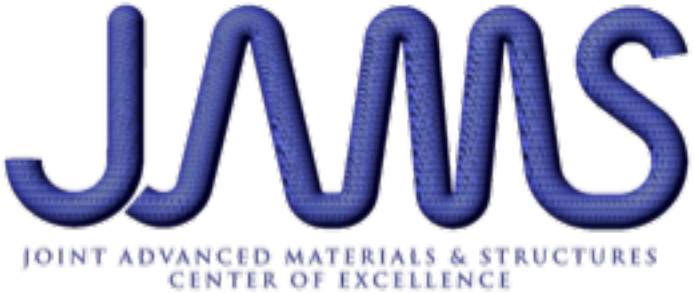

Ceramic Matrix Composite Materials Guidelines for Aircraft Design and Certification

John Tomblin, Wichita State University
Rachael Andrulonis, Wichita State University
Matt Opliger, Wichita State University

JAMS 2018 Technical Review
May 23-24, 2018

Ceramic Matrix Composite Materials Guidelines for Aircraft Design and Certification

- Motivation and Key Issues
  - Expanded use of CMCs in engine and other hot section applications
  - CMCs require their own set of rules separate from more established PMCs
  - No “fully approved” data in CMH-17
  - Similar complexity to PMCs in terms of anisotropy, fiber architecture, high strength/stiffness fibers, and production process sensitivity and variability, they are also different in many ways such as:
    - Composite constituents
    - Degradation, damage, and failure mechanisms
    - High temperature life predictions
    - High temperature bonding challenges
    - NDI challenges
    - Repairability

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Development of Qualification Program

- **Technical Monitor**: Ahmet Oztekin

- **NIAR Contacts**: John Tomblin, Rachael Andrulonis, Matt Opliger
- **Industry Partners**: Axiom Materials (prepreg), AC&A (panel), 3M (fiber and fabric), several steering committee members

- **Overall Goals**
  - Primary goal: To develop a framework for the qualification of new and innovative composite material systems including guidelines and recommendations for their characterization, testing, design and utilization.
  - Secondary goal: To transition the test data and guidelines generated in this program into shared databases, such as CMH-17.

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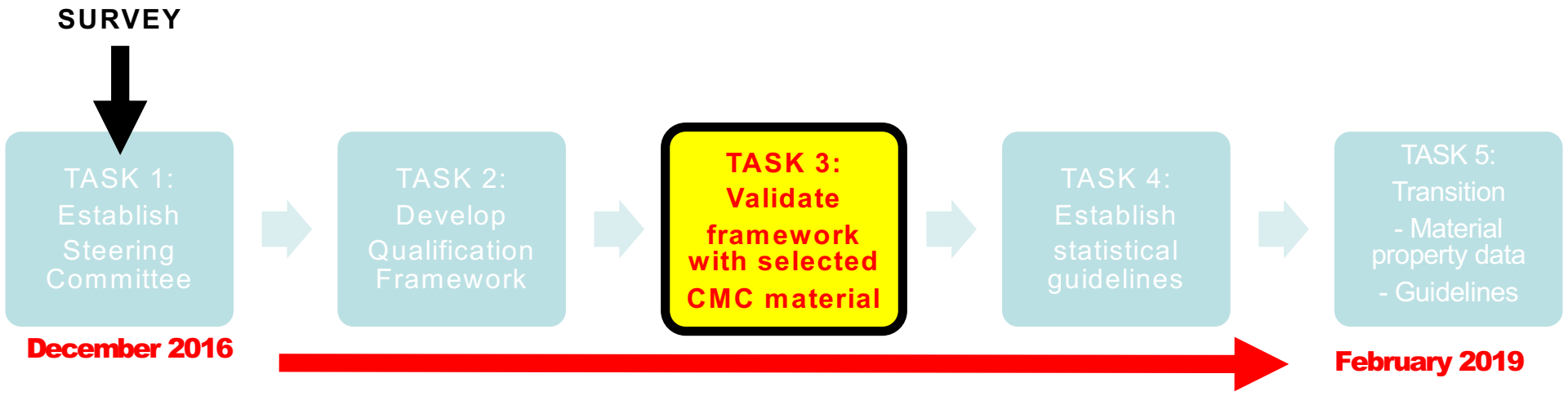
Technical Approach

- Develop a framework to advance CMC materials into the aerospace industry.
- Utilize the experience and framework of the NCAMP composite program as an example of process sensitive material characterization.
- Assess the validity with equivalency testing.



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Task 1: Steering Committee

- Steering committee formed with interested individuals
- Kick-off meeting was held in December 2016, Monthly meetings
- Collaboration with CMH-17
- Includes participants from industry (Pratt & Whitney, Free Form Fibers, Honeywell, Rolls Royce, Boeing, GE, 3M) and government (NASA, AFRL, FAA)
- Review and provide feedback on qualification plan, documents and resulting data
  - Overall test plan
  - Material specification
  - Process specification
  - Pedigree/documentation
  - Data
  - Statistical analyses

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NCAMP Portal

- All members of the Steering Committee have access
- Monthly meeting charts
- Documents for review
- Related research

http://www.niar.wichita.edu/ncampportal/CMC/tabid/177/Default.aspx

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Task 2: Development of Qualification Program

GOAL: Generate the framework for a qualification test program including material and process specifications, test matrices, and documentation requirements.

Objectives:

- Select an established CMC material and process to initially develop this framework. The material will be selected with input from the steering committee.
- Determine the critical process parameters and how they affect material properties.
- Address quality aspects of the selected CMC process and the framework for a quality assurance program.
- Draft material and process specifications for selected CMC material. *These will be very specific – material, material supplier, processing.*
- Develop CMC test matrix including required physical and mechanical data.
- Generate substantial mechanical property test data necessary for development of statistical guidelines using accepted test standards for CMC materials.

