Workshop: Assembly & Joining of Composite Materials

George “Nick” Bullen, FSME, CPIM, Technical Fellow, Northrop Aerospace Systems
Assembly & Joining of Composite Materials Workshop

Monday, March 8, 2017
1:00 pm-4:00 pm
ROOM 102

By
George N Bullen
Nick
Housekeeping

Roster/Attendance
Introductions
Handouts/USB flash drives
Cell Phones
50 Minute Hour
Numbers Game
What Can Expect Out of This Workshop?

Leave with a general knowledge for some of the various processes for assembling parts made from composite materials.

Understand their primary applications and the corresponding benefits and challenges of each process.
Overview

- The Basics for Assembling Composite Parts
- Adhesive Bonding
  - Enabling Technology
- Fastening Composites
  - Enabling Technology
- Assorted Assembly Enablers (Click Bonds and Z-pins)
- Unified Structure
  - Advantages and Disadvantages
Workshop Guidelines

- This Workshop is primarily focused on a “non-expert” audience
- Questions are encouraged…please interrupt
- Not intended as a “Death-by-Viewgraph” marathon
- There will be brakes
- There will be team challenges, discussion, and videos
Overview

Defining the Future State of Airframe and Automotive Assembly

The Future of the Airplane Factory: Digitally Optimized Intelligent Airplane Assembly

Coming Soon
Overview

We Start Here
Tacit Rainbow

• Composite Body – Aluminum Bulkheads
• Glued Together Using Automation
• Positioned with Determinant Assembly Features
Tacit Rainbow

- Apply adhesive to the bulkhead grooves
- Insert bulkheads
- “Stuff” body
- Apply adhesive to top body cover and bulkhead grooves
- Position and seat the cover on bottom half (Determinant Assembly)
- Clamp, squeeze-out, and cure
- Glue on the nose
- All Automated
- Easy peazy!!!! Right?
Tacit Rainbow

A bridge too far
Program cancelled
Composite Material Parts Assembly
The Basics
Trapping the Gap
Team Challenge One

The F35 (Center Section) has composite skins fastened onto precision machined bulkheads.
Why is this challenging (for assembly)?
What can be done about it?
Adhesive Bonding
Composite Bonding Definitions

- **Co-curing:** The act of curing a composite laminate and simultaneously bonding it to some other uncured material, or to a core material such as balsa, honeycomb, or foam core.
  - All resins & adhesives are cured during the same process.

- **Co-bonding:** The curing together of two or more elements, of which at least one is fully cured and at least one is uncured.
  - Requires careful surface preparation of the previously-cured substrate.
  - Additional adhesive may be required at interface.
Composite Bonding Definitions

- **Secondary Bonding**: The joining together, by the process of adhesive bonding, two or more pre-cured composite parts, where the only chemical or thermal reaction occurring is the curing of the adhesive itself.
  
  - Requires careful preparation of each previously cured substrate at the bonding surfaces.
  - Usually requires well designed fixtures to align & clamp parts during processing.
  - Re-heating previously cured substrates can be risky.
**Problem:**
Conventional design and assembly methods for composite airframe structures severely limit meeting future DoD airframe needs.
- Shorter build cycles
- Aggressive budgets
- Rate flexible for limited quantities to full production
- “Change-friendly” designs for multi-variant platforms

**Action:**
Use Rapid Airframe Production Integration Demonstration (RAPID) to design and build a composite fuselage section
- Integrated complex contour inlet duct
- Integral fuel floors / testable wet bays
- High load introduction (e.g. Nose Landing Gear, Catapult & Trap Hook)
- Fabricated/assembled with minimal tooling
- Used Out-of-Autoclave MTM®45-1 and Cycom®5320

**Results:**
- Details and bonded structure designs validated by analysis
- Bonded assembly reduced fasteners by 68%
- Mid course design change had minimal cost/schedule impact
Fixed Floor pi preform co-bond
Paste & co-bonded shear clips
Co-bonded pi preform skin caps
Duct co-bonded with pi preforms to upper substructure
Co-bonded lower substructure
Skin paste bond

Assembly Operations
Bagging Lessons Learned

- Engineered bags simplified bagging complex configurations
- Need improved vacuum bag leak detection capability, consider IR
- Need to reassess the leak check procedures for large structures *(large size and sandwich structure act as vacuum accumulator)*
- Need improved methods for strip bagging over surfaces where peel ply has been removed

Assembly Operations
Skin Bonding Lessons Learned

- MB7500 paste adhesive was easy to process, had good squeeze out
- For larger structures, recommend meter mix application equipment
- Hard pin location worked well for relocating the skin during the paste bonding operations
- Recommend investigating alternative clamping methods / tooling in lieu of dead weight for recurring production
- Recommend developing skin handling tools / slings for future use
- Optimize quantity of applied paste adhesive for future processes

Assembly Operations
Additional Lessons Learned

- Local co-bonding with small heaters worked well for splice
- Corner clip paste bonding process needs improvement
  - Staggered pattern of small holes minimized voids in the bond line, but adds cost
  - Magnets did not work for clamping
  - Cleco clamping problematic
- Recommend using co-bonded corner clips where practical
- Need simpler fuel bay leak check process
  - Water difficult to completely remove
  - Requires drying structure prior to next operation

