Resin Infused Fiber Reinforced Materials Guidelines for Aircraft Design and Certification Process

April 2023 UPDATE

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Michelle Man
Royal Lovingfoss

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Introduction

• Resin Infused Fiber Reinforced Materials Guidelines for Aircraft Design and Certification Process

• Project Participants
  • Dr. John Tomblin, Rachael Andrulonis, Royal Lovingfoss, Michelle Man

• FAA Technical Monitor: Dave Stanley

• FAA Sponsors: Cindy Ashforth, Larry Ilcewicz

• Industry Partnerships/Other Collaborations
  • Solvay, Teijin, Fiber Dynamics, several other industry committee members

Motivation and Key Issues

• Interest in resin infused fiber reinforced composite materials are growing
• Resin infusion process would be ideal for low volume medium to large scale applications
• Complex geometric parts as a unitized structure; optimizing production
• Reduces capital and ongoing cost of large structure manufacturing
• Easier to manipulate dry reinforcements over tooling
• Currently there is no resin infused qualification data in NCAMP database or CMH17
Background

**Objective and Scope**

- **Primary goal:** To develop a framework for the qualification of resin infused fiber reinforced materials including guidelines and recommendations for their characterization, testing, design and utilization using the NCAMP process.
- **Secondary goal:** To transition the test data and guidelines generated in this program into shared databases, such as CMH-17.

### Current Status

- **2020:** Survey & Establish Steering Committee
- **2021-2022:** Develop Qualification Framework
- **2022-2023:** Validate framework with selected materials
- **2023:** Establish statistical guidelines
- **2023-2024:** Transition - Material property data - Guidelines
Technical Approach Overview

- Survey OEM designers, manufacturers/user and experts on material selection
- Committee Review Group established – Industry users, suppliers, FAA
- Material selection narrowed
  - Resin: Solvay PRISM™ EP 2400
  - Reinforcement: Tenax™-E IMS65 Non-Crimp Reinforcement (Stitched); UD Fabric, Bi-axial (0/90), and Bi-diagonal (+/-45)
- Processing Method – VARTM
- Trials to determine project needs, challenges, critical process control parameters
- Set framework for Material Qualification
- Develop M&P Specifications
- Develop Mechanical, Physical, and Chemical requirements
  - Qualification test data sufficient for developing statistical guidelines and allowables
  - Data and Guidelines
Milestones & Timeline

**Done Jan 2023**

- Documentation
- Test Plan
- Process Specification
- Laminate Material Specification
- Fabric Material Specification
- Resin Material Specification

**Feb - Aug 2023**

- Panel Production
  - Batch A
  - Batch B
  - Batch C

- Specimen Prep
  - Machining & Conformity
  - Specimen to Chamber
  - Testing (~Aug 2023)

**Feb – mid Aug 2023**

**Mid Aug – Oct 2023**

- Testing
  - Ambient
  - Fluid Screening
  - Moisture Equilibrium
  - Data Availability

**Q1 2024**

- Data Review
  - Concerns?
  - Retests?
  - Summary Sheets

**Q2 2024**

- Documentation
  - Data Report Draft
  - Statistics Report Draft
  - NMS/NPS updates
  - FAA Guidance Doc

I’m done!
Active/Ongoing
Next task

Done Jan 2023
Feb - Aug 2023
Feb – mid Aug 2023
Mid Aug – Oct 2023
Q1 2024
Q2 2024
Material Forms

- **Reinforcement**: Tenax™-E IMS65 Non-Crimp Reinforcement
- **Material Forms**:
  - Biaxial (BA) – carbon fibers in 0°/90° or 90°/0°
  - Bidiagonal (BD) – carbon fibers in +45°/-45° or -45°/+45° (also in ±30° and ±60°)
  - UD (woven with yarn)
- **Toughening veil**: TA1903s (polyamide veil) used to improve material toughness.
- **Powder binder**: Hexion EP05311 binder resin improves material cutting and handling and aids in preforming and tacking two layers of textile together.
- **Stitching Yarns**:
  - NCF: K-203 (EP1390) 33 dtex a co-polyamide yarn
  - UD Woven: polyester and co-polyamide Z-85 combi-fuseable bonding yarn, 200 dtex.
- **Resin**:
  - Solvay PRISM™ EP 2400
  - One-part toughened epoxy resin
  - 2 hour cure at 356°F cure
  - Intended service temp >250°F
  - Superior toughness, low viscosity, and extended pot-life

**Detail Construction of Bidiagonal NCF**
Effect of Veil

Compression After Impact Test – 3 x 30J in acc. to EN6038; Stacking [+45/0/-45/90]_3s
UD woven fabric (194gsm/layer); CF: Tenax®-E IMS65 E23 24K 830tex; Resin: 180°C epoxy resin
Teijin NCF Manufacturing Facility
Reinforcement – Stitching Techniques

