Composites 101
Workshop

Carroll Grant – Aerospace Composites Consulting
Workshop will be conducted as a “101” overview of the composites industry
.....Presentation material has been developed for people who know very little about the composites industry

Workshop intent is to provide attendees with a basic understanding of “composites”

Workshop will focus on “aerospace” composites as this is experience base of the instructors
Workshop Topics

• Composites Industry Overview (Carroll Grant)
  ......history and industry segments
  ......materials and design basics

• Aerospace Composites Processes (Dick Lofland)
  ......basic processes
  ......automated Processes (Carroll Grant)

• Inspection of Composite Parts (Dick Lofland)
  ......two primary processes

• Questions & Comments

• A special thanks to Dave Dickson of Boeing
And now ...........

On with the show
What are composites?

• A “composite” is a material form made of at least two materials
  – Visually distinct: you can see the fiber and resin areas
• The Advanced Composites that we use for Aerospace typically have a “matrix” (e.g. an epoxy or BMI resin) and a “reinforcement” (can be carbon fiber, fiberglass, Kevlar, etc.)
• Two main classes of advanced composites: thermoset and thermoplastic.
  – Thermoset – cross-linking of the resin molecules is not reversible.
  – Thermoplastic – possible to re-heat and melt the resin
• Other types: ceramic matrix, metal matrix
• Materials are very unique in their properties and applications
• Many processes involved in creating high-quality parts
  – Attention to detail very important - must get each step right!
What’s an “Advanced Composite”? 

- Advanced Composites are typically thought of as those with fiber volumes (or fiber fractions) greater than 50%
  - Qty of fiber / total composite laminate including fiber & resin
- Typical aerospace Advanced Composites have fiber volumes of around 55%
- Materials used and manufacturing processes deliver these types of parts.

787- Advanced Composite  
Boeing illustration

Usually Not Advanced Composite  
Dickson photo
Advantages of Composites

- High strength/weight
- Low CTE
- Excellent in fatigue properties
- Won’t corrode
- Can tailor laminate to loads
- Can enable very significant part count reductions

747 – 1% composite: 1M fasteners
787 – 50% composite: < 10K fasteners
Sampling of Composite Products

1. Boeing 787
2. BMW i3
3. Windmill Blades
4. Blackbird Guitar
5. Various Sporting Goods
6. BMW/Oracle America’s Cup Yacht
The Main Constituents

- Fibers: Carbon, Glass, Kevlar® (Aramid), Boron, Quartz & other natural fibers (hemp, flax, basalt)
- Matrix (resins): Thermosets, Thermoplastics, Ceramics and Metals (both less common)
- Cores & inserts (honeycomb, foam, balsa, grommets, etc.) at times.

Main focus of this presentation will be Carbon Fiber/Epoxy laminates
Resins

• The matrix (resin) transfers load from fiber to fiber
• Resins are typically high CTE materials; the fibers are most typically low CTE
• Thermosets: Epoxy, Bismaleimide (BMI) & phenolic most typically for aerospace. Others: polyester, vinyl ester, cyanate epoxy, etc.
  – Resin constituents cross-link (cure) in a chemical reaction: shape is permanent.
• Thermoplastics: PEEK, PEI, PPS, PEKK most typically for aerospace. Others: PP, PS, PET, PA, TP PI
  – Resin melts and solidifies on cool-down. Can be re-melted and re-formed to different shape.
Fibers and Yarns

• Carbon Fibers are actually quite small. Fibers are bundled together to make yarns.
• The Yarns, or “Tow” come in many sizes:
  – Small Tow: 3K, 12K, 24K
  – Large Tow: Larger than 24K
• Example – 1K fiber has 1,000 fibers per yarn

Fibers are 5 microns in diameter
Producers of Carbon Fiber

- Hyosung
- SGL
- Zoltek
- Mitsubishi Rayon
- Toho Tenax
- Toray

## Global Production of CF by Tow Size

<table>
<thead>
<tr>
<th>Year</th>
<th>Small Tow (3k-24k)</th>
<th>Large Tow (&gt;24k)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>72,145</td>
<td>39,640</td>
<td>111,785</td>
</tr>
<tr>
<td>2013</td>
<td>79,845</td>
<td>44,640</td>
<td>124,485</td>
</tr>
<tr>
<td>2014</td>
<td>94,345</td>
<td>46,200</td>
<td>140,545</td>
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<tr>
<td>2015</td>
<td>101,645</td>
<td>48,700</td>
<td>150,345</td>
</tr>
<tr>
<td>2016</td>
<td>106,145</td>
<td>50,700</td>
<td>156,845</td>
</tr>
<tr>
<td>2017</td>
<td>109,145</td>
<td>51,700</td>
<td>160,845</td>
</tr>
<tr>
<td>2018</td>
<td>111,145</td>
<td>52,700</td>
<td>163,845</td>
</tr>
<tr>
<td>2019</td>
<td>113,145</td>
<td>53,700</td>
<td>166,845</td>
</tr>
<tr>
<td>2020</td>
<td>115,600</td>
<td>53,700</td>
<td>169,300</td>
</tr>
</tbody>
</table>

*metric tonnes*

How are carbon fiber prepreg materials made?

- PAN (Polyacrylonitrile), pitch or rayon precursors
- Superheated to 4900°F (pyrolysis)
- Spun into fiber
- Ultrahigh heating, oxidation, carbonization & graphitization
- PAN-based: typically higher strength
- Pitch based: higher modulus
- Rayon-based – industrial grades
- Aerospace companies typically use PAN-based fibers
Carbon Fiber Properties

- Fibers that are made into prepregs come from several providers – Hexcel (HexTow), Toray (Torayca), Mitsubishi Rayon (Grafil), Toho (Tenax), Cytec (Thornel) – there are others.
- Aerospace fibers tend to be categorized by their modulus

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Tensile Modulus</th>
<th>Tensile Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Volume Grade</td>
<td>&lt;25MSI</td>
<td>250–500 KSI</td>
</tr>
<tr>
<td>Standard Modulus (SM)</td>
<td>32–35MSI</td>
<td>500–700 KSI</td>
</tr>
<tr>
<td>Intermediate Modulus (IM)</td>
<td>42–43MSI</td>
<td>600–900 KSI</td>
</tr>
<tr>
<td>High Modulus (HM)</td>
<td>50–65MSI</td>
<td>600–800 KSI</td>
</tr>
</tbody>
</table>

Primary Source: ASM Handbook Vol.1
Source: USG DoE
Basic Steps in Carbon Fiber Production (PAN Precursor shown)

Raw Material (powder)
- Poly-Acrylonitrile (PAN) goes through polymerization (turned into powder that will stick)
- solvent is added to turn into a spinning dope.