Assembly Operations
Savings: RAPID vs. Conventional Composite

- Assumes same weight and % of composite fuselage structure
- Based on RAPID actual costs factored for differences in production environment
- Non-recurring tooling: 59% savings
- Recurring Fabrication: 4% savings
- Recurring Assembly: 39% savings
- Combined Recurring Labor: 25% savings
- Recurring Material: (17%) increase (driven by pi preform costs)
- Overall Combined Savings 38% @ T1

Tooling Hours Total Savings = 53.5%
Tooling Material $ Savings = 72.2%
Total Savings = 59.1%
Completed RAPID Fuselage Structure
Metal Bonding

- **Metal Bonding**: The same as secondary bonding except with metal substrates instead of cured composite substrates.

- Sometimes metals are bonded directly to composites using one or more processes.
  - Metals require very stringent surface preparation including application of corrosion inhibiting primer prior to bonding to obtain long term bond-durability at the metallic interface.
  - Care must be taken when bonding metal to carbon as galvanic corrosion can occur in the metal substrate
Basic Bonding Requirements

Apply uniform clamping pressure
5-50 psi

Properly prepare substrate surfaces

Correctly mix and/or apply adhesive

Control the bond-line thickness

Properly cure the adhesive
Loads on Adhesive Bonded Joints

- **Tension**
- **Compression**
- **Shear**
- **Cleavage**
  - Both parts are rigid
- **Peel**
  - One or both parts are flexible
Common Joint Designs

- Single Lap
- Tapered Single Lap
- Single Strap Lap
Common Joint Designs

Double Lap

Double Tapered Strap Lap

Double Strap Lap
Common Joint Designs

Tapered Scarf Joint
Failure Modes in Adhesive Bonds

- **Adhesive Failure**: Failure of a bonded joint between the adhesive and the substrate.
  - Primarily due to a lack of chemical bonding between the adhesive and the bonding substrate.
    - Can be indicative of poor surface preparation or contamination.
    - Or, incorrect adhesive selection for the substrate materials.
Failure Modes in Adhesive Bonds

- **Cohesive failure**: Failure of an adhesive joint occurring primarily in the adhesive layer.
  - Optimum type of failure in an adhesive bonded joint when failure occurs at predicted loads.
    - Lower failure loads are indicative of poorly cured adhesive or moisture or other contaminants present in the adhesive.
1) Poor, Non-Uniform, and Uncured Adhesive Bond-lines to OML Skin
Adhesive bond failure between core and precured VARTM skin (Poorly cured Adhesive)
MLAS Manufacturing Timeline

- **April '08**
  - MLAS Manufacturing Timeline
  - Fwd Fairing 3&4 (15.6' x 13’)
  - Boost skirts 1&2 (9.3' x 13’)
  - Boost Skirts 3&4 (9.3’ x 13’)

- **Aug. 11**
  - Second MRB process execution.

- **Aug 11th**
  - Third MRB process execution.

- **Aug 26th**
  - First MRB process execution.

- **June 11th**
  - Remakes using single co-infusion for Boost skirts 3&4 (9.3’ x 13’) Aug 27th
    - Fabricated using co-infusion process.
  - Discovery of Disbonds in Delivered Panels. Visual Inspection, confirmed with Destruct Tests Aug 27th – Oct 1st
    - Co-infusion Process Panel Test
    - 3 Step Process Panel Test

- **Sept ’08**
  - Fifth MRB process execution. Aug 27th (Co-infusion Decision)

- **Oct ’08**
  - Remakes using single co-infusion for Boost skirts 3&4 (9.3’ x 13’) Aug 27th
    - Fabricated using co-infusion process.

- **Nov ‘08**
  - Decision to OK scrim side down June 11th

- **LEGEND**
  - Flight Hardware
  - Test
  - MRB
Low & Variable Core to OML Skin Bond Strength

1.0 Low & Variable Paste Adhesive Material Strength

1.1 Bad or Incorrect Paste Adhesive
   - 1.1.1 Incorrect Paste Adhesive Selection Decision
   - 1.1.2 Expired Paste Adhesive

1.2 Bad or Incorrect Paste Adhesive Mix
   - 1.2.1 Incorrect Curative Selection or Ratio
   - 1.2.2 Expired Curative
   - 1.2.3 Incomplete Resin & Curative Mixing

1.3 Incorrect Paste Adhesive Application
   - 1.3.1 Adhesive Too Thick or Too Thin

1.4 Incorrect Paste Adhesive Cure
   - 1.4.1 Paste Adhesive Set before Core is Applied & Bagged
   - 1.4.2 Insufficient Bag or Clamping Pressure
   - 1.4.3 Inadequate time for Adhesive to Set before VARTM Infusion
   - 1.5 Adhesive not Properly Stored Prior to Use

Legend
- X.X Potential Fault Eliminated
- X.X Potential Contributor
- X.X Root Cause