• Tricot - Pillar Stitch
  • Compromise between performance and drapeability
  • Used in Bidiagonal NCF

Top side

Bottom side
Reinforcement – Stitching Techniques

• Tricot Stitch
  • Best drapeability
  • Additional improvements possible – stitching length and loop stitch
  • Used in Biaxial NCF (tricot loop)
Reinforcement – UD (woven)

- UD Woven
  - Warp – Carbon fibers
  - Weft – Combi-fuseable yarn woven into the fibers
  - Provide localized reinforcement
  - Veil and Fiber
  - Increasing crossing point improves permeability
  - Balance between crossing point and mechanical performance
Trial Phase

• Panel fabrication
  • 26 Panels fabricated at Fiber Dynamics

• Properties evaluated
  • Mechanical: Tension, Compression, Flex, and Shear tests conducted
  • Physical: Fiber volumes, resin contents, voids, etc.

• General processing challenges
  • Identifying variables that need to be controlled

• Manufacturing process differences
  • Vacuum Assisted Resin transfer Molding vs Resin Transfer Molding (VARTM vs RTM)
  • Qualification vs. equivalency; challenges, feasibility
## Trial Phase

### Lamina Table, All test at RTA

<table>
<thead>
<tr>
<th>Layup</th>
<th>Approx Target Thickness (in)</th>
<th># of NCF layers</th>
<th>D3039 Tension</th>
<th>D6641</th>
<th>D3518 In-Plane Shear</th>
<th>D2344 Short Beam Shear</th>
<th>D790 Flex</th>
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</thead>
<tbody>
<tr>
<td>[45/-45]3s</td>
<td>0.087 - 0.090</td>
<td>6</td>
<td>5 (rotated panel)</td>
<td>5*</td>
<td>5</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>[0/90]3s</td>
<td>0.087 - 0.090</td>
<td>6</td>
<td>5</td>
<td>5 in 0 and 5 in 90</td>
<td>5 (rotated panel)</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>[45/-45]6s</td>
<td>0.174 - 0.180</td>
<td>12</td>
<td>5</td>
<td>5 in 0 and 5 in 90</td>
<td>5 (rotated panel)</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>[0/90]6s</td>
<td>0.174 - 0.180</td>
<td>12</td>
<td>5</td>
<td>5 in 0 and 5 in 90</td>
<td>5 (rotated panel)</td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

* additional 5 for Dogbone D695 geometry

### Laminate Table, All test at RTA

<table>
<thead>
<tr>
<th>Layup</th>
<th>Approx Target Thickness (in)</th>
<th># of NCF layers</th>
<th>D6484 Open Hole Compression</th>
<th>D5766 Open Hole Tension</th>
<th>D7136/D7137 CAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>[45/-45/0/90]2s</td>
<td>0.116</td>
<td>8</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
Determining Processing Method

RTM Panel

VARTM Panel

RTM Panel

VARTM Panel
Determining Processing Method

- VARTM – more consistent, easier to work with, better process control
- Better panel quality
- Comparable results to RTM
- VARTM selected

![Tension Specimens Post-Test for RTM and VARTM](image)

![Data Comparison of VARTM and RTM Properties](image)
Processing Challenges

- Porosity, Improving Permeability
- Controlling fiber volume
- Initial weft density resulted in porosity and high infusion times.
- Varying weft density & changed flow media

VARTM Uni-Fabric Panel
Courtesy of Fiber Dynamics, Inc.
Process Optimization

- NIAR and Teijin visited Fiber Dynamics
- Modification made to bagging scheme:
  - Varying flow media
  - Increased resin infusion temp.
  - Made port adjustments to improved infusion process
  - Adjusted tubing placement
  - Optimizing Infusion time and process
  - More repeatable FV
    - Target is 57% ± 3%
  - Weft density construction of UD material
Weft Density

Compared data and panel quality.