Material Selection and Process

Aluminum Silicate Slurry

Autoclave and sintering

- **Prepreg production and panel fabrication is ongoing**
- **Screening tests are concluding at NIAR**
- **Site visit/audit at Axiom took place in November 2017 – PCD has been signed**

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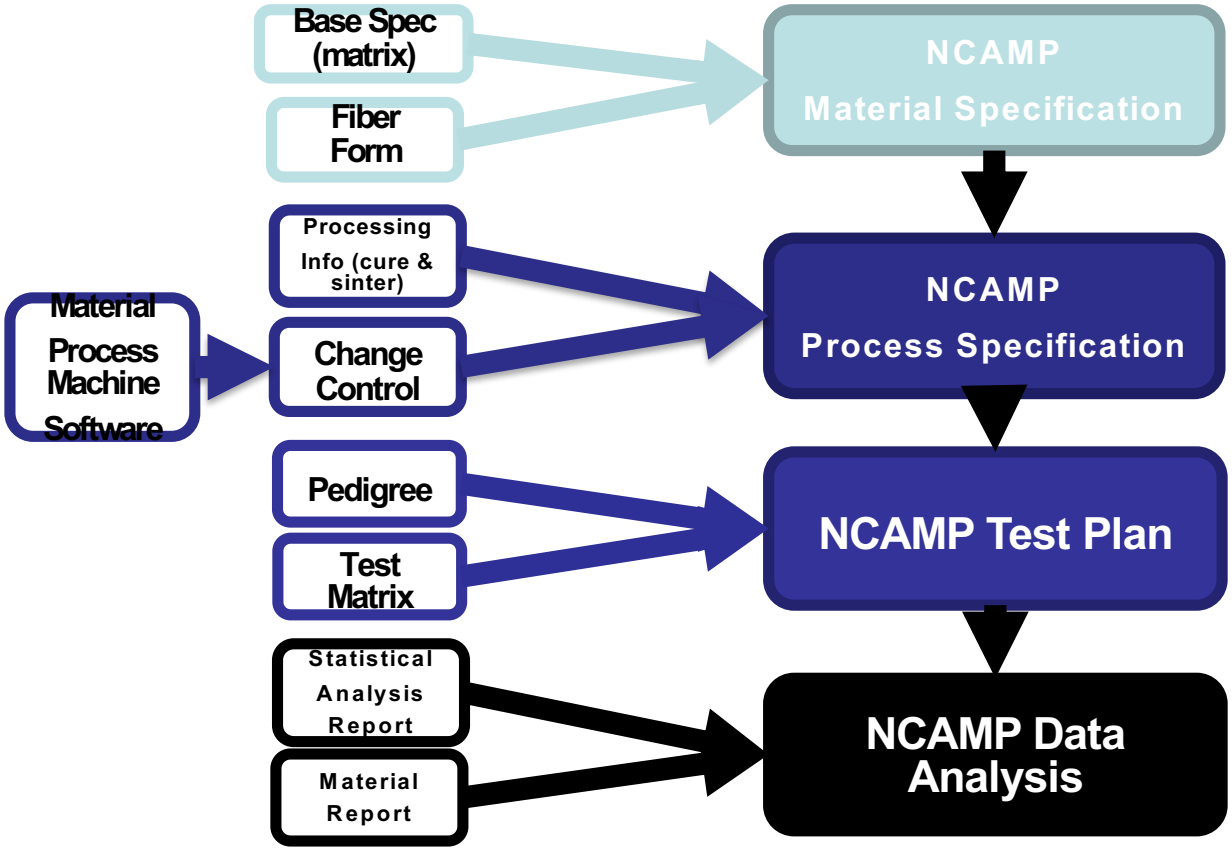
Qualification Documentation



STATUS

- Material selection complete
- Material Spec – complete
- Process Spec – complete
- Test Matrix – complete
- Test Plan – released

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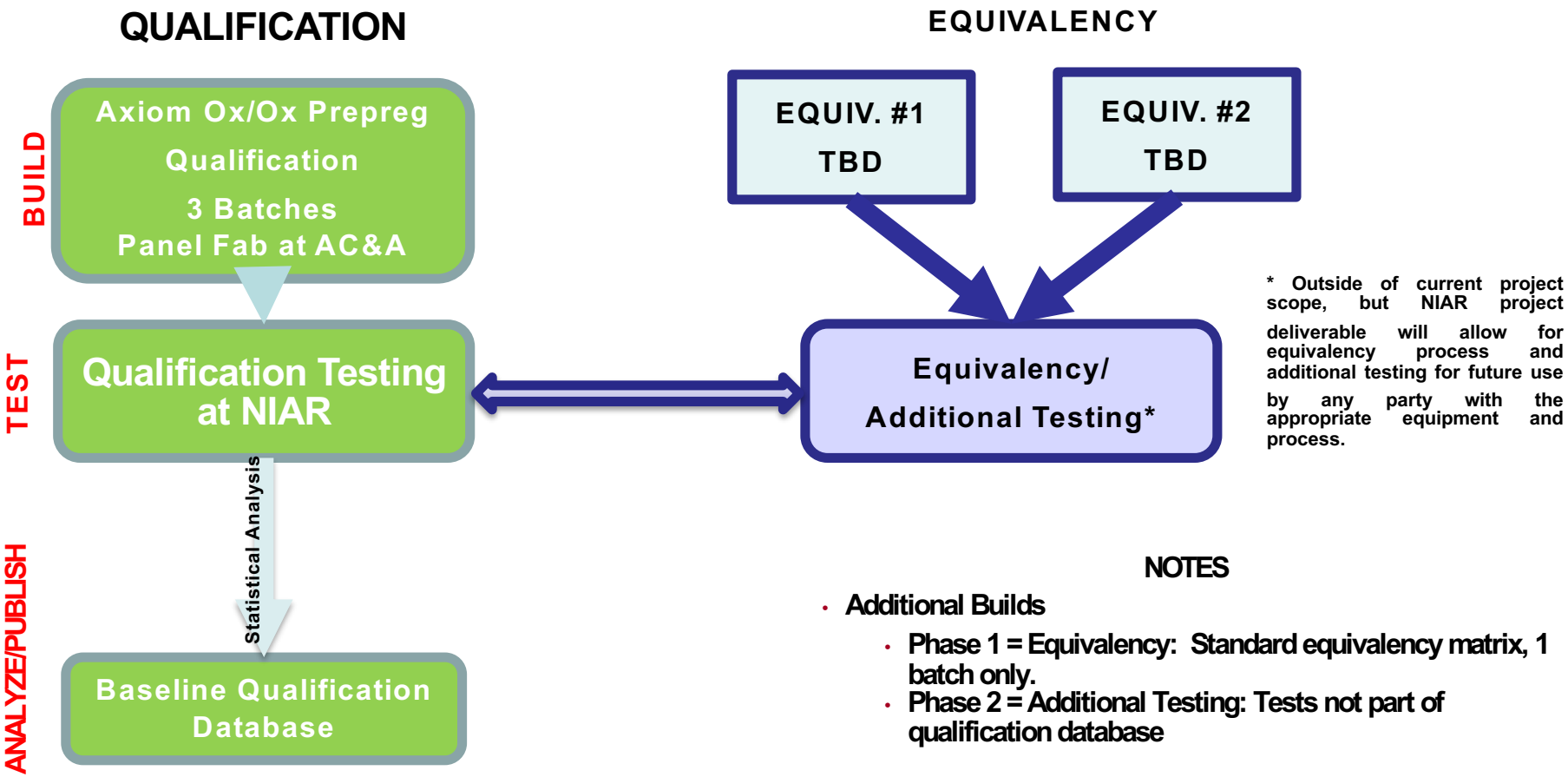
Qualification Program