Continued on next slide
MLAS Bond Strength Fault Tree

2.0 Low & Variable Core Tensile Strength
   - 2.1 Bad or Incompatible Core Batch
     - 2.1.1 Bad or Incompatible Core Material
     - 2.1.2 Incompatible Core Scrim Adhesive
   - 2.2 Contaminated Core Surface

3.0 Incompatible VARTM Resin & Paste Adhesive
   - 3.1 Resin Incompatible with Cured Paste Adhesive
   - 3.2 Resin Incompatible with Partially Cured Paste Adhesive

4.0 Process Control Inadequate
   - 4.1 Quality Verification Process Inadequate
   - 4.2 Manufacturing Process Control Inadequate

Legend
- X.X Potential Fault Eliminated
- X.X Potential Contributor
- X.X Root Cause
The MLAS Team maximized used advanced design, development, Rapid Prototype, and manufacturing tools leveraging the digital tapestry across the a wide geographic landscape.

- Design through launch = less than one year
- OoA cure of autoclave materials
- Determinant assembly (No fixtures)
Time to Cure

Global Hawk
First certified military aircraft constructed using an all bonded primary structure.
Failure Modes in Adhesive Bonds

- **Substrate** failure: Inter-laminar fracture in composite structures, usually between the first and second plies adjacent to the bond-line; can be common in composite laminates especially those with brittle epoxies.
Adhesive Bonding

• A wide variety of materials are available when adhesives are used to bond materials together.

• The choice of which adhesive is best is usually dictated by the type of composite to be bonded, the application of the bonded composite, the service environment, and cost.

• The most common polymers in the structural adhesives class are: epoxies, polyurethanes, acrylics, cyanoacrylates, silicones, and phenolics.
Selection of a proper adhesive

- Thermal Conductivity of adhesive.
- Chemical Compatibility.
- Viscosity.
- Temperature resistance.
- Mechanical strength of adhesive.
Aerospace Structural Adhesives

- **Epoxies**
  - Wide range of high-strength adhesives available with a variety of curing & service temperatures
- **Bismaleimide (BMI)**
  - High temperature cure/service (up to 600°F)
- **Cyanate Ester**
  - Good dielectric properties
  - Low Coefficient of Thermal expansion (C.T.E.)
- **Hybrids**
Marine Adhesives

• Polyester
  • Polyester is less expensive than epoxy and is widely used in marine and other industrial applications.
    • Putty joints and fillets are used in many marine designs.
    • Polyester is a chemically weak adhesive Vs. epoxy.
      • High degree of shrink inherent to polyester resin.

• Vinyl Ester
  • Higher strength, modulus, and elongation than polyesters.
    • Both polyesters & vinyl esters are co-polymerized with polystyrene and release high levels of volatile organic compounds (VOC’s).
Liquids, Pastes, & Film Adhesives

- **Liquids**
  - Viscosities typically range between 100-6000 cps.
  - Generally works best in thinner bond-lines and provide for a higher degree of direct load transfer than pastes.
    - Effective thickness range: .002-.010 inch.
    - Can run out of thicker bond-lines with too low of a viscosity.
  - Liquids tend to be more brittle and less resistant to peel and cleavage loads than pastes or films.
  - Often “liquid” adhesives are categorized as “pastes” without distinction by the various adhesive manufacturers.

* Water at 70 degrees F = 1 - 3 centipoise (CPS)
Liquids, Pastes, & Film Adhesives

- **Pastes**
  - Paste adhesive viscosities typically are > 8000 cps
  - Generally works better in slightly thicker bondlines
    - Effective thickness range: .005-.020 inch
    - Thicker shim or gap filling applications are not necessarily considered structural – sometimes used with fasteners
  - Different fillers offer a wide range of properties
    - Minerals, rubbers, thermoplastics, & metals are common
  - Pastes usually do not wet-out as well on the substrate as liquids due to the influence of the added filler
Liquids, Pastes, & Film Adhesives

• **Film Adhesives**
  • High-performance structural pre-preg film adhesives
    • Stored frozen & thawed to room temperature before use
    • Requires an elevated temperature cure cycle
  • Different carriers for maintaining bond-line thickness control
    • Woven scrim cloth
    • Knit carrier
    • Non-woven (mat)
      • Typically carriers are made of treated Polyester or Nylon fibers
Reticulation

A pattern or arrangement of interlacing lines resembling a net.

- Reticulating film adhesives
  - Bonding to honeycomb core
    - Heating an unsupported or knit supported film adhesive, causing the adhesive to flow and fillet the core cell ends
  - Reticulating perforated skins in acoustic panels
    - Heating an unsupported film adhesive, causing the adhesive to flow away from the small holes in the acoustic skin prior to bonding it to a honeycomb or other open cell core material
Bonding to Honeycomb Core

Adhesive fillet at core cell walls
Bonding to Foam Core

Adhesive attaches to porous foam surface

Failure occurs along the “zip-line” in the weaker foam core surface
Surface Preparation of Composites

• **Goal**
  • Raise the surface-free energy of the composite substrate to enhance wetting of the surface and to facilitate molecular cross-linking.
  • Raise surface energy without damaging fibers in the laminate
    • Ref: Armstrong & Allen; Surface Tension/Surface Energy

• **Methods**
  • Scotch Brite or sandpaper abrasion
  • Grit-blast with alumina, silica, or other abrasive media
    • High risk method - somewhat operator dependent
Surface Free-Energy Exchange

If the surface tension value of the liquid is greater than the surface-free energy value of the substrate the liquid molecules stay bound together.