Selected 1.5 threads/cm
Setting the Qualification Framework

• Specifications are organized for versatility and future use/expansion

• Properties will be generated from 5 products:
  • Two forms of BA
  • Two forms of BD
  • One form of UD

• Lamina and laminate properties
  • Individual form
  • Combined forms
Specification Series

- **NMS 241F** – Base Fabric Specification (defines requirements for the dry reinforcements)
  - NMS 241F/1 – Biaxial DRNF
  - NMS 241F/2 – Bidiagonal DRNF
  - NMS 241F/3 – UD Woven DRWF

- **NMS 241R** – Base Resin Specification (defines requirements for the resin)
  - NMS 241R/1 – EP2400

- **NMS 241** – Base Laminate Specification (defines requirement for the finished laminates)
  - NMS 241/1 – Biaxial Laminates
  - NMS 241/2 – Bidiagonal Laminates
  - NMS 241/3 – UD Woven Laminates

- **NPS 82401** - Process specification describes the methods of fabricating test panels using a vacuum assisted resin transfer molding process with PRISM™ EP2400 Resin System.
Test Plan

• Test plan – lamina and laminate testing
  • Lamina properties for Biaxial, Bidiagonal and Unidirectional
  • Laminate properties for combination of materials
  • Quasi, Soft, Hard
  • -65°F, RTD, 180°F, 250°F
### Test Plan – Lamina (BA, BD, UD)

#### Biaxial Lamina Mechanical Test Matrix

<table>
<thead>
<tr>
<th>Fiber Layup</th>
<th>Test direction</th>
<th>Test Type</th>
<th>Property</th>
<th>CTA (4)</th>
<th>RTA</th>
<th>ETA</th>
<th>ETW1</th>
<th>ETW2</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0/90]_st</td>
<td>0°</td>
<td>ASTM D3039 Tension</td>
<td>Strength, Modulus, and Poisson’s Ratio</td>
<td>3x2x3</td>
<td>3x2x3 (3)</td>
<td>3x2x3</td>
<td>3x2x3</td>
<td></td>
</tr>
<tr>
<td>[0/90]_st</td>
<td>0°</td>
<td>ASTM D6641 Compression</td>
<td>Strength and Modulus</td>
<td>3x2x3</td>
<td>3x2x3 (1)</td>
<td>3x2x3</td>
<td>3x2x3</td>
<td>1x2x3</td>
</tr>
<tr>
<td>[0/90]_st</td>
<td>90°</td>
<td>ASTM D3039 Tension</td>
<td>Strength and Modulus</td>
<td>3x2x3</td>
<td>3x2x3 (3)</td>
<td>3x2x3</td>
<td>3x2x3</td>
<td></td>
</tr>
<tr>
<td>[0/90]_st</td>
<td>90°</td>
<td>ASTM D6641 Compression</td>
<td>Strength and Modulus</td>
<td>3x2x3</td>
<td>3x2x3 (1)</td>
<td>3x2x3</td>
<td>3x2x3</td>
<td></td>
</tr>
<tr>
<td>[45/-45]_st</td>
<td>0°</td>
<td>ASTM D3518 In-Plane Shear (2)</td>
<td>Strength and Modulus</td>
<td>3x2x3</td>
<td>3x2x3 (3)</td>
<td>3x2x3</td>
<td>3x2x3</td>
<td></td>
</tr>
<tr>
<td>[0/90]_st</td>
<td>0°</td>
<td>ASTM D3518 In-Plane Shear (2)</td>
<td>Strength and Modulus</td>
<td>3x2x3</td>
<td>3x2x3 (1)</td>
<td>3x2x3</td>
<td>3x2x3</td>
<td></td>
</tr>
<tr>
<td>[0/90]_st</td>
<td>0°</td>
<td>ASTM D2344 Short Beam</td>
<td>Strength</td>
<td>3x2x3</td>
<td>3x2x3 (3)</td>
<td>3x2x3</td>
<td>3x2x3</td>
<td></td>
</tr>
<tr>
<td>[0/90]_st</td>
<td>0°</td>
<td>ASTM D7264 Flex (5)</td>
<td>Strength and Modulus</td>
<td>3x2x3</td>
<td>3x2x3 (1)</td>
<td>3x2x3</td>
<td>3x2x3</td>
<td></td>
</tr>
</tbody>
</table>

#### Bidiagonal Lamina Mechanical Test Matrix

<table>
<thead>
<tr>
<th>Fiber Layup</th>
<th>Test direction</th>
<th>Test Type</th>
<th>Property</th>
<th>Number of Batches × Number of Panels × Number of Test Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0/90]_st</td>
<td>0°</td>
<td>ASTM D3039 Tension</td>
<td>Strength, Modulus, and Poisson’s Ratio</td>
<td>3x2x3 × 3x2x3 × 3x2x3 × 3x2x3</td>
</tr>
<tr>
<td>[0/90]_st</td>
<td>0°</td>
<td>ASTM D6641 Compression</td>
<td>Strength and Modulus</td>
<td>3x2x3 × 3x2x3 × 3x2x3 × 3x2x3</td>
</tr>
<tr>
<td>[45/-45]_st</td>
<td>0°</td>
<td>ASTM D3518 In-Plane Shear (2)</td>
<td>Strength and Modulus</td>
<td>3x2x3 × 3x2x3 × 3x2x3 × 3x2x3</td>
</tr>
<tr>
<td>[0/90]_st</td>
<td>0°</td>
<td>ASTM D2344 Short Beam</td>
<td>Strength</td>
<td>3x2x3 × 3x2x3 × 3x2x3 × 3x2x3</td>
</tr>
<tr>
<td>[0/90]_st</td>
<td>0°</td>
<td>ASTM D7264 Flex (5)</td>
<td>Strength and Modulus</td>
<td>3x2x3 × 3x2x3 × 3x2x3 × 3x2x3</td>
</tr>
</tbody>
</table>
## Test Plan – Lamina (UD)