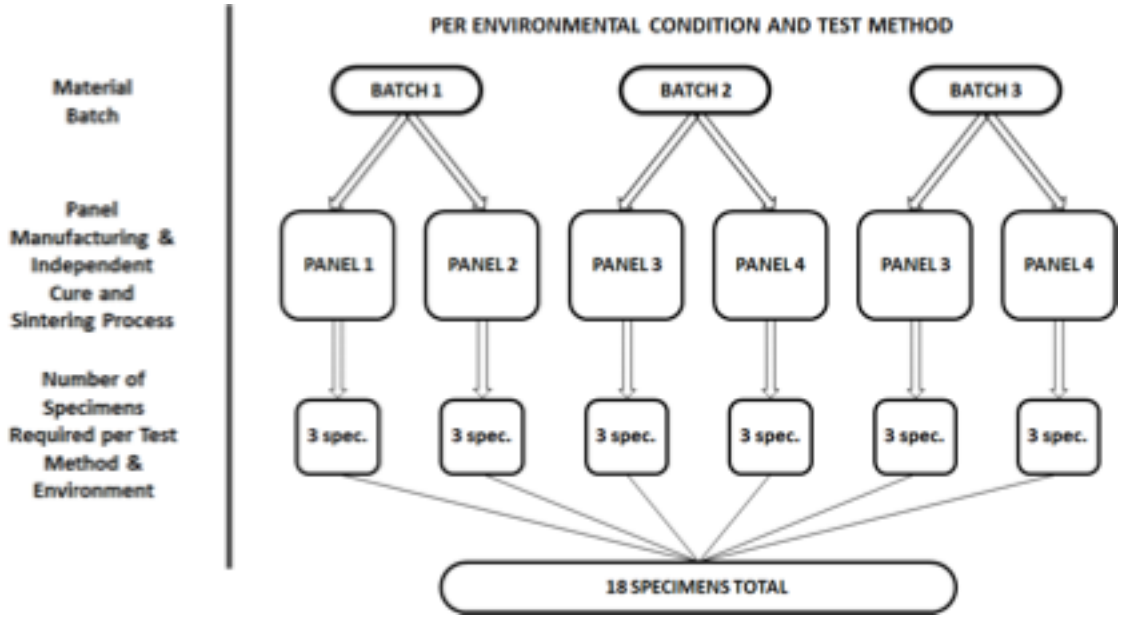
NOTES

- Additional Builds
  - Phase 1 = Equivalency: Standard equivalency matrix, 1 batch only.
  - Phase 2 = Additional Testing: Tests not part of qualification database

Test Plan Overview

- Resources:
  - Steering Committee
  - PMC NCAMP test matrix
  - CMH-17 Volume 1 and 5
  - DOT/FAA/AR-03/19
  - DOT/FAA/AR-06/10
  - DOT/FAA/AR-02/110
- Selected property and/or conditions for preliminary studies

Process Definition



Lamina Level Mechanical Tests

Layup	Test Type and Direction (See Note 9)	Property	Test Method	Number of Batches x No. of Panels x No. of Specimens	
				Test Temperature	
				RTD	ETD
[0]5S	Warp Tension (See Notes 1, 7, 8, and 10)	Strength, Modulus, and Poisson's Ratio (RTD Only)	ASTM C1275 (RTD) ASTM C1359 (ETD)	3x2x3	3x2x3
[90]5S	Fill Tension (See Notes 1, 7, 8, and 10)	Strength and Modulus	ASTM C1275 (RTD) ASTM C1359 (ETD)	3x2x3	3x2x3
[0]6S	Warp Compression (See Notes 2, 7, 8, and 10)	Strength and Modulus	ASTM C1358	3x2x3	3x2x3
[90]6S	Fill Compression (See Notes 2, 7, 8, and 10)	Strength and Modulus	ASTM C1358	3x2x3	3x2x3
[45/-45]2S	In-Plane Shear (45/-45 Tension) (See Notes 3 and 8)	Strength and Modulus (RTD Only)	ASTM D3518	3x2x3	3x2x3
[0]7S	In-Plane Shear (V-Notch Shear) (See Notes 4 and 8)	Strength and Modulus	ASTM D5379	3x2x3	
[0]7S	Interlaminar Shear (Double-Notch Shear) (See Note 5)	Strength	ASTM C1292 (RTD) ASTM C1425 (ETD)	3x2x3	3x2x3
[0]28	Interlaminar Shear (Short-Beam Strength) (See Note 6)	Strength	ASTM D2344	3x2x3	

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Laminate Level Mechanical Tests

Layup (See Note 12)	Test Type and Direction (See Note 10)	Property	Test Method	Number of Batches x No. of Panels x No. of Specimens	
				Test Temperature	
				RTD	ETD
$[0]_{7S}$	Flexure (See Notes 1, 9, and 11)	Strength and Modulus	ASTM C1341	3x2x3	
$[0]_{10}$	Interlaminar Tension (Trans-Thickness/ Flatwise Tension) (See Note 2)	Strength	C1468	3x2x3	
$[0/90]_{5}$	Interlaminar Tension (Trans-Thickness/ Flatwise Tension) (See Note 2)	Strength	C1468	1x1x6	
$[0/90]_{14}$	Interlaminar Shear (Short-Beam Strength)	Strength	ASTM D2344	1x1x6	
$[45/0/-45/90/-45/90]_{S}$	Unnotched Tension (See Notes 3, 9, and 11)	Strength and Modulus	ASTM C1275 (RTD) ASTM C1359 (ETD)	3x2x3	3x2x3
$[45/0/-45/90/-45/90]_{S}$	Unnotched Compression (See Notes 4, 9, and 11)	Strength and Modulus	ASTM C1358	3x2x3	3x2x3
$[45/0/-45/90]_{2S}$	Open-Hole Compression (See Notes 5 and 11)	Strength	ASTM D6484	3x2x3	3x2x3
$[45/0/-45/90/-45/90]_{S}$	Open-Hole Tension (See Notes 6 and 11)	Strength	ASTM D5766	3x2x3	3x2x3
$[45/0/-45/90/-45/90]_{S}$	Filled-Hole Tension (See Notes 7 and 11)	Strength	ASTM D6742	3x2x3	3x2x3
$[45/0/-45/90/-45/90]_{S}$	Single Shear Bearing (See Note 11)	Strength	ASTM D5961 (Procedure C)	3x2x3	3x2x3
$[45/0/-45/90/-45/90]_{S}$	Tension After Impact (See Notes 8 and 11)	Strength	ASTM D7136 ASTM D5766	1x2x3	1x2x3