Poor wetting means a poor bond!
When the surface free energy value of the substrate is higher than that of the liquid it allows the liquid to uniformly wet the surface. This is important to achieving a good bond.
Clean the Freshly Energized Composite Surface

Objective: Remove dust and debris from bonding surface without inducing contamination.

- Solvent wipe with **clean cheesecloth** or approved wipes
  - Double wipe method often specified: Use a solvent saturated wipe followed with a clean dry wipe to pick-up residual contaminants
  - High risk of inducing moisture or other contaminants onto freshly energized/slightly porous composite surface
- What effect does wiping with solvent have on the surface-free energy of the freshly prepared composite surface?
- **Alternative: Dry wipe with clean cheesecloth or approved wipes**
  - Multiple wipes may be required to remove dust sufficiently
  - Low risk of inducing moisture or other contaminants
Water-Break Test on CFRP Panel

Water beads-up in unprepared areas  Water wets-out in abraded areas

*Water-break testing is not recommended for actual panels to be bonded*
What About Peel-Ply Surfaces?

- Non-coated Nylon or polyester fabrics
  - Leaves no trace contaminants on part surface
  - Does not always peel off easy
- Release treated Nylon or polyester fabrics
  - Can transfer release agent to part surface
- P.T.F.E. Coated Glass Fabrics
  - Easy to remove from part surface with low risk of damage to part
- Produces a fairly low-energy surface on the composite
Effect of Peel Ply on Surface

Resin Matrix

Peel Ply Fabric

Cross-section through peel ply on surface of laminate
Effect of Peel Ply on Surface

Remove the peel ply from the surface
Effect of Peel Ply on Surface

Peel ply leaves small fractured peaks of resin on the surface

Would you want to bond to this surface?
Adhesive Application Issues

• Applying Film Adhesives
  • Simple to apply along the faying surface of one or both substrates that are to be joined
  • Heat may be required to form some films to complex shapes

• Applying Liquid & Paste Adhesives
  • Goal: to apply slightly more adhesive than required and close the joint in a timely fashion
  • Provide enough adhesive along the joint to do the job
    • *Refer to application template design sketch
    • Excess adhesive = excess weight
Application Template Design

Equal Spaces

2X Required Adhesive Thickness
Using the Application Template

Template

Adhesive

Part
Open Time is the Enemy

• A freshly energized surface will try to stabilize over time and subsequently lose the desired effect
  • The surface takes on H2O and other contaminants when left exposed to the normal shop/clean-room environment
• Adhesive left open on the surface for extended time may also be affected by the environment (H2O & CO2)
  • Amine Carbonate formation can inhibit most room temperature curing epoxy adhesive systems
  • *Refer to Hysol EA 9394 Open Time Considerations
Bond-line Thickness Control

- Consistent bond-line thickness of the adhesive layer is critical, without uniform thickness the joint strength is only as good as its weakest point

- Options for thickness control media:
  - Micro-Beads (mixed in the adhesive)
  - Scrim Cloth
  - Knit Carriers
  - Non-Woven Carriers (Mat)
Bondline Thickness Control

Unequal stress distribution through an unevenly bonded joint
Uniform Clamping Pressure

- Uniform clamping pressure is required to achieve good wet-out and optimum bond strength
  - Added force contributes to free-energy exchange
  - Typical bonding pressures range from 5-50psi
- Mechanical clamping requires sturdy fixturing
- Vacuum bagging can provide uniform pressure
  - Vacuum bagging can also cause micro-porosity in the joint due to frothing of the adhesive under vacuum
Curing the Adhesive

• To achieve maximum performance and ultimate structural & thermal properties, the adhesive must be properly cured and/or post-cured
  • Room temperature curing systems usually take several days to achieve good structural properties
    • The standard definition of room temperature is 77°F (25°C)
  • Elevated temperatures lower the adhesive viscosity and enhancing the wet-out (energy exchange) characteristics
  • High performance adhesives usually require an elevated temperature cure and/or post-cure for best performance
Lap Shear Coupons

• **Single lap coupon**
  • ASTM D1002: Standard Test Method for Lap Shear Adhesion for metallic Bonding
  • ASTM D5868-01: Standard Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic (FRP) Bonding
    • Somewhat useful for quality assurance testing of adhesives and surface preparation methodology
  • The varying stiffness of different substrate materials influence the apparent adhesive shear strength in the lap shear test*

*Ref. L.J. Hart-Smith, The Bonded Lap Shear Coupon-Useful for Quality Assurance But Dangerously Misleading for Design Data
Single Lap Shear Coupon

• Not useful for generating actual design data*
  • Example: 1 inch wide x ½ inch overlap coupon fails at 3000 lbs breaking loads.
  • Multiply the breaking strength x 2 = 6000 psi.
  • However - with a 1 inch wide by 1 inch overlap the breaking number is significantly less than 6000 lbs.
  • The joint strength is not doubled with the overlap length