Pre-cursor (white fiber)
- Dope is spun into fiber, washed, dried, & chemically treated.
- Commercial pre-cursor used only to make low end fiber (chop application).
- high quality continuous ribbon used to make aerospace quality.

Carbon Fiber: Simplified, the process is heating and stretching precursor material through several oven stations ranging from 400F to 2500F. (Burnt String)
Next – Creating the Product Forms

• Getting the fibers into the right place
  – Unidirectional (UD, or “Uni”) Materials – Tapes, Roving, Towpreg, Slit Tape
  – Woven Materials – Fabrics, Braids, 3D Weaves
  – Chopped Fibers (short)
  – Milled Fibers (very short)

• Impregnating with resin
  – Prepregging by material manufacturer, or
  – Resin Infusion Processes (by part manufacturer)
Basic Steps in Pre-impregnation Process

- One of two methods are used to impregnate the dry carbon fiber with polymeric matrix (resin).
- Different matrices have different properties (toughening, etc).
- Material is time and temperature sensitive after impregnation….must be kept frozen to maintain chemical and handling properties until cure.
Uncured composite materials typically have “shelf life” limits:
- How long they can be refrigerated (frozen)
- How long they can out of refrigeration, uncovered
- How long they can be held, under a vacuum bag, before autoclave curing

Time limits are dependent on type of material. Typical example:
Typical Prepreg Product Forms
Aerospace Applications

Unidirectional Tape
- Typically 3”, 6”, 12” wide
- Most typically used with automated layup
  - Will follow tool contours
  - Not typically used on outer plies – drilling quality issues

Unidirectional Tow
- Various narrow widths
- Can be made by slitteing tape
- Always used with automated layup
  - Several bands laid at once
  - Steerable (to a certain extent)
  - Not typically used on outer plies – drilling quality issues
  - More gaps/laps issues than with tape

Woven Fabrics
- Typically 30” or 60” wide rolls
- Most typically used with hand layup
- Various weaves – some have better drapability
- Typically used on outer plies – least drilling breakout
- Generates most scrap

Boeing Photos
<table>
<thead>
<tr>
<th>Tow / Slit Tape Widths</th>
<th>Tape Widths</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.125”</td>
<td>1”</td>
</tr>
<tr>
<td>0.157”</td>
<td>1.5”</td>
</tr>
<tr>
<td>0.182”</td>
<td>3”</td>
</tr>
<tr>
<td>0.250”</td>
<td>6”</td>
</tr>
<tr>
<td>0.500”</td>
<td>12”</td>
</tr>
</tbody>
</table>
Tape Width Drivers

Narrower

Surface contour/steering
Knockdown for gaps
Ply width increment
Crenulation fidelity
Fly-away splices
Buy-to-fly ratio
Raw material cost*
Spool/Roll length
Head complexity

* Except for towpreg

Wider
What’s a Crenulation?

• Jagged excess left by automated layup machines.
  – Machines trim ply courses at 90° to head travel.
  – Must layup so that there is full coverage of ply material.

1.0” Excess Line (usually scribed on tool)
Net Trim Line

Crenulations
Typical Fabric Weaves

- **Plain Weave (PW)**
  - Good fabric stability
  - Least pliable

- **Basket Weave**
  - Flatter, stronger than PW
  - Less fabric stability, more pliable than PW

- **Leno Weave**
  - Low number of yarns
  - Good fabric stability
  - Not often used for Aero

- **4 Harness Satin (4HS) Weave (AKA Crowfoot Satin)**
  - Less fabric stability
  - More pliable than PW
  - Good drapability

- **8 Harness Satin (8HS) Weave**
  - Low fabric stability
  - Very pliable, drapable
  - Only used on curved surfaces

- **Twill Weave**
  - Better fabric stability than satin weaves
  - More pliable than PW

- **PX (Bias) Weave**
  - Good fabric stability
  - Least pliable
  - Can eliminate confusion of +/-45° plys

Textreme (Oxeon)

• Woven unidirectional spread-tow fabric materials
- Quasi-Isotropic Reinforcement in a Single Braid Layer
- Symmetric and Balanced with One Ply

![Graphical representation with 33% uniform stiffness in all directions and 0° (axial) and ±60° (bias) orientations.]
Specialty/Decorative Weaves

Photos used by permission of CFA
The Radius Filler or “Noodle”

- Composite materials are inherently stiff
  - Sharp corners are avoided (not producible and structurally bad)
- For certain types of geometry (blades / back-to-back angles, I or J-shapes) a void is formed between the “halves” of the shape. The more plys in the laminate, the bigger the void
- The void must be filled with material
- Area is prone to quality issues
“Noodle” former (radius filler)

• At simplest form, can be a hand-held die.
• Automated machinery has been made - forms radius filler from folded tape
  – Material pulled through a die by machine

Fiberglass

- Fiberglass prepreg has lots of aerospace applications in non-structural parts
  - Fairings
  - Radomes
  - Interiors parts
- Non-aerospace: boats, car/truck bodies, windmill blades
- Fiberglass plys are also used on composite laminates between carbon fiber plys and aluminum structure as an isolation patch to prevent corrosion.
- Fiberglass has also been used for tool leak tests (2 or 3 plys cured on layup tool; leaks show as a starburst pattern on the cured plys)
Corrosion & CFRP

- Aluminum will corrode when in contact with CFRP
- Certain fastener materials can also be inappropriate.

Dry (Unimpregnated) Product Forms

• Many traditional fabrics are available without added resin
  – No cold storage requirements
• Typically used in “infusion” processes in aerospace, wet layup in other applications
• Unique braided, woven product forms have been developed to address producibility issues.
Dry Fiber Products

<table>
<thead>
<tr>
<th>2-D triaxial braid</th>
<th>Woven fabric</th>
<th>Knitted multi-axial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tailorability limited (no 90’s)</td>
<td>Drapability excellent</td>
<td>High laydown rates for hand layup</td>
</tr>
<tr>
<td>Excellent material usage</td>
<td>Fiber orientation less tailorable</td>
<td>Fiber orientation tailorable (less crimp)</td>
</tr>
<tr>
<td>Good for contour</td>
<td>Poor material usage</td>
<td>Poor material usage</td>
</tr>
<tr>
<td>Automated process</td>
<td>Crimped fibers</td>
<td>Generally higher cost</td>
</tr>
<tr>
<td>0-fibers follow neutral-axis</td>
<td></td>
<td>Limited contour use</td>
</tr>
</tbody>
</table>
Woven preforms