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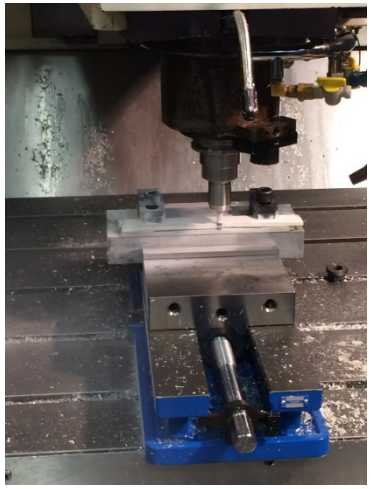
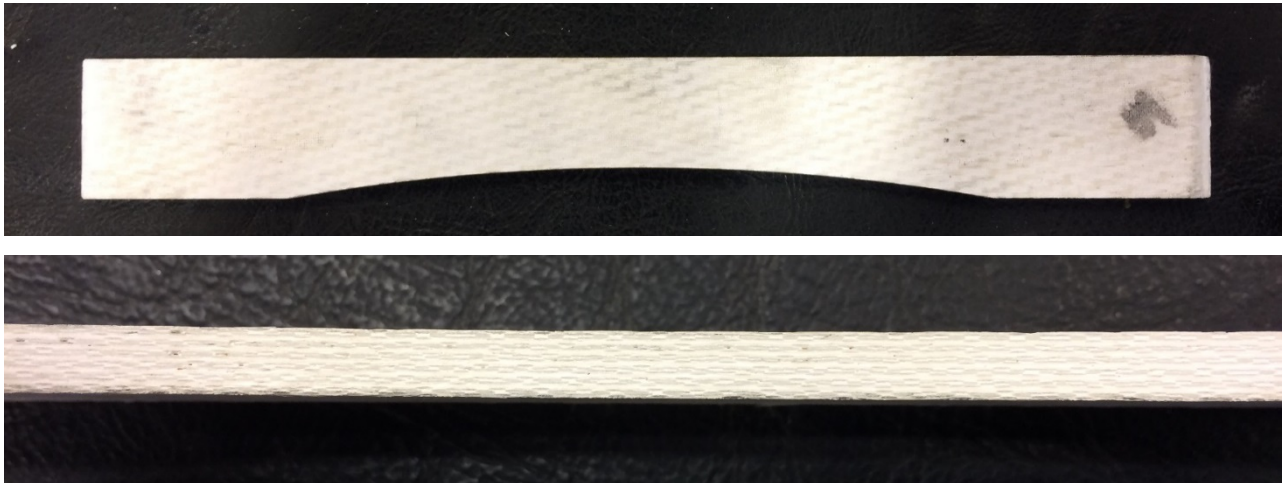
Other Test Types Included

- Uncured Physical Tests
- Cured and Sintered Physical and Thermal Tests
- Fluid Sensitivity Tests
  - Short beam strength on $[0]_{28}$
  - Includes extended contact, short duration and control tests
  - Post-immersion conditioning – require 60 minutes minimum at 1650°F

Machining Studies

- Waterjet Cutting – Pressure and Cutting Speed
- Grinding – Abrasives, Grit size, Rotational Speed, and Removal Rate
- Milling – End Mills and Coatings, Rotational Speed, and Feed Rate





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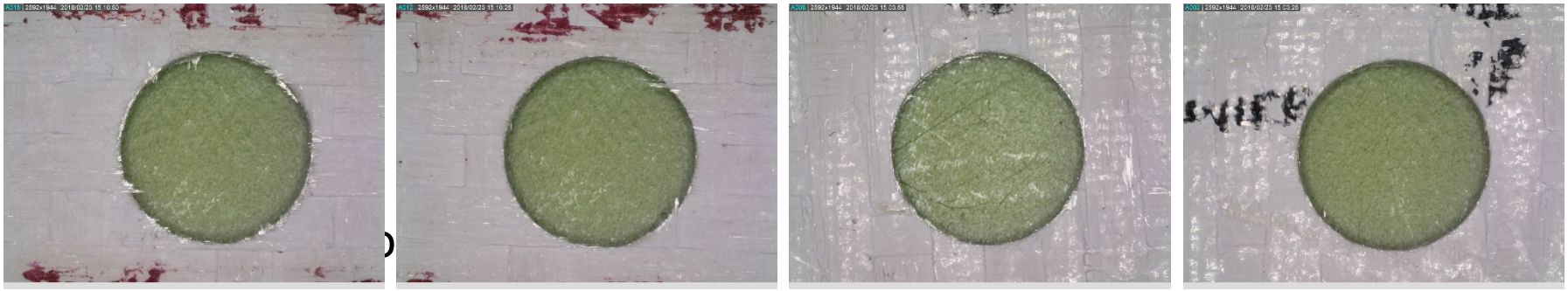
Machining Studies

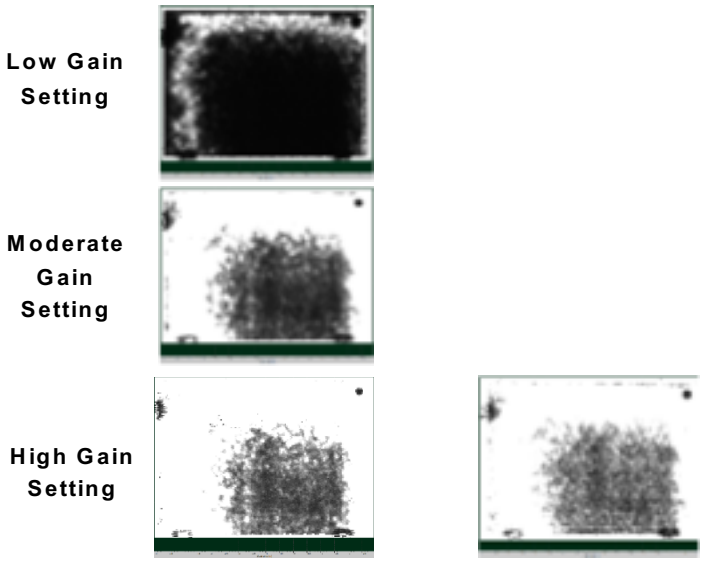
- Drilling – Drills and Coatings, Rotational Speed, and Feed Rate