*Ref. L.J. Hart-Smith, The Bonded Lap Shear Coupon-Useful for Quality Assurance But Dangerously Misleading for Design Data
Single Lap Shear Coupon

Peak stresses in both shear & peel concentrated at edges of single lap coupon induced by deformation of specimen when loaded
Common Substrate Failure in Composite Lap-Shear Specimens

Failure typically occurs between the first and second plies from the bond surface in one or both substrates.
Double Lap Shear Coupons

- Double lap coupon (ASTM D 3528-96)
  - Also useful for quality assurance testing of adhesives although not generally referenced in data sheets from mfr's
  - More useful for generating design data or predicting shear load capabilities through a bonded double-lap joint

Stress distribution through a double-lap coupon
Failure of Metallic Lap Coupon

Coupon usually narrows or "necks" when yielding

Angle of break corresponds with type of alloy and temper used in the specimen
Effect of Different Fiber Forms at the Faying Surfaces in a Bonded Joint

- **Uni-directional Tape**
  - Should run directly across the joint for best results
  - Normally not recommended as faying layer in joint design

- **Bi-directional woven fabrics**
  - Plain & Twill weaves
    - Generally good surface materials for faying layer in joint design
  - Harness-satin weaves
    - Warp/fill face orientation dominance must be considered

- **Multi-axial stitched fabrics**
  - Functions like a unidirectional tape dependent on faying layer orientation

- **Non-woven mats**
  - Diminished load transfer through mat surface layer
Effect of Different Fiber Forms at the Faying Surfaces in a Bonded Joint

Uni-directional fibers at faying surfaces:
Orient fibers across the bonded joint in primary load direction
Effect of Different Fiber Forms at the Faying Surfaces in a Bonded Joint

90° Fibers tend to “roll” off of the underlying ply of the substrate

Effect of 90° uni-directional fibers at bond joint
Effect of Different Fiber Forms at the Faying Surfaces in a Bonded Joint

Bi-directional plain-woven fabrics at faying surfaces provide uniform load transfer across bonded joint
Summary

• To achieve an optimum bond with metals
  • Clean surfaces free of oils & dirt if applicable
  • Refresh oxide layer with suitable process
  • Chemically etch or couple to fresh oxide layer
  • Apply corrosion inhibiting primer (Aluminum)
  • Use appropriate adhesive for the application
  • Provide uniform bond-line thickness
  • Provide constant clamping pressure along B/L
  • Cure adhesive to achieve structural properties
Summary

• To achieve an optimum bond with composites
  • Abrade or energize the surfaces to be bonded
  • Clean surfaces free from dust or debris
  • Use appropriate adhesive for the application
  • Provide uniform bond-line thickness
  • Provide constant clamping pressure along bond-line
  • Cure adhesive to achieve structural properties
Example
Bonded Structure

**Suggested Reading**

- DARPA's Transition Reliable Unitized STUructure (TRUST) project.


When will fasteners go away?

**AT THIS CONFERENCE**

Enabling Technology

**Technical Sessions**

Tuesday – 11:30 AM

Laser Bond-line Inspection

David Lahrman, VP Business Development

LSP Technologies, Inc.
Questions?
Fastening Composites
Why don’t we just “glue’ stuff together and get rid of fasteners?

Even if we could……..
The current “batch” and many emerging airplane types use and will continue to use fasteners to hold all the pieces of the airplane together.
Why Address Fastening?

- **Airplane Cost**: 65% Assembly, 35% Other
- **Assembly Cost**: 65% Drill & Fill, 35% Other
- **Drill & Fill**: 80% Defects, 20% Other
- **Drill & Fill**: 80% Lost Time Injuries, 20% Other

NOTE: Increased use of composites has complicated the assembly process.
Continues to be labor intensive
Why address fastening

Safety

- 250,000 to 7 Million Holes

ZIPPER EFFECT

With Fasteners
Why is this important

On April 28, 1988, an Aloha Airlines 737's fuselage blew open at 24,000 feet, killing a flight attendant and injuring eight people.
Black Metal

Joining Metal Pieces Together

Drilling Metal to Metal

Uniform Thickness
Tight Mating Surface

Uniform Predictable
Fastener Grip Length
Black Metal to Black Gold

Drilling through composites - challenging

Every hole is different
Drilling through composites - challenging

Every outcome is different
Drilling Effects

Peel up

Push Down

(a) radiography (b) ultrasonic C-Scan (c) computerized tomography
Limitations of touch probes

- Current gauges meant for metal
Limitations of touch probes

Current gauges meant for metal

Regions of uncertainty
Current gauges designed/meant for metals

In composites – the impact is large
Complexity of drill and fill

- Drill and Countersink
- De-stack, Inspect, deburr, repair, clean, re-stack
  - EYES ON Human operation
  - 100% of holes Composites
- Re-stack and Install fasteners
Drilling through stacks of dissimilar materials.