- Complex woven shapes or flat shapes
- Can have extreme drapability
- Can make thick preforms

Fiberglass Pi-Chord Preform
Braids

- Braids typically a “sock” or “hose” – like form
- Fibers both in axial or bias directions
- Bias fibers can range from 10 to 80 degrees
- No 90 degree fibers

Biaxial Braid

Triaxial Braid
Braids

- Braids typically a “sock” or “hose” – like form
- Fibers both in axial or bias directions
- Bias fibers can range from 10 to 80 degrees
- No 90 degree fibers

Biaxial Braid  Triaxial Braid
Discontinuous fiber products

- Used on extreme contours/shapes wouldn’t allow other products to be used
  - Stretch-Broken Carbon Fibers
  - Cytec D-Form (mainly for Tooling)
Non-cramp fiber products

- Fibers in traditional woven fabrics “crimp”.
  - Reduces load-carrying capability in direction of fiber
- NCF fabric is created by stitching unidirectional layers together
  - Fibers not woven, no fiber crimp
- Can have several layers stitched together
Molding Compounds

• Short fibers compounded with resin for compression molding
  – Sheet Molding Compound (SMC)
  – Bulk Molding Compound (BMC)
  – Low mechanical properties
• Randomly-oriented strips of unidirectional tape prepreg
  – HexMC from Hexcel

HexMC\textsuperscript{tm} (and HexTool\textsuperscript{tm})
Image courtesy of Hexcel
Demand by Product Form

### Global Carbon Fiber Production Demand, by Fiber Form, 2012-2020*

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Woven Fabric</td>
<td>20,770</td>
<td>24,220</td>
<td>26,840</td>
<td>32,590</td>
<td>36,880</td>
<td>38,470</td>
<td>43,690</td>
<td>47,630</td>
<td>53,640</td>
</tr>
<tr>
<td>Thermoset UD Prepreg</td>
<td>42,420</td>
<td>45,950</td>
<td>49,300</td>
<td>52,950</td>
<td>57,280</td>
<td>61,160</td>
<td>66,210</td>
<td>71,000</td>
<td>76,470</td>
</tr>
<tr>
<td>Thermoset Fabric Prepreg</td>
<td>36,330</td>
<td>41,190</td>
<td>49,850</td>
<td>56,960</td>
<td>61,400</td>
<td>62,780</td>
<td>69,390</td>
<td>74,290</td>
<td>78,640</td>
</tr>
<tr>
<td>Thermoplastic Prepreg</td>
<td>6,830</td>
<td>9,010</td>
<td>9,460</td>
<td>11,280</td>
<td>13,070</td>
<td>14,100</td>
<td>18,830</td>
<td>23,830</td>
<td>27,340</td>
</tr>
<tr>
<td>Raw Fiber</td>
<td>19,990</td>
<td>21,240</td>
<td>24,880</td>
<td>27,000</td>
<td>30,440</td>
<td>31,760</td>
<td>35,870</td>
<td>37,140</td>
<td>40,770</td>
</tr>
<tr>
<td>Molding Compounds</td>
<td>25,070</td>
<td>26,150</td>
<td>30,450</td>
<td>34,840</td>
<td>38,960</td>
<td>40,630</td>
<td>41,290</td>
<td>44,850</td>
<td>44,580</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>151,410</td>
<td>167,760</td>
<td>192,780</td>
<td>215,620</td>
<td>238,030</td>
<td>248,900</td>
<td>275,280</td>
<td>298,740</td>
<td>321,440</td>
</tr>
</tbody>
</table>

*metric tonnes*

Cores

• Cores are used to stiffen products, with the addition of only minimal weight
• Aerospace cores tend to be honeycomb materials (lightest and most expensive)
• Other products use balsa, foam & other unique cores
• In-service problems with cores tend to be in areas where minimum gage laminates (few plys) are damaged or porous, allowing moisture to accumulate in core
  – Freeze/thaw cycles, corrosion, etc.
Honeycomb Core

- Various materials
  - Nomex®, Korex® aramid
  - Fiberglass
  - Polyimide/PAI
  - Graphite
  - Aluminum, etc
  - Ultem PEI

- 1/8”, 3/16”, 1/4”, 3/8” cell sizes are typical
- Core Densities 1.5 – 19.5 lbs/cu ft
- “Ribbon” – directionality: core bends / flexes easily in transverse direction, stiff in ribbon direction
- Typically milled to shape with valve stem cutter or formed
  - Edge chamfers
  - Contour

Core Orientation
- T – Thickness or cell depth
- L – Ribbon (or longitudinal) direction
- W – Transverse direction
- d – Cell size
Common Aerospace Cores

Face plys

Film Adhesive

Core

Face plys

Film Adhesive

Core can be milled or formed to shape

Hex Core

Flex Core

Over-expanded Core
Other cores
(Mainly non-aerospace)

• Cores are available in product forms that are optimized for the process used (i.e. resin infusion or wet layup)
• Cores used in infusion allow resin to travel along grooves & through holes to wet-out tool-side pllys
• Balsa
• Foam
  – Rohacell has been used in aero structure
• Soric – combination core & infusion medium (fabric-like)
• Parabeam – non-traditional infusion product

Dickson photos
Core Stabilization

- Prevent plys over core from slipping
- (Contributes to core crush)
Products for Lighting/HIRF Protection
(HIRF-High Intensity Radiated Field)

- Metal airplanes – nearly entire airplane surface is very conductive; lots of ability to dissipate lightning strikes
- Composites – special treatments are typically necessary to prevent lightning from creating holes in structure & penetrating fuel cells
- Schemes allow conduction of current away from fasteners
- Interwoven Wire Fabric (IWWF)
- Expanded Aluminum Foil
- Sealing of “fay” (interfacing) surfaces, panel edges, cap seals on fasteners, etc.
Part Engineering Drawings
(and/or Specs)

What you can expect to see:

• Scale drawing or dataset showing ply boundaries
• Ply orientation rosette
• Splice requirements
• Ply table
• Core definition (if present)
• Materials used
• Quality requirements (dimensional, porosity, etc.)
Fabric Terminology & Ply Orientation

Typical Ply Orientation Rosette As-Scribed on Layup Tool

Ply Orientation (ref)

- 45°  90°  + 45°  0°
Ply Splices

• Splices may be required due to material size limits
• Drawings don’t always say where to splice
• “No Splice” areas usually noted

Splice Types
  – Overlap joints
    • Not allowed in faying regions or in filler plys
    • Often a .50” or less overlap
  – Butt joints
    • Often a .06” or less gap
Example Drawing

(Schematic, NoScale)
Ply Drops and Padups

- In many cases, localized plys are added for load carrying purposes, increased thicknesses for fasteners, etc.
- Plys are tapered (or dropped-off) gradually so as to not create stress riser or quality problems.