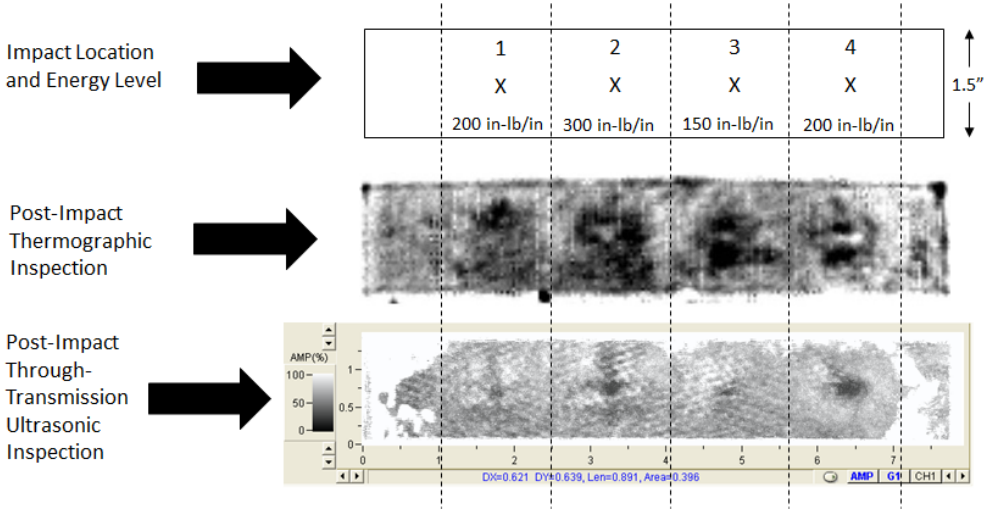
Inspections – Non-Destructive

- Non-Destructive – Ultrasonic (Through Transmission) and Thermography

Flat Panel Inspections - Through Transmission



Post-Impact Inspections – Thermographic and Through Transmission Ultrasonic



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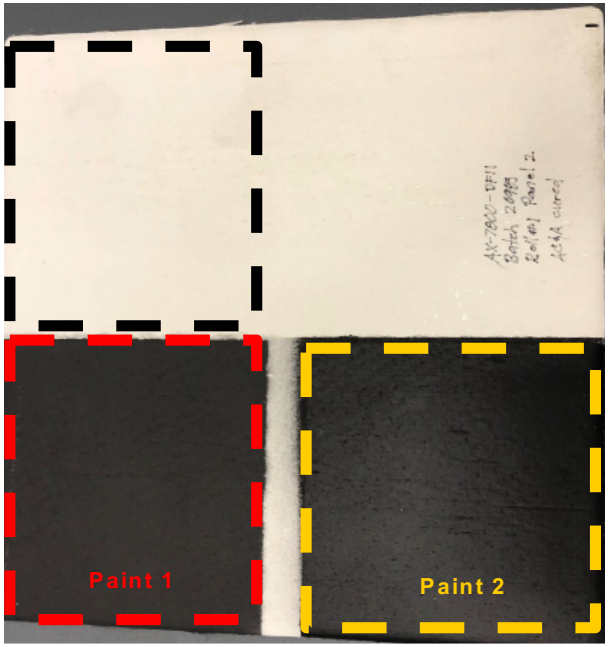
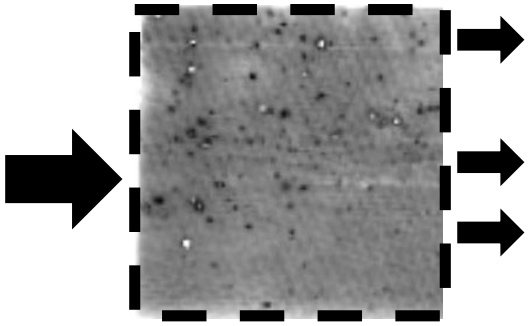
Pulsed Thermography Studies

- Surface Condition – Painted and Unpainted

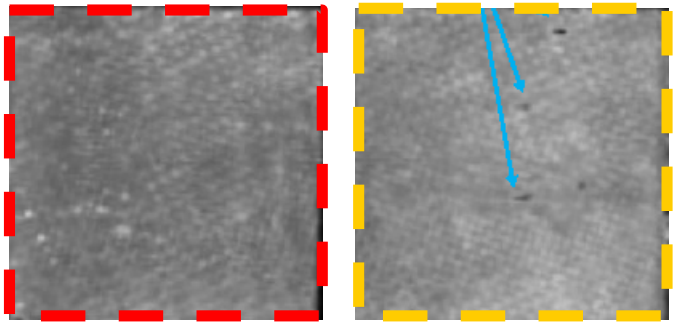




Inspection with an unpainted surface resulted in significant reflection of light. As a result, surface features appear as defects.

Areas with high reflection appear bright.

Areas with high absorbance appear dark.



Inspection with a painted surface minimized reflection of light. As a result, surface features do not appear as defects, but actual surface defects were still detectable.