- Composite
- Liquid Shim
- Metal
Composite/Composite Stacks
Automated Drilling/Countersink Dissimilar Material Stacks “One Shot”

Encoder

Spindle

Compression Cylinder

Controller

Pressure Foot

Terms:
- Tracking
- Engagement
- Detection
- Compression
- Drill & Drill/Peck
- Countersink

Preset distances

Composite/Titanium Stack

ON ASSEMBLY
Drilling/Countersink Dissimilar Material Stacks “One Shot”

Encoder

Spindle

Controller

Compression Cylinder

Tracking: Distance from the surface of the workpiece to the surface of the pressure foot when moving from hole to hole.

Composite/Titanium Stack
Drilling/Countersink Dissimilar Material Stacks “One Shot”

Engagement & Detection

1. Pressure foot touches workpiece
2. Pressure foot presses shaft against encoder
3. Encoder sends signal to controller
4. Controller activates drill/countersink routine
Drilling/Countersink Dissimilar Material Stacks “One Shot”

Compression

1. As drill approaches workpiece the pressure foot presses against the compression valve.
2. The compression pushes against the workpiece to hold the stack together.
Drilling/Countersink Dissimilar Material Stacks “One Shot”

Drill

1. Drill high RPM and high IPM through composites
2. Reduce speed before engaging titanium to low RPM and Low IPM
Drilling/Countersink Dissimilar Material Stacks “One Shot”

Drill

1. Drill into titanium just past drill point
2. Rapid retract to clear chip
3. Rapid return to previous drill stop less .050” to account for workpiece spring-back
4. Continue drilling with same peck routine until titanium is drilled (Approx. .100” each peck)

This is called peck drilling
Drilling/Countersink Dissimilar Material Stacks “One Shot”

Countersink

1. Engage countersink RPM and IPM
2. Countersink workpiece
   1. Dwell at bottom of countersink .5 seconds
3. Full retract
Drilling/Countersink Dissimilar Material Stacks “One Shot”

Encoder
Spindle
Compression Cylinder

Controller

Tracking: Distance from the surface of the workpiece to the surface of the pressure foot when moving from hole to hole.

Return to tracking distance

Composite /Titanium Stack
On-assembly Drill Head Examples

JGADS F35 Wing
Lockheed

ADS F35 Fuselage
Northrop Grumman

Aeroscan probe inside pressure foot (Cut away)

Impact from drilling composites (Boeing)
Steps in de-stacking

- De-stack, inspect, deburr, repair, clean, re-stack
- Eyes on Human operation
On-assembly automated drilling
Tooling for vibration/deflection mitigation

Tooling/Fixture

Exaggerated compressive drilling operation forces against the workpiece
Some Effects of De-Stacking

- Gapped Fasteners
  - Drill misaligned to normal
  - De-stack

Allowable if you can install a .002 shim and not contact the shank?

Gap is allowable up to 40% of the circumference.

Photo Courtesy of TRULOCK Precision Measuring Instruments
Complexity of inspection

- Inspection – eyes on
  - Each hole size (range) = one gauge
  - Each Countersink size (range) = one gauge
  - Measure grip length = one gauge
  - Visual Inspection (de-stack observation)

NOTE: Each airplane can have a thousand gauges
Complexity of inspection

- Example F/A18 Vertical Stabilizer (composite)
  - One skin
  - 634 holes
  - 34 fastener sizes (diameter)
    - 34 grip lengths
    - = 25 gauges
    - = 1150 independent measurements
Why Automate
Automating the Process

Automated Assembly Cell
Northrop Grumman
F35 Integrated Assembly Line (IAL)
Palmdale, California
Why is this important

- Automation
  - Improves throughput
  - Fewer defects & rework
  - Decrease accidents & repetitive motion disabilities
Two processes separated by humans

Humans impact throughput
Drill, Inspect, Fill (DIF)
Three separate operations
## Automating the gauging process

### Automation
- Enables automated one shot drill & fill
  - One gauge & operation
  - No de-stack
  - 7% assembly cost savings
  - Eliminates eyes-on
  - Provides complete hole diagnostics
    (required for composite parts assembly)

### Handheld
- One gauge & operation
- No de-stack
- 5% assembly cost savings
- Objective inspection
- Provides complete hole diagnostics
  (required for composite parts assembly)

Also helps when hands drill product.
Enabling Technology

Non-Contact Ring Laser Technology

• Countersinks
  • Countersinks are simultaneously scanned using the same probe
  • No hardware modification is needed
  • Determines countersink depth
• Destack

• Aeroscan proactively can identify gaps, burrs, and debris as part of the inspection and diagnostic process reducing or eliminating the need for Destacking or post-drill process evaluations.*

* Potential
Sample Application

Same nose piece and locking mechanism
Operation transferred to an automated gauge
One gauge – one measurement cycle
Vertical Stabilizer Double Sided Automated Drilling System
VADS

In Operation since - 2002
Aeroscan Retrofit - 2016
Applied Drilling Systems (ADS)

In Operation since - 2010
Aeroscan Retrofit - 2016
Future Applications
Advantages include:
• Automating the entire process DIF
• Improved composite assessment
• In-process tool monitoring
• Eliminate de-stack
• Data analytics
• Independent actionable machine decisions

Disadvantages include:
• No multi step checks and balances
  *Scary Stuff!!!*
• Glass (Questionable Robustness)
• Pricy$$$$
Rigid testing can mitigate risk.