Henkel test panel with more extreme ply drops
Balanced, Symmetric Layup
(Different Example)

- A balanced, symmetric layup helps prevent laminate warpage
- A balanced layup “balances” the off-axis plys (e.g., equal numbers of $+45^\circ$ & $-45^\circ$ or $+60^\circ$ & $-60^\circ$ plys)
- Not always possible in all areas of a part (e.g., where pad-ups exist)
- A symmetric “quasi-isotropic” layup is common
  $[0/+45/-45/90]$ $[90/-45/+45/0]$ or
  $[0/+45/-45/90]$,
  - 25% $0^\circ$, 25% $90^\circ$, 25% $+45^\circ$, 25% $-45^\circ$
  - Isotropic in-plane only
- Quasi-isotropic: $180^\circ$ /Number of ply orientations that you need

Example Layup

<table>
<thead>
<tr>
<th>Ply</th>
<th>Orient.</th>
<th>Mat'l</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0°</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>$+45^\circ$</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>$90^\circ$</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$-45^\circ$</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$+45^\circ$</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>$90^\circ$</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>$-45^\circ$</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>$+45^\circ$</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>$+45^\circ$</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>$-45^\circ$</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>$90^\circ$</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>$+45^\circ$</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>$-45^\circ$</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>$90^\circ$</td>
<td></td>
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<tr>
<td>19</td>
<td>$+45^\circ$</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>0°</td>
<td>1</td>
</tr>
</tbody>
</table>

Mat’l 1 callout: type, weight, Mfr.
Mat’l 2 callout: type, weight, Mfr.
Issues that make parts warp

- **Unbalanced laminate**
- **Poor compaction/resin imbalance**
  - Less resin, lower CTE
  - More resin, higher CTE

- **Excessive Tool CTE**
  - Tool/ply friction
  - Ply/ply slippage

Unbalanced stresses in part causes warpage

Warped part on cool-down

Tool growth
Composites Processes

- Ply Cutting of Prepreg Materials
- Hand Layup
- Composites Tools
- Vacuum Bagging
- Autoclave Curing of Composites and Out of Autoclave Curing OoA
- Resin Infusion, Resin Transfer Molding, Resin Infusing Molding and Stand Alone Molding
- Filament Winding
Steps in making parts from prepreg

1. **Pull prepreg from freezer**
   - Record time
   - Use Now

2. **Cut hand-laid plys**
   - Use Later
   - Kit & seal for later use
   - Return to Freezer

3. **Layup**
   - Temp bag or Reusable bag

4. **Compaction or Debulk Cycles**

5. **Final Bag**
   - Record time

6. **Cure**
   - Remove part from tool

7. **Trim**

8. **NDI**

9. **Assembly**
Ply Cutting

• Larger Shops use ultrasonic cutters
  – Gerber, AGFM, Eastman, others
  – Accuracies to .003”
  – Fast cutting
  – Integrated nesting to minimize waste

• Many plys are cut by hand
  – Scizzors, “pizza wheels”, steel rule dies, etc.
  – Knives only if backing material used
Manual Cutting Methods

• Cutting devices
  – Razor blade / Razor knife
  – Hand held shears
  – Rotary ("Pizza") cutter
  – Steel rule die
• Most manual cutting devices are less accurate than automated methods
• Allow “trim to fit” (cuts during layup)
• Cuts should use backing boards
• CAN DAMAGE TOOLS if done improperly.
• Can lead to CTD injuries
Ply Cutting & Kitting

- Plys nested – minimize waste
  - Automated

- Plys kitted for layup
  - Doublers
  - Padups
  - Refreeze if not immediately used

Boeing illustrations
Hand Layup

• Smaller aerospace parts, all boats, sporting goods all are done by hand layup
• Plys that are cut to the right shape are placed, or “laid-up” in the right place and orientation
• Very sensitive to process anomalies – mistakes, leaving extraneous materials in the laminate, poor technique, contaminants...
• MUST do things correctly, per the drawing, per the process documents and the planning instructions.
Locating Plys

- Plys are most typically located by laser projection devices or by physical templates
  - Red or green lasers
- Templates are sometimes necessary, even when shop has a laser projector.
  - Tool fabrication, rework, maintenance costs

Boeing photos
Layup Aids

- Shops typically have a palette of shop aids available
  - Sweeps
  - Silver pencils
  - Scissors
  - X-Acto™ knives
  - Tapes
  - Gloves
  - etc.
Tooling for Hand Layup

- Variety of materials available
- Aerospace mfrs use Invar 36 for most production applications unless tool weight is an issue
- Many varieties of composite materials
- Steel, Aluminum, Nickel also used
- Usually best to use best match with the CTE of the part

Typical Aerospace Tooling Materials

- Steel, Nickel
- Alum, Steel, Nickel — Can be exceptions!
- Invar or Carbon Fiber/BMI or Benzoxazine

Production
Prototype

Foam, MDF, RP Materials
GFRP
Carbon Fiber/Epoxy

3 ft
6 ft
(Over)
Composite Tools

- Composite materials primarily used for Outside Mold Line tooling applications (i.e. cover panels)
- Most composite tools will require a master or pattern to lay up on. (HexTool product may not necessarily require them)
- Eggcrate or tubular substructures
- ~1/3 the weight of a comparable Invar tool
- Longevity dependent on many things – how well they are made, how well they are treated in production, environmental conditions, etc.
Composite Tool Examples

NONA Composites (CamX paper)\textsuperscript{24}  
Pic: Janicki Industries\textsuperscript{25}

www.burnhamcomposites.com\textsuperscript{26}  
Boeing /Spirit Sect. 41 fuselage mandrel\textsuperscript{27}
Invar Tools

- Tool size & shape dependent on part
- Outside Mold Line & Structural Parts
- Many tools will require 6” or more excess
- Panel tools – eggcrate or partial eggcrates with tubular frames
- Welding, machining & annealing processes
- Billeted tools for smaller parts
- Extremely durable – should last for over 1,000 cycles
Invar Tool Examples

Rib Layup Mandrel/Mold

RTM Die for Helicopter Rib (North Coast Tool & Mold)

Nacelle Layup Mandrel/Mold (Coast Composites)

787 Wing Skin LM
Vacuum Bagging

• Vacuum bags help compress or “compact” plys in the layup shop environment.
• The bag, sealant tape, tool and fittings make up a system that has to be vacuum-tight, especially for liquid resin infusion processes.
• Two main methods:
  – Consumable (throw-away) bags
  – Reusable bags
Rolls of Material