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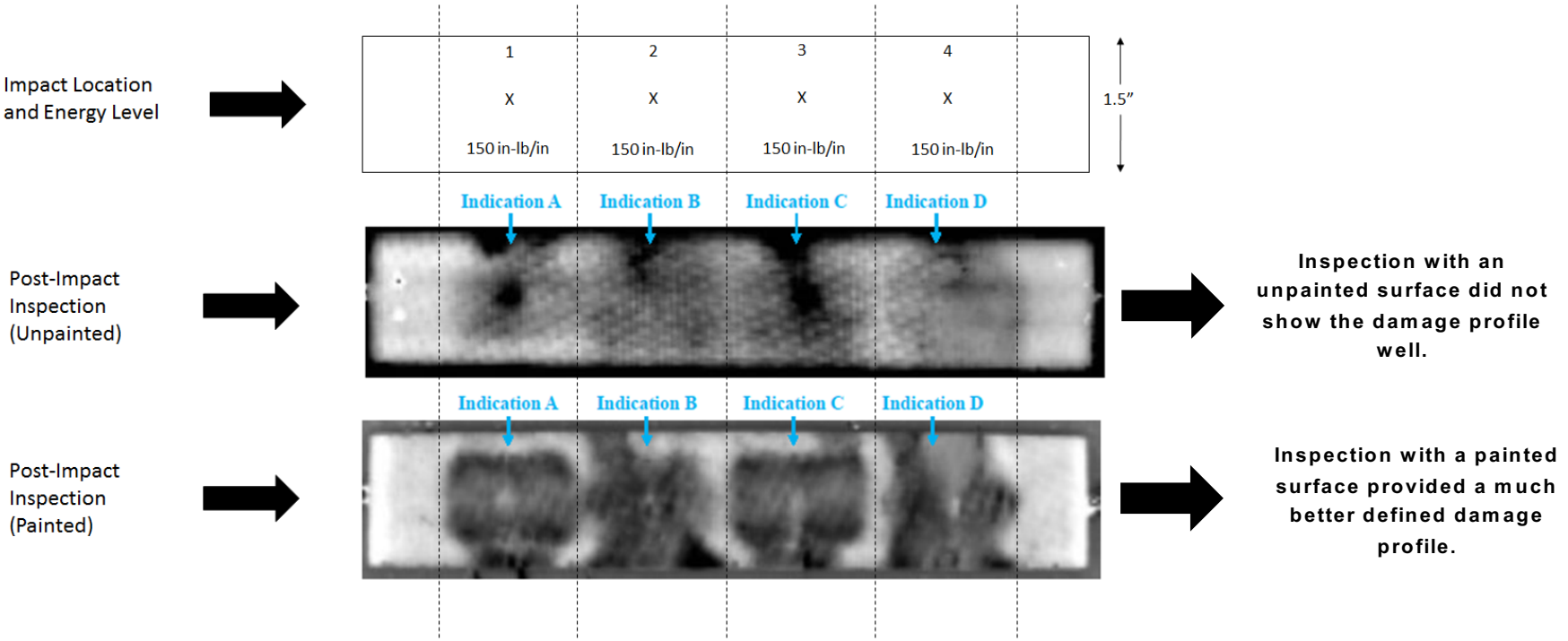
Pulsed Thermography Studies

- Impact Damage – Surface Painted and Unpainted



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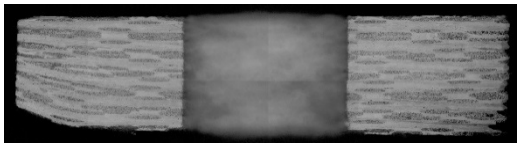
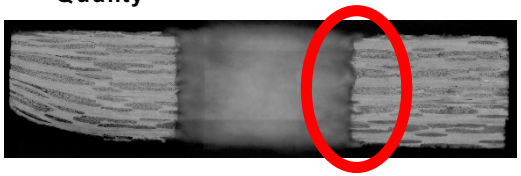
Inspections – Destructive

- Destructive – Microscopic Analysis for Determination of Void/Porous Content, Hole Quality, and Impact Damage Assessment

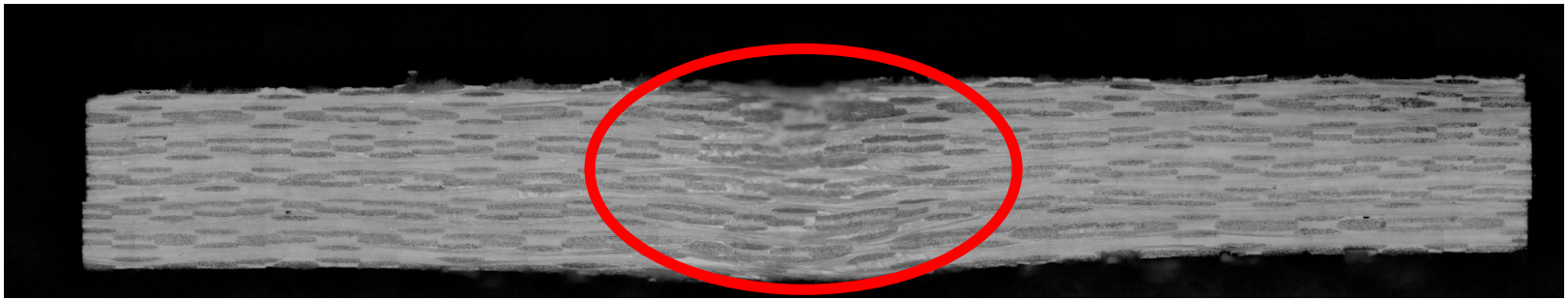
Good Quality



Poor Quality



Impact Damage Assessment



Screening Tests – Physical Tests

- Density and Apparent Porosity per ASTM C373
- Fiber and Matrix Content per ASTM D3171 Method II with Correction for Voids/Porosity

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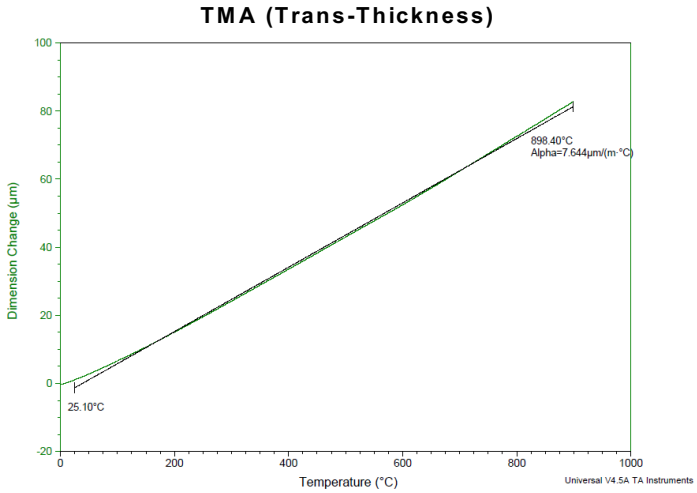
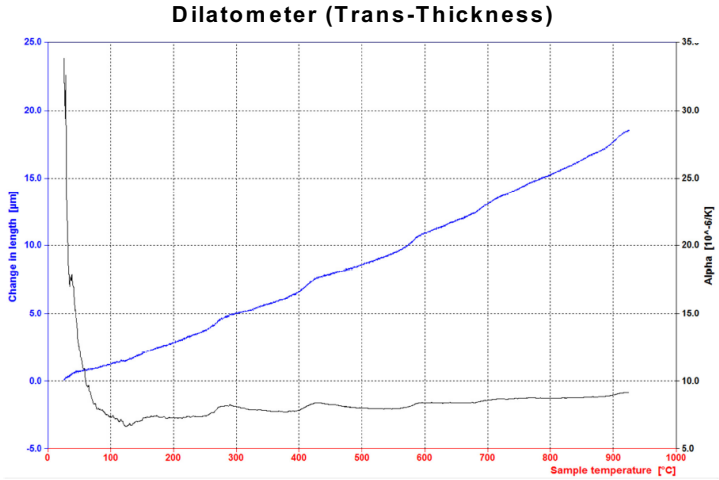
Screening Tests – Thermal Tests

