>
<tr>
<td>● nominal density and test method</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>● commercial designation and material specification</td>
</tr>
<tr>
<td>● manufacturer</td>
</tr>
<tr>
<td>● date of manufacture, minimum and maximum</td>
</tr>
<tr>
<td>● lot number for each lot</td>
</tr>
<tr>
<td>● fiber surface treatment (Y/N)</td>
</tr>
<tr>
<td>● surface finish (sizing) identification and amount</td>
</tr>
<tr>
<td>● interphase coating type, thickness (and measurement method) and structure</td>
</tr>
<tr>
<td>● interphase coating method of manufacture</td>
</tr>
<tr>
<td>● density (average per lot) and test method</td>
</tr>
<tr>
<td>● nominal filament count</td>
</tr>
</tbody>
</table>
Database for Design Data

Design Data Capture per CMH-17

<table>
<thead>
<tr>
<th>Preform</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>● preform architecture</td>
<td></td>
</tr>
<tr>
<td>● preform identifier</td>
<td></td>
</tr>
<tr>
<td>● preform manufacturer</td>
<td></td>
</tr>
<tr>
<td>● preform method of manufacture</td>
<td></td>
</tr>
<tr>
<td>● number of preform layers</td>
<td></td>
</tr>
<tr>
<td>● interphase coating type and structure</td>
<td></td>
</tr>
<tr>
<td>● interphase coating method of manufacture</td>
<td></td>
</tr>
<tr>
<td>● total coating thickness</td>
<td></td>
</tr>
<tr>
<td>2-D Fabric</td>
<td></td>
</tr>
<tr>
<td>+ fabric manufacturer/weaver</td>
<td></td>
</tr>
<tr>
<td>● fabric family (weave pattern)</td>
<td></td>
</tr>
<tr>
<td>● fabric standard style number</td>
<td></td>
</tr>
<tr>
<td>● fabric sizing identification</td>
<td></td>
</tr>
<tr>
<td>● fabric sizing content</td>
<td></td>
</tr>
<tr>
<td>● fabric warp and fill tow count per inch</td>
<td></td>
</tr>
<tr>
<td>● fabric warp and fill filament count</td>
<td></td>
</tr>
<tr>
<td>● fiber areal weight per batch</td>
<td></td>
</tr>
<tr>
<td>● fabric fill fiber type (if different than warp)</td>
<td></td>
</tr>
</tbody>
</table>
3-D Woven Materials (including triaxial fabric)
- interlock description
- warp fiber filament count
- weft fiber filament count
- bias fiber filament count
- weaver yarn filament count
- percentage of warp yarn
- percentage of weft yarn
- percentage of bias yarn
- percentage of weaver yarn
- angle of bias yarn (positive with respect to axial yarn)
- through-thickness angle of weaver yarn
- warp end count
- weft end count
- bias yarn end count
- weaver yarn end count
Database for Design Data

Design Data Capture per CMH-17

<table>
<thead>
<tr>
<th>Process Description - appropriate group required for all composite materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>● development/production status and process specification</td>
</tr>
<tr>
<td>● date of manufacture</td>
</tr>
<tr>
<td>● composite/matrix fabrication type</td>
</tr>
<tr>
<td>● forming/shaping method</td>
</tr>
<tr>
<td>+ final machining condition</td>
</tr>
<tr>
<td>+ maximum fabrication temperature</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part Description - required for all composite materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>● form (panel, tube, etc.)</td>
</tr>
<tr>
<td>● ply count</td>
</tr>
<tr>
<td>● lay-up code</td>
</tr>
<tr>
<td>● nominal fiber volume and test method</td>
</tr>
<tr>
<td>+ matrix content (weight or volume), nominal and test method</td>
</tr>
<tr>
<td>● void content, nominal, by batch or part, and test method</td>
</tr>
<tr>
<td>● density, nominal, by batch or part, and test method</td>
</tr>
<tr>
<td>● per ply thickness, nominal, by batch or part, and test method</td>
</tr>
<tr>
<td>● external coating type</td>
</tr>
<tr>
<td>● external coating method of manufacture</td>
</tr>
<tr>
<td>● external coating total thickness</td>
</tr>
</tbody>
</table>
### Database for Design Data

#### Design Data Capture per CMH-17

**Mechanical and Thermal properties testing**

- number of specimens
- test procedure (citing *all* deviations from standard procedures including reporting requirements. It is assumed that, other than the deviations reported, the test method was followed.)
- date of applicable standard
- date of testing
- specimen orientation
- specimen geometry and machining method
- specimen thickness for each specimen
- specimen conditioning standard method
- conditioning temperature
- conditioning humidity
- conditioning time
- conditioning environment (if not lab air), standard designation of fluids if available
- equilibrium (Y/N)
- test temperature, loading direction, testing rate, test control method (load, strain, displacement)
- test environment (temperature, humidity), soak time at test conditions prior to load initiation
- strain measurement method, loading fixture type, standard test method and reporting parameters
- shear strain at which test was truncated (shear)
- failure load, strength, failure mode identification and location
- all non-normalized (raw) data (proportional limit, strength, modulus, strain at failure, stress-strain response, etc.)

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Database for Design Data

Design Data Capture per CMH-17

- method of loading, load control, strain control or displacement (fatigue, creep)
+ loading waveform (fatigue)
- loading frequency (fatigue)
- cyclic stress (or strain) ratio, R-ratio (fatigue)
- cycles to failure or termination (fatigue test data to indicate whether test was a failure or runout)
- time to failure (creep rupture)
- method of calculating fracture toughness (fracture toughness)
- fastener type and torque-up conditions (bearing, mechanically fastened joint (MFJ), filled hole)
- hole diameter (open/filled hole, bearing, MFJ)
+ hole clearance, countersink angle and depth (filled hole, bearing, MFJ)
- nominal thickness, width, and material for each member (bearing, MFJ)
- edge distance (bearing, MFJ)
- fixture torque-up (filled hole, bearing, MFJ)
- test temperature range (thermal expansion, thermal conductivity, specific heat)
- atmosphere (thermal expansion, thermal conductivity)
+ specimen initial and final thickness (thermal expansion, thermal conductivity)
- purge gas type, flow rate, purity (specific heat)
- heating rate (specific heat)
- specimen mass loss (specific heat)
Design Allowables Generation per CMH-17

- Data from multiple (at least three) batches (or multiple panels) and multiple (at least two) environmental conditions are needed.

- Data are pooled across environments in order to improve the estimate of variability.

- The CMH-17 STATS computer code is used to perform the calculations associated with this process.

**A-basis Value** - At least 99% of the population of material values is expected to equal or exceed this tolerance bound with 95% confidence.

**B-basis Value** - At least 90% of the population of material values is expected to equal or exceed this tolerance bound with 95% confidence.
Design Data

Design Allowables Generation per CMH-17

CMH-17 STATS software is available through the National Institute for Aviation Research (NIAR) at Wichita State University.


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Summary

• CMC materials need special considerations in the design, development and validation of commercial aviation hardware – variability in constituents, fiber architecture, processing, testing, etc.

• The Composite Materials Handbook (CMH-17) provides proven, reliable engineering information and standards for CMCs that have been thoroughly reviewed.

• The Building Block Approach helps reduce program cost and risk while meeting technical and regulatory requirements.

• CMH-17 also provides industry with standard data capture and design allowables procedures and tools.
Questions?