Specific Risks

1. Technical
2. Cost
3. Integrator Involvement
4. Migration (TTP)
5. Workforce Development
6. Program
7. Facility Requirements
8. Reduce Uncertainties
ALTERNATIVES
Conoscopic Holography

The first sensor takes several reference points while the second sensor attached to a periscope is able to get into holes and measure both the depth and side walls. By using a periscope’s co-linearity technology the gage can scan inside deep holes to get depth, diameter, and sharp angles such as countersinks.
Non-contact capacitive hole diameter probes are made by installing two, three, four or more non-contact capacitive displacement sensors around a circular metal probe.
Air Probes

The air probe (also referred to as an air plug gage, air spindle or mandrel) consists of a precision ground hardened steel body incorporating two or more air gage nozzles. Air is passed through the probe body to the nozzles where a back pressure is produced by the surface of the workpiece. An air gage readout (air comparator) senses the resulting back pressure and displays the size of the workpiece.
Automated countersink measurement methods which require contact with the workpiece are susceptible to a loss of accuracy due to cutting debris and lube build-up. A non-contact method for countersink diameter measurement on CFRP eliminates the need for periodic cleaning. Holes are scanned in process using a laser profilometer. Coordinates for points along the countersink edge are processed with a filtering algorithm providing a highly repeatable estimate for major and minor diameter.

Laser Profilometer
Electroimpact
Ring Laser Non-Contact Probe

Current Peacekeeper and small ICBM guidance systems require measurement tolerances of 5 microinches (five millionths of an inch) on bores used in critical bearings in the SFIR (Specific Force Integrating Receiver) and TGG (Third Generation Gyro). Quest Integrated, Inc., conducted a Phase I program to investigate the feasibility of developing a noncontact measurement system based on the principle of optical triangulation for characterizing the diameter and cylindricity of these bores. The study showed that the fundamental limitations to the measurement technique are in the sub-microinch range. A first prototype probe was constructed and used to demonstrate the measurement of internal diameters to the resolution limit of the AID converters employed (8 microinches).

The probe has been further developed and allows easy measurement of the internal dimensions of cylindrical shapes. This tool has wide applications as a generic precision measuring tool.
The substrates used for the probe body were abrasive-waterjet (AWJ) machined and drilled at Quest from ULE™ coefficient glass. This high titanium glass supplied by Corning Glass has a thermal expansion coefficient of approximately 30 ppb per degree Fahrenheit at room temperature.
The substrates were Abrasive Water Jet (AWJ) cut to 0.130-inch square blocks 0.875-inch long. They were then AWJ drilled. With a few days of experimentation, the two one-hole substrates were drilled without damage to a hole diameter of 0.098 inch with less than 0.001 inch of taper over the entire length of the hole. Coincidentally, this hole diameter is ideally suited for mounting standard 0.5-mm-diameter (0.019685”) GRIN lenses.
FURTHER READING:


AT THIS CONFERENCE:

Integrated Assembly II/S-1

Wednesday February 10

From 2-4 PM

*Non-Contact Holistic Measurement of Aerospace Fastener Holes with Ring Laser Adaptive Optics* Dr. Harris Bergman, VP, Engineering Innovation, United Sciences

Integrated Assembly I/S-1

From 10:30 – 10:55 AM

*Automation for Families of Parts* George Bullen
NOTE
Automation need not be complex or expensive
What is advanced analytics?
Advanced Analytics are analytical techniques applied to as-manufactured data, which go beyond simply describing the data –

Includes a Digital Imagery Plan to document as built configurations that are reconciled back to the original engineering.
ADVANCED ANALYTICS

instead they explore the hidden relationships and patterns within the data.

They allow us to infer things that are happening that cannot be seen with simpler cross-tab analysis.
ADVANCED ANALYTICS

The idea is to get to red
ADVANCED ANALYTICS

Automated exploration of as-manufactured data.

Reduces time to decision.

As A General Rule of Thumb: As Much As 75% Of On-Part Dimensional float Are Due To Variations Beyond Machine Performance!
ADVANCED ANALYTICS

For automated assembly begins with enterprise operations intelligence software that enables event-driven analytics and process improvements.
• The engineers thought the digital tapestry was a beautiful thing
ADVANCED ANALYTICS

• At the assembly (on the shop floor) it looked like this

Mechanics view of the digital thread
Automation for Families of Parts
10:30 AM – 10:55 AM
Wednesday
Assorted Assembly Enablers
(Click Bonds™ and Z-pins)
Click Bond™
Nut-plates
Three for One

• Applied for many reasons
  • Remove and Replace (R&R) parts
Nut-plates
Three for One

- Primary holes are drilled
  - Secondary nut-plate attach holes are drilled
    - Specialized nut-plate pneumatic drill motor
    - By hand (standard d pneumatic drill motor)
Nut-plates
Three for One

• Blind fasteners are installed and “pulled”
  OR

• Rivets are installed and squeezed
Nut-plates
Three for One

Nut plate process

- Drill Primary Hole
- Drill Nut-plate Holes
- Install Nut-plate

- One Hole
- Two Holes
- Three Holes

- One Fastener
- Two Fasteners
- Three Fasteners
Click Bond™

Replaces holes and fasteners with adhesive
An Installation Process For Optimum Efficiency

Apply the adhesive to the baseplate.