- Coefficient of Thermal Expansion by both Thermomechanical Analysis (TMA) and Dilatometer per ASTM E228





- Thermal diffusivity by laser flash method per ASTM E1461

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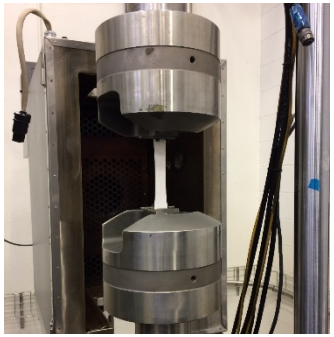
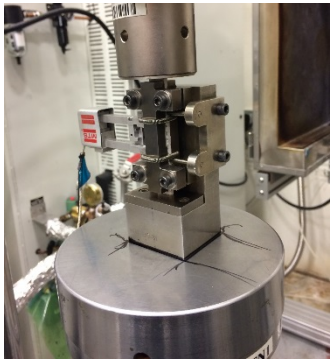
Mechanical Screening Tests

- Tensile Strength and Modulus per ASTM C1275



- Compressive Strength and Modulus per ASTM C1358 using ASTM D695 Face Supporting Stabilization Fixture



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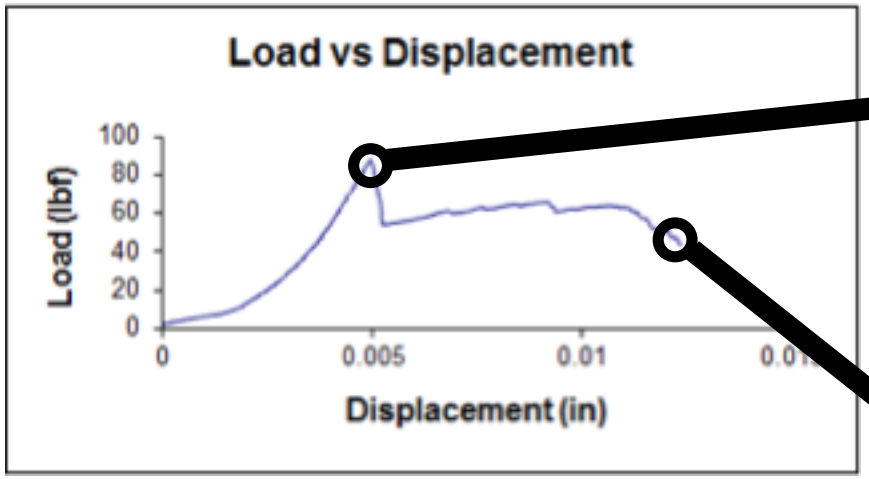
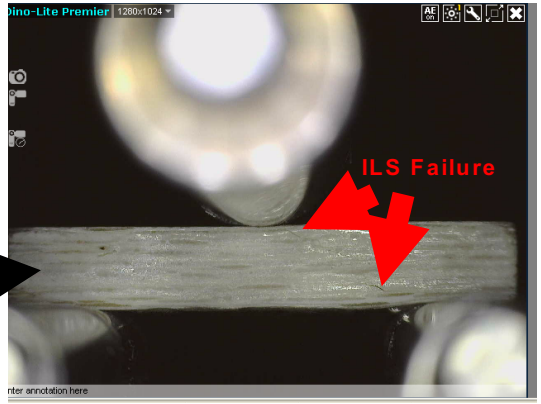
Mechanical Screening Tests

- Short-Beam Strength per ASTM D2344





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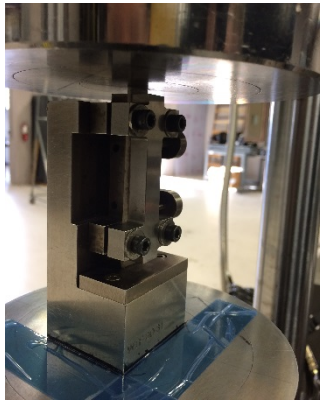
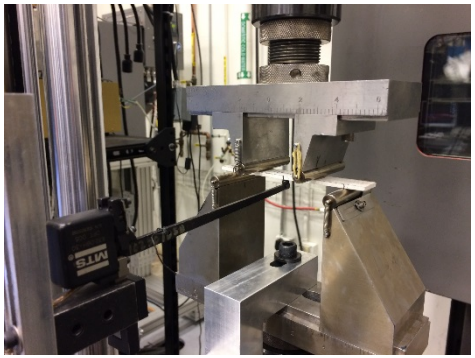
Mechanical Screening Tests

- Double-Notch Shear per ASTM C1292 using ASTM D695 Face Supporting Stabilization Fixture

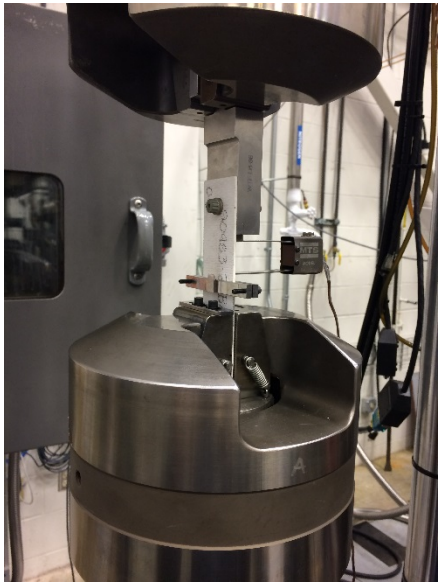


- Flexural Strength and Modulus per ASTM C1341



Mechanical Screening Tests

- Interlaminar (Trans-Thickness) Tension per ASTM C1468 using Standard and Oversized Test Specimens
- Pin Bearing Strength per ASTM D5961 Procedure C