• Airtech
• Cytec (former Richmond Aircraft Products)
• Others?
• Pre-kitted/pre-seamed bags available
Consumable Bags

• Bagging films – various materials, depending on application (nylon, kapton, etc.)
• Pleats help ensure pressure transfer
  – Allow bag to be fitted to complex geometry
Example Bagging Schematic (Prepreg parts)

- Bagging Film
- Breather cloth
- FEP release film
- Peel Ply or caul *(optional)
- Laid-up Part Plys
- Tool

Consumables

* Caul is reusable

Typical Spec Diagram
Reusable Bags

- Fabricated elastomeric bag
- Fitted to part – eliminates pleating
- Big time saver in production
  - Compaction & debulk cycles
  - Cure cycle
- Often have proprietary sealing methods

Custom bag for NASA AST Wing

“Sprayomer” Bag

Silicone Bag (Smooth-On)
General Description

- Vacuum bag de-bulking
- Vacuum bag curing both autoclave and oven at 350 to 400 F and autoclave pressures up to 200 psi.
- Vacuum Assisted Resin transfer Molding (VARTUM) used on medium to large FRP structures.
DESIGN OVERVIEW
(KEYHOLE SEAL W/PREFORMED BAG)

New Tool Material Design Parameters

Fig. 1
Design Overview
(Keyhole seal w/Preformed Bag)

Eliminating Complexity of Vacuum Bag
Fabricated Composite structures

RPBS™ showing a Wax Mock-up of Final Layup

Auto-Vac™ with channel bonded onto tool showing a completed part used for Mock-Up
Materials

BP 102.080-G Uncured “B” Stage Elastermer .080” Thick (Grey)

BP 103 CH&K-05
Silicone Extrusion Channel & Keyhole Seal .250”

BP 103 CH&K-05
Silicone Extrusion Channel & Keyhole Seal .500”
Vacuum Leak Detection

• Various methods
  – Listen for audible leak
  – Use stethoscopes, sniffers, etc
  – Static tests (measure vacuum loss over a time period, e.g. 2” Hg loss in 5/10/20 mins. – dependent on tool size)
  – Helium leak check
  – Phenolphthalein leak test
  – 2 or 3 ply fiberglass prepreg layup/cure
Compaction & Debulk

• For thick laminates, even transfer of pressure can be difficult.
  – Potential issues: Ply bridging, resin richness/starvation, etc.

• Intermediate steps often taken in layup:
  – Ply compaction – bag the plys and let it compress under vacuum (some times as often as every two plys)
  – Hot debulk: bag the part, heat it and let it compress (lower temperature than cure temp), e.g. 200° F for 350° F curing prepreg (done much less often than RT compaction)
Autoclave Cure

- Parts cured per a spec
  - Heatup requirements
  - Dwell requirements
  - Cooldown requirements
  - Parts monitored by thermocouple and vacuum level
    - Watch for exotherms

- Often a nitrogen atmosphere is used in autoclave
  - Prevents fires from exotherms, etc.
  - Some sealant tapes actually perform better in nitrogen (foaming prevention)

- All autoclaves are not created equal (P, T)
Out-of-Autoclave (OoA)

• Resin Infusion processes (some may still use Autoclaves)
• Oven Cures
  – May use specially-formulated prepregs
• Stand Alone Cures
  – Integrally-Heated Tools
Resin Infusion

• Typically, a dry preform is laid-up, placed under a vacuum bag and mixed resin is drawn into the preform.
• Many different variations to this, with numerous patents involved.
Steps in making parts infused parts

1. Layup
2. Install Consumable Items
   - Peel ply,
   - Resin Distribution Media
   - Vacuum Lines
   - Resin Distribution Lines
   - Vacuum bag
3. Draw Vacuum
4. Mix Resin, Infuse & Cure
5. Remove part from tool
6. Trim
7. NDI
8. Assembly

Create Preform
- Stitching A/R, Add Tackifier
Creating the Preform

- Methods used typically depend on part complexity
- Simplest – cut plys and place them on mold in correct position, typically with a sprayed tackifier
- Often use Non-Crimp Fabrics (NCF) for rapid ply buildup
- Complex – stitch plies together to form integral stiffeners, etc.
Robotic Ply Placement for Automotive Applications

- Most typically for Resin Transfer Molding (RTM) applications:
  - Plys are nested and cut
  - Plys are located by “pick and place” operations – robots with vacuum or needle gripper end effectors
Large Preforms → Large Parts

Latecoere Passenger Door

NASA AST Wing Preform
Some of the Processes
(everybody’s got an acronym)

• CAPRI (Boeing) – Controlled Atmospheric Pressure Resin Infusion
• RTI (Bombardier) – Resin Transfer Infusion
• SCRIMP – Seeman Composites Resin Infusion Manufacturing Process
• VaRTM – Vacuum-assisted Resin Transfer Molding
• VIP – Vacuum Infusion Process
• VAP (Airbus) – Vacuum-Assisted Process
How Resin Infusion Works (typical simplified schematic)

- Vacuum Pump
- Resin Trap
- Advancing Resin Flow Front
- Vacuum Line Around Periphery
- Peel ply over part
- Resin Distribution Media
  Approx 16 “ or so apart
- Unclamped Resin Line
- Clamped-off Resin Lines
- Mixed Resin
How Resin Infusion Works (typical simplified schematic)

- Vacuum Pump
- Resin Trap
- Advancing Resin Flow Front
- Vacuum Line Around Periphery
- Peel ply over part
- Resin Distribution Media
  Approx 16 “ or so apart
- Unclamped Resin Line
- Unclamped Resin Lines
- Mixed Resin
Notes on Infusion Media

• Infusion materials (throw-away)
  – Round tube for resin
  – Spiral-cut tube for vacuum
  – Omega shapes and other various media for resin distribution

• Some products (plastic netting) used in lieu of breathers
Resin Transfer Molding (RTM)

• Preformed plys are placed in a (very expensive) mold and resin is injected and cured.
• Matched mold halves are often held in a press
• Molds machined to close tolerances
• Often liquid-heated (oil or pressurized water)
• Fast cycle times – less than 30 minutes typically
Aerospace RTM Part Examples

A350 HTP Leading Edge
One-shot RTM
Aernnova

Sine Wave part

Radius SQRTM Roof Panel (HPC)

Latecoere A350 Door

Hexcel/Eurocopter
A380 Hinge Fitting

Comparable Metal Part

757 Door
(Boeing Photo)
Light-RTM

- Closed mold system – one side is hard tool, other is semi-rigid (~8 plies fiberglass mat).
- Resin drawn into preform by vacuum; may be assisted by a pump (2psi).
Figure 1 shows the process of the vacuum pulling the resin from the external reservoir into the part. It also shows the position of the RDM and vacuum bag as indicated by the arrows.
Project Title: Stitched RFI

Stitched Preform

- Material- carbon fiber warp-knit hybrid
- Preform size- 10’ x 5’
- Skin thickness- 0.072”
- Vectran thread
Resin Tile Installation

- Resin tiles placed on IML side in each bay (vs. OML)
- Resin material: Hexcel 3501-6 RC
Project Title: Stitched RFI

Cured Part

- Success Criteria: +/-0.030” on stiffener location
- 100% of 238 stiffener data points taken by laser tracker were within +/-0.030”!!!
- Next step- Ballistic Test!
Stand-Alone Quickstep

- Unique process that uses a “heat transfer fluid” and “floating mold technology” to cure parts.
Stand-Alone
Windmill Blade Mold

• Molds use hot liquid channels, electrical heating cables or blown hot air to cure parts.
• Size typically can require powered hinge system
Resin Film Infusion (RFI)

- Gelled, cast resin tiles are placed on the tool and preform placed over the tiles
- Part is bagged and heated in autoclave.
- Resin liquifies and wicks into the preform.

NASA AST Wing Project (SAMPE)
Debag & Tool / Part Separation

• Consumables (bag, breather, tape, etc) are removed and disposed-of.

• Part must be removed from tool CAREFULLY
  – Don’t want to damage tool or part
  – Use relatively soft tools to assist
    • Phenolic or plastic wedges
    • Wooden tongue depressors around periphery
    • Work around tool until the part breaks free

• In some cases, features designed-into the tool may offer good assistance
  – Threaded holes in stiffener mandrels
  – Cavities for wedges – cure over the wedge in part excess.
Thermoplastics

• Thermoplastics are used mainly for secondary structures and Interiors in aircraft
• Significant research in Europe for using T/Ps for more and more structure
  – TAPAS: Integral tail structure
  – Airbus: In-situ layup/consolidation of fuselage barrel structure
• PEEK, PEKK, PPS, PEI in Aerospace
• PP, PA, PBT/PET, PPS in Automotive
Benefits of Thermoplastics

• Very fast cycle times for some applications
  – Press cures: low labor cost
• Ability to re-melt & re-form
• Can be welded
• Easy to recycle
• Drawbacks are mainly material cost & high processing temperatures (600 – 700 °F).
Press-Forming of Thermoplastic Parts

Die typically has a steel half and an elastomeric half
Welding of Thermoplastics

• **Ultrasonic welding** (localized areas, e.g. inserts) – think “spot welding”

• **Resistance Welding** – a “weld strip” is placed within the part-to-part interface and is heated.

• **Induction welding** – a magnetic field induces current in the carbon fiber, creating heat
Part Trim
(Thermoset or thermoplastic parts)

• Parts in most cases are trimmed net
• Sometimes fastener holes are drilled while on the same tool
• Typical methods:
  – Hand-held router with a guide
  – Pin shaper with a guide
  – Multi-axis NC router
  – Multi-axis waterjet/abrasive waterjet
Small Parts – Trim with Routers and Pin Shapers

- Edge of router fixture tool is used to guide the router
- Router shoulder also rides on tool – ensures 90 degree cut
- Requires skilled labor – easy to gouge-up the part
Large Parts – Trim with NC routers

• Various styles of tool – may allow gage reduction/milling

Want to contain/capture the dust!
Cutters for composite trimming

- Carbide cutters (short life)
- Various grades of diamond coatings
- PolyCrystalline Diamond (PCD) Coatings – very durable
- Various geometries
Large Parts – Trim with Automated Waterjet

- Edge trim and cut-outs (doors, windows, etc.)
- Often use Universal Holding Fixtures (next slide)
- Very powerful stream of high-pressure water, with or without garnet abrasive particles
Universal Holding Fixtures

Micado “Snake System” (Repositionable Posts) 74

Micado “Hedgehog” 74

Micado “Pogostick Gantry” (Passive pogos) 74

M Torres “TorresTool” – example configurations 75
Assembly

• Traditional assembly involves “drilling and filling” – drill holes for fasteners, disassemble and deburr parts, shim parts & wet-install fasteners.
• Some technologies (e.g. orbital drilling) may eliminate the deburr operation.
• Co-curing or co-bonding parts can eliminate many downstream assembly operations, related tools and drilling equipment.
Some Assembly Considerations

- Fabric is typically used on outer plys to help prevent drilling breakout
- Fiberglass isolation plys are used where carbon and aluminum would otherwise be in contact (corrosion prevention)
- Airplane wings typically carry fuel – sealing and the lightning protection scheme are of critical importance!
Drilling Composites

- Carbon fiber is very abrasive
- Requires special skills and drills
- Clearance fit holes often used, but sometimes need to be tighter (for EME or load)
- Carbide drills used for hand drilling and/or power feed have limited life (150-200 holes), easier to resharpen
- PCD drills used for power feed equipment only, have longer life (2000-3000 holes), more expensive to resharpen
- CFRP/Ti stackups especially hard to drill

Boeing photos
“Mainstream Production” vs “One-off” / “Prototype”

- The same approaches are typically not used for prototyping vs. serial production unless you already have the equipment (tape layers, fiber placement machines, etc.)
- The place where corners may be cut is in the tooling (NEVER cut corners on production tools), but there will be trade-offs
  - Dimensional integrity
  - Warpage
  - etc
Composite Materials for Prototyping

• Materials that cure at low temperatures allow higher CTE tooling materials to be used.

• Examples:

• Cytec LTM-series – can do initial cures at 140° F
  – Elevated free-standing post cure necessary (i.e. 15 min @ 392° F then 8 hrs @ 375° F
  – Infusion resins
    • RenFusion 8615: 24 hrs @ 77° F, 4 hrs @ 250° F, 4 hrs @ 350° F
    • NONA – cures by it’s own exotherm

• Expect trade-offs!
Examples of Prototype Tooling

• Layup/cure:
  – Plaster/Bondo
  – Wood/MDF
  – Foams from General Plastics, Coastal Enterprises, Stepan, etc
  – Cfoam carbon foam with surface filler
  – Additive Mfg materials (FDM Ultem)
  – REN RP4040 “LCTC” patties over alum. honeycomb
  – Aluminum rather than Invar

• Trim:
  – Foam with a vacuum chuck or hold part with drywall screws in part excess or with double-back tape
  – Additive Mfg materials (e.g. SLS Nylon or FDM ABS)
  – Hand layout/hand trim with straight edge guide

• Assembly
  – Layout holes with mylar plot and hand drill
  – Use metrology assist (Laser Tracker)
Planes, Blades and Automobiles

• Quick overview of how parts are made
Fabrication of Composite Aircraft Structure

- Upper Panel
- Lower Panel
- Spars (2 or more)
- Ribs
- Stringers (various types!)
- Rib Posts (at each rib/spar joint)
- Shear Ties (upper & lower at each rib)

Dickson illustration
A few Examples of Production Curing Methods

Composite Aircraft Wing Skins

• Co-bond
  – Pre-cured stringers with uncured panel

• Reverse-Co-bond
  – Pre-cured panel with uncured stringers

• Resin Transfer Infusion
  – Resin infused into panel and stringers through stringer caps
  – Co-bonded vent stringers (hats)
Stringers

- Stringer geometry (i.e. “hats” “blades”, “I’s” or “omegas”) can be a determining factor of cure method and tooling concept.
- Drape forming, roll forming, press forming commonly used prior to cure.
A few Examples of Production Curing Methods Composite Aircraft Wing Spars

- **Hot Drape Forming** most common
  - Uni-tape laid flat, then formed to channel shape under heat and bladder pressure

- **Other methods** (mostly studies):
  - Automated Fiber Placement
  - OoA Prepreg
  - RTM
A few Examples of Production Curing Methods
Composite Aircraft Fuselages

• One Piece Barrels
  – AFP & Co-cure of stringers and skins on IML tooling

• Build-up from panels
  – AFP & Co-bond cured stringers and uncured skins on IML tooling
  – Some smaller airplanes have used hand layup and honeycomb-stiffening

• Studies – OoA prepregs, Resin Infusion
Honeycomb-Stiffened Parts

• Most typically hand layup
• Autoclaved cures, 350° F at 45-60 psi
• Ribs, control surfaces (e.g. flaps, ailerons, rudders, fairings, etc.)
• Control surfaces can be multi-stage cures due to having complex components in a bond assembly (spars, fittings, close-out ribs, etc.)
Future A/P Fabrication

• EU research: thermoplastic fuselages & wings
  – (TAPAS, FUBACOMP, FUSCOMP, other “Framework programmes”)
• Use of more OoA technologies (prepregs, RTM, VaRTM, integrally-heated tools, etc)
Wind Generation

• Due to size, processes rely on resin infusion and OoA cures
• Traditionally fiberglass with foam, balsa cores in skins and foam cored spars
Wind Generation

• More recently – use of Non-crimp fabrics
  – Glass/Carbon/Aramid hybrids
    • Faster laydown rates

• As blades get larger, more carbon will likely be necessary

• More layup automation
  – Fives Cincinnati, Danobat, M Torres, others
Autos

• Big push to drive down cost
  – Carbon Fiber:
    • BMW with SGL
    • Ford with DowAksa
    • ORNL low cost carbon
  – Production efficiency
    • Plasan 16 minute cures on Corvette hoods
      – Globe “Rapid Claves”
      – BMW automated preform handling for RTM
Bikes

• Prepreg plys cut
• Layup in a female mold with a bladder
• Mold closed & placed in a press
• Bladder is pressurized
• Part is cured & demolded
• Fittings are secondary-bonded

Trek Bike pictures courtesy of High Performance Composites

90
End of Life: Recycling

- Thermoplastics are the easiest to recycle.
- Thermosets are most often used.
- Thermoset recycling most often means separating fiber and resin (cured or uncured) – Pyrolysis, Fluid Bed Oxidation, Solvolysis, etc.
- Long fiber products become short fiber and recombined with resin (molding compounds, etc.)
- Development work: fiber alignment

https://www.youtube.com/watch?v=-ZQzfwdHf1I
Filament Winding Process

- Types of Filament Winding Machines
  - Tube Winders
  - Longo Winders
  - Complex Shapes 3 Axes or more
  - Ring Winder
Pros and Cons of Wet Filament Winding verses Prepreg Winding

• Pros
  – Cost of materials
  – You control the quality of the fiber impregnation
  – No storage of prepreg material and worry about material running out of date.

• Cons
  – Some feel it saves time using prepreg material
Wet Filament Winding For Process Control
Three Axes Filament Winding Machine With Fiber Impregnation On Machine
Filament winding of outer skin using Prepreg fibers
Filament Winding Machine - Winding Spar Tube
Race Track Winder
Manufacturing spar caps
For Composite Main Rotor Blade
Race Track Winder – showing resin impregnation of fibers
Filament winding of prepreg spar cap

Spar cap assembly
Four axes electrically driven computer controlled unidirectional fiber placement machine with 16 rotating fiber spools

Manufactured by Century Design
Tooling and Filament Winding Process
This filament winding machine has 5axis
Ring Winder – A developmental machine with a stationary mandrel and rotating fibers
Machine Layup

- Prepreg Tape, Slit Tape, Towpreg or Roving is laid-down in a pre-determined orientation by automated machines
- Flat tape laminators (3-axis)
- Contoured tape laminators (5-plus axes)
- Automated Fiber Placement (AFP) machines
- Automated Filament Winders (sometimes uses wetted-out roving)
- Pultrusion machines
- Typically the machines come in a number of configurations/sizes/etc.
Machine Layup

• Machine layup is most effective when they can lay-down very long courses of material, uninterrupted
  – Starts and stops for short courses reduce effectiveness
    • E.g. 90 and +/-45° plys on long, narrow parts
• Name of the game is lbs/hr in laydown
  – Varies considerably with complexity of part design and basic geometry
  – Traditional machines anywhere from 5 – 25 lbs/hr
  – Machine mfrs working to move this closer to 100 lbs/hr
Automated Tape Layers

M Torres

Fives Cincinnati machine
At Exelis

777 Skin Panel Layup
(Boeing photo)
Automated Fiber Placement

More traditional machines

Ingersoll – Vertical

Ingersoll – Horizontal (787 Alenia)

ElectroImpact

Fives Cincinnati
Methods of Fiber Delivery

Spools at head

Central Creel-house

M Torres Photos\textsuperscript{32}
Relatively new – Automated Fabric Laydown (for infusion processes)

Fives Cincinnati Rapid Mat’l Placement System (CompositesWorld\textsuperscript{38})

M Torres Wind Blade System (CompositesWorld\textsuperscript{38})

Danobat – Gelcoat Application (SME Composites Mfg 2012)\textsuperscript{39}

Engineering TV Video (Fives Cincinnati machine)
Robotic AFP Machines

Coriolis Composites

Fives Cincinnati “Robotic Viper”

ElectroImpact

Automated Dynamics
What’s next? Robots working in unison

DLR Center for Lightweight Production Technology
GroFi Platform

M Torres Robotic ATL Cell
Tools for Automated Layup

• Tool designs must consider how the tools will be indexed to the automated layup equipment, plus any special load cases
  – Rotating tool supported by spindles?
  – Special load cases: dynamic frequency, emergency stop
  – Types of indexes required
Purpose-Built Machinery

• Large Airframers and Sub-contractors often build unique equipment to perform layup and other functions.

• Example: ATK Stringer & Frame formers

Hooper, et al (SAMPE)45
Tool Preparation

• Tools are routinely cleaned before/after each use
  – Remove resin flash, tape residue, etc.
• Tools are treated with a sealer before each use and after stripping release coat buildup
• Tools are very often treated with release coats before each use.
Non-Destructive Inspection (NDI)

• Laminates can be checked by various methods
  – Visual inspection
  – Tap tests
  – Large “monument”-type NC-driven Ultrasonic Testing (UT) machines very common in aerospace
  – Conventional and digital X-ray
  – Numerous types of hand-held devices – Pulse-echo, Laser shearography, Flash thermography, FTIR, etc

• NDI devices are calibrated by “Standards”
  – Sample parts with a known flaw
Visual Inspections

• Should be able to find:
• Warpage
• Obviously crushed core
• Surface Anomalies (resin richness/starvation, sink marks, etc.)
• Surface wrinkles
• Cracks, delaminations, etc.
• Obviously mislocated details (stiffener migration, etc.)
Monument-type NDI Equipment
Typically $Millions for larger equipment

- Ultrasonics (e.g. TTU, AUSS, Laser UT, etc.)
  - Various configurations, many have specially-designed arrays, transducers or sensors

- X-Ray (conventional or digital)

Boeing photos, except as noted
Hand-held NDI Equipment

Increasing sophistication and cost

- Tap Hammer / Quarter
- Calibrated Tap Hammer
- Pulse-Echo
- Bond Testers
- FTIR
Types of Ultrasonic Scans

- **A-Scan**: Ultrasonic pulse will show that there is a defect, displayed as a simple wave form showing amplitude vs time. Signal reflects either off the opposite side of the part (long amplitude) or off an anomaly (shorter amplitude).

- **B-Scan**: Multiple A-scans along a line.

- **C-Scan**: Records the A-scan and displays the plan view of defect boundaries (an image).
Many Devices Use All Three
What do we look for?

Some common types of Laminate Anomalies

Porosity

Wrinkles

Disbonds, Delaminations, Cracks

Voids (>0.25 in)

Inclusions (e.g. backing poly)

Ply bridging

Boeing photos
Core Anomalies

Production Issues
- Condensed or Crushed Core
- Blown Core

In-service Issues
- Water in core cell (X-ray image)
- Corroded Core With Skins Removed
- Loose Pieces of Cells
- Boeing photos

Crushed core
In-Service Issues

• Examples of types of damage composite parts might typically experience
Aircraft - FAA
Categories of Damage

Category 1: Allowable damage that may go undetected by scheduled or directed field inspection (or allowable manufacturing defects)

Category 2: Damage detected by scheduled or directed field inspection at specified intervals (repair scenario)

Presented by L. Ilcewicz at 11/10/09 Montana State Univ. Seminar

Used by permission
Aircraft - FAA

Categories of Damage

**Category 3**: Obvious damage detected within a few flights by operations focal (repair scenario)

**Category 4**: Discrete source damage known by pilot to limit flight maneuvers (repair scenario)

- Accidental Damage to Lower Fuselage
- Lost Bonded Repair Patch
- Rotor Disk Cut Through the Aircraft Fuselage Belly and Wing Center Section to Reach Opposite Engine
- Severe Rudder Lightning Damage

Presented by L. Ilcewicz at 11/10/09 Montana State Univ. Seminar

Used by permission
Aircraft - FAA

Categories of Damage

**Category 5**: Severe damage created by anomalous ground or flight events (repair scenario)

- Birdstrike (flock)
- Maintenance Jacking Incident
- Propeller Mishap
- Birdstrike (big bird)
Automotive Damage

10 inch crack to Fender Liner

Driver’s side door rocker channel impact damage

Pictures courtesy of Lou Dorworth, Abaris Training. Used by permission.
Automotive Damage

10 inch crack to Fender Liner

Driver’s side door rocker channel impact damage

Pictures courtesy of Lou Dorworth, Abaris Training. Used by permission.
Windmill Blade Damage

North American Windpower pic86.

Daily Mail (UK) pic.87

London Express88

CompositesWorld89
Repairs

• First step – decide whether it's easier/more cost effective to replace the part rather than repair
  – You often have to deal with or at least work-around underlying structure
• Repairs typically involve inspecting, removing the damage and restoring the damaged plys
  – Want to maintain close to the same strength & stiffness as the original part
• Extent of the repair depends on the extent of the damage
Typical Repairs

- **Bolted**
  - Repair patch is bolted to the damaged area
    - Cosmetically poor; may be OK in areas out of airstream

- **Bonded**
  - Step-cuts
    - New – robotic and applied devices that mill steps
  - Scarf cuts (<10° taper sanding)
    - Skilled tech’s with rotary grinder, e.g. Dotco
  - Plies cut to shape, compacted, applied with a caul and cured with heat blanket
  - Plies follow same orientation as original plies
Class Summary

- Materials – resins & reinforcements
- Processes – layup, trim, assembly
- Automation
- Inspection (in-factory and in-service)
- Repairs
- Applications – aerospace, wind, automotive
- Recycling
Questions?
Thanks to The Boeing Company and the many other companies that provided illustrations for this tutorial!

Special thanks to CompositesWorld and SAMPE for many illustrations used in this presentation.
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1. Boeing 787 photo, courtesy of The Boeing Company
2. BMW i3 – Dickson photo
5. Misc. Sporting goods: Dickson photos
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18. Core illustrations: Dickson

22. Various cutters: Dickson photo.
23. Steel rule die: www.durabledependabletools.com
28. Rib Layup Mandrel: Boeing image
30. Resin Transfer Molding Die : Dickson photo (SAMPE conference display) Additional info: www.nctm.com
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31. 787 Wing Skin Mandrel at MHI. Boeing photo
36. 787 Fuselage barrel section layup at Alenia: Boeing photo


53. 787 wing skin mandrel in autoclave at MHI in Japan: Boeing photo
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