Pull the fixture through the hole in substrate.

After the adhesive has cured, remove the fixture from the nutplate and discard.
Click Bond™

Used on the F/A18 E/F and many other airplanes

NASA qualified for space vehicles
Click Bond™

One for One

Click Bond™ process

1. Drill Primary Hole
2. Install Nut-plate
3. One Hole
4. One Fastener
CAUTIONS
One Example

Boeing Alert Service Bulletin 777–78A0065, Revision 2, dated May 6, 2010, describes procedures for reviewing the airplane maintenance records to determine whether sealant was added; repetitive detailed inspections of all thrust reverser (T/R) inner wall insulation blanket edges, grommet holes, penetrations, and seams for sealant that is cracked, has gaps, is loose, or is missing; repetitive general visual inspections of click bond studs,
Z-pins™
**Z-pins™**

What are Z-pins?

- Z-pinning is a technique to insert reinforcing fibers (also called Z-pins or Z-fibers) along the Z-direction of continuous fiber-reinforced plastics.
- Z-pins can be made of metal or pre-cured unidirectional composite fibers. It is designed for use within pre-preg technology.
  - There is extensive experimental evidence that Z-pinning dramatically improves the resistance of the composite structure to delamination.
Several ways of inserting Z-pins have been developed to date. One method involves the use of an ultrasonic hammer that forces the Z-pins through the uncured preform while inducing high frequency vibrations to them. The vibrating chamfered tip of the Z-pins locally heats up and softens the resin allowing the Z-fiber to penetrate the preform with minimal disruption of the long fibers.
Z-pins™

Figure 4(a)/(b): Z-Pinning process an alternative to stitching.

Stage 1: Place Z-Fibre Preform on top of Prepreg and then enclose in vacuum bag.

Stage 2: Standard cycle or debulk cycle, heat and pressure compact preform foam, forcing the Z-pins into the Prepreg composite.

Stage 3: Remove compacted preform foam and discard. Finish with cured Z-pinned composite.

(a) Primary insertion stage and residual preform removal.

(b) Secondary insertion stage.
Z-pins™
Case Example

Application of Z-Pins to F/A – 18 E/F
Mechanical Fastener Attachment

**Requires:**
- Pre-Curing of Multiple Details
- Drilling/Countersinking of Fastener Holes
- Application of Liquid Shim
- Wet Installation of Fasteners

**Demonstrated Benefits**
- Reduced Touch Labor
- Reduced Weight
- Reduced Part Count
- Reduced Defect Count
- Increased Interlaminar Capability
- Improved Damage Tolerance

Advanced Attachment with “Z-Pins”

**Requires:**
- Integration of Composite Lay-ups
- Installation of Z-pins Prior to Cure
- Backside OML Sealing

**Demonstrated Benefits**
- Reduced Touch Labor
- Reduced Weight
- Reduced Part Count
- Reduced Defect Count
- Increased Interlaminar Capability
- Improved Damage Tolerance

Pre-Cured Composite Skin

Co-Cured Composite Hat Stiffener

Pre-Cured Composite Radius Block

Co-Cured Composite Skin

.011” Dia. GR/BMI Z-Pins (420 pins/in2)
Co-cured Hats With Z-Pins

Inlet Duct Skins

Mechanically Fastened Hat Configuration
FE42 Installation

Current Z-Pin Hat Configuration
FF42 Installation

4,800 Fewer Fasteners
Part Number Breakdown

Cocured Hats With Z-Pins

Inlet Duct Skins

74A342709 (2/2)
74A328511 (3/3)
74A328509 (8/8)
74A325620 (7/7)
74A342725 (4/4)

74A341701 (1/1)
74A341701 (5/9)
74A328326 (7/7)
74A328615 (2/2)
74A325604 (9/9)
74A326729 (2/2)
74A328853 (7/11)
74A328852 (10/11)
74A328855 (20/20)
74A328854 (14/14)
74A328851 (15/21)
74A328509 (7/11)
74A341701 (2/2)
74A326753 (2/2)
74A328646 (3/3)

74A325620 (7/7)
74A328509 (8/8)
74A328511 (3/3)
74A325604 (9/9)
74A326729 (2/2)
74A328853 (7/11)
74A328852 (10/11)
74A328855 (20/20)
74A328854 (14/14)
74A328851 (15/21)
74A328509 (7/11)
74A341701 (2/2)
74A326753 (2/2)
74A328646 (3/3)

- Z-Pin Cocured Hat Stiffened Part (TOW Placed)
- Z-Pin Cocured Hat Stiffened Part (Hand Lay-Up)
Structural Certification

• **Joint Design Must Meet Conventional Acceptance Criteria Plus:**
  • 30% Increase on Fatigue Spectrum Design Loads As a Robustness Factor
  • Cannot Change Load Paths/Failure Mechanisms
  