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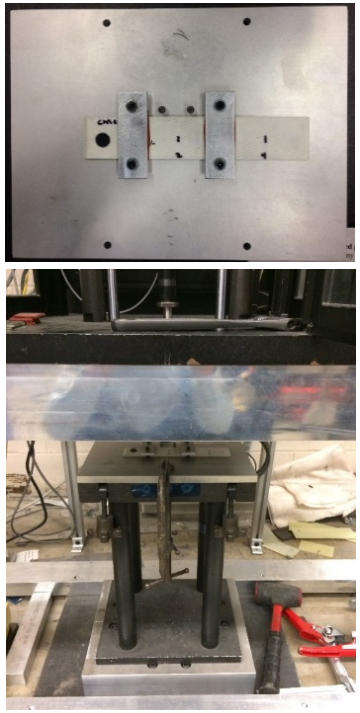
Mechanical Screening Tests

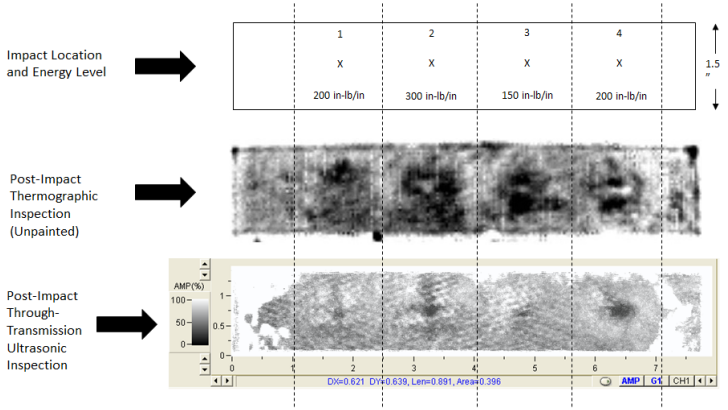
- Impact Resistance per Modified ASTM D7136



Impact Resistance Study – Round 1

Specimen Details
Thickness: 0.185 in
Density: 2.72 g/cm^3
Porosity: 24.8%

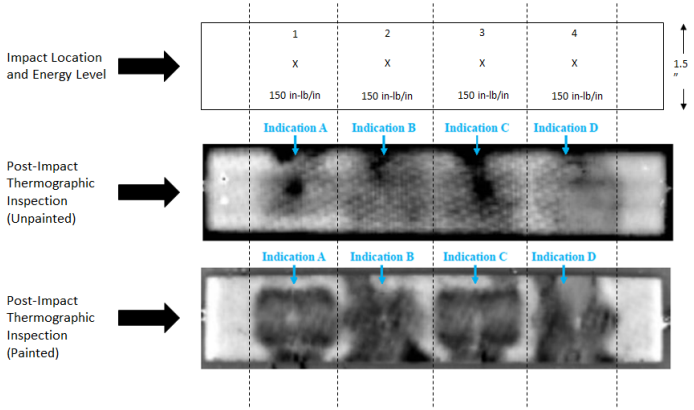
Impact Energies Evaluated



Impact Resistance Study – Round 2

Specimen Details
Thickness: 0.079 in
Density: 2.50 g/cm^3
Porosity: 32.6%

Impact Energies Evaluated



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Task 4: Guidelines and Recommendations

GOAL: To provide guidelines to industry for the collection of statistically meaningful critical data that designers need to utilize CMC materials potentially including:

- Creation of a shared CMC database including test data, material and process specifications and statistical analysis methods.
- Development of handbook data and guidelines (i.e., CMH-17).
- Coordinate with other standards and specification organizations to develop specifications from this program.

Status – Based on FY2017 Deliverables

	Activity	Target Date	Milestone / Deliverable	Complete?
1.2	Industry Steering Committee - Establish group of participants - Create online portal for document sharing and data repository	12/15/2016	Milestone	✓
1.3	Preliminary drafts of qualification framework - Material and process specifications - Test plan - Conformity documentation	6/30/2017	Deliverable	✓
1.4	Qualification Audit	11/10/2017	Milestone	✓

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Status – Based on FY2017 Deliverables

	Activity	Target Date	Milestone / Deliverable	Complete?
1.1	Trial / Screening Studies (ongoing) - Perform physical and mechanical tests to assist in final test matrix development and selection of machining and NDI methods - Present data to FAA, Industry Steering Committee, NCAMP Partners	1/15/2018	Milestone	✓
1.2	Qualification Material - Site audit complete (scheduled for 11/7-11/8/2017) - Panels built and delivered to NIAR	2/1/2018	Milestone	Panels in process
1.3	Qualification Testing - Perform physical and mechanical testing on qualification panels. – Generate test data for qualification program.	8/31/2018	Milestone	
1.4	Develop Statistical Guidelines based on qualification data	10/1/2018	Milestone	
1.5	NCAMP Reports on Qualification Data - Material technical report - Statistical analysis technical report	12/31/2018	Deliverable	
1.6	CMH-17 - Submit content, data, and protocols to Composite Materials Handbook 17 (CMH-17)	2/28/2019	Deliverable	
1.7	Final Report - Final Technical Report on the Guidelines for CMC Qualification.	2/28/2019	Deliverable	

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Looking forward

- Benefit to Aviation
  - Publically available CMC data linked to M&P specs
  - Addition to CMH-17 handbook
  - CMC – PCD and process spec guidelines

- Future needs
  - Validate qualification data with equivalencies
  - Trial studies needed:
    - Processing effects on CMCs
    - SiC/SiC or C/SiC composites
    - Effects of thermal and environmental barrier coating

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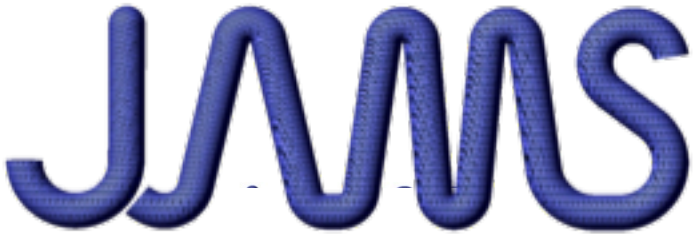
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