<table>
<thead>
<tr>
<th>Fiber Layup</th>
<th>Test direction</th>
<th>Test Type</th>
<th>Property</th>
<th>Number of Batches x Number of Panels x Number of Test Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0/90]_w</td>
<td>0°</td>
<td>ASTM D3039 Tension</td>
<td>Strength, Modulus, and Poisson’s Ratio</td>
<td>3x2x3 3x2x3 (3) 3x2x3 3x2x3</td>
</tr>
<tr>
<td>[0/90]_w</td>
<td>0°</td>
<td>ASTM D6641 Compressive</td>
<td></td>
<td>3x2x3 (1) 3x2x3 3x2x3 1x2x3</td>
</tr>
<tr>
<td>[0]_w</td>
<td>0°</td>
<td>ASTM D3538 Tabbed Tension</td>
<td>Strength and Modulus</td>
<td>3x2x3 (3) 3x2x3 3x2x3 1x2x3</td>
</tr>
<tr>
<td>[0]_w</td>
<td>0°</td>
<td>ASTM D6641 Compressive</td>
<td>Modulus</td>
<td>3x2x3 (1) 3x2x3 3x2x3 1x2x3</td>
</tr>
<tr>
<td>[0/45]_w</td>
<td>0°</td>
<td>ASTM D3518 In-Plane Shear</td>
<td>Strength and Modulus</td>
<td>3x2x3 3x2x3 3x2x3 3x2x3</td>
</tr>
<tr>
<td>[0/32]</td>
<td>0°</td>
<td>ASTM D2544 Short Beam</td>
<td>Strength</td>
<td>3x2x3 3x2x3 3x2x3 1x2x3</td>
</tr>
</tbody>
</table>

**UD Woven Lamina Mechanical Test Matrix**
Laminate Mechanical Properties

- The construction of the laminates are done using a combination of the non-crimp and woven fabric forms to produce the desired quasi, soft, and hard orientation.
- The layup angles 0/90, 90/0, 45/-45 and -45/45 refer to the specific DRNF, i.e. biaxial (0/90 or 90/0) and bidiagonal (45/-45 or -45/45) reinforcement fabric.
- The stacking sequences were chosen based on several factors:
  - to assess the scope of material properties from a soft, quasi and hard construction
  - to assess the interactions of the different preforms
  - to assess the process ability of the different preforms when used jointly.

Properties include:
- Unnotched Tension
- Unnotched Compression
- Short Beam Shear
- Open Hole Tension
- Filled Hole Tension
- Open Hole Compression
- Filled Hole Compression
- Single Shear Bearing
- Interlaminar Tension
- Compression After Impact

Fluid Screening:
- Woven Fabric
- Short Beam Shear
- 13 fluids + controls
- RT and ET testing
Lessons to Learn

Surface picture of Panel A-C2-2 number 330688

Most severe creases of all panels
Lessons to Learn

Zero tension Panel A-C2-2 number 330688

Nominal 0.118 in

Deep crease ~ 0.07 in deep
Ongoing Activity

**Qualification Documents**
- Approved by project AER and released

**Qualification Panels**
- Raw materials (resin and fiber) received mid/late 2022
- Panel production began Dec 2022
- Batch A in progress
  - Batch B and C to follow
- 44 panels received
  - 28 scanned/machined

**Challenges**
- Processing
  - Vacuum leak rates
- Surface porosity/dry
  - Adjustments to bagging media
- Wrinkling
  - Teijin worked with Fiber Dynamics for resolution
  - Efforts ongoing
  - 4 panels affected
- Lessons Learned Report
  - Processing
  - Material Property data effects
Publications

• FAA Annual Reports submitted: 2020, 2021
• Upcoming Tech Report submission: ECD May 31, 2023
  • Detail pre-qualification trials
  • Reference qualification
• Planned Reports:
  • Qualification Reports – NCAMP, FAA
  • Specifications - NCAMP
  • Material Specification Guidelines – FAA
  • Lessons Learned Report – NCAMP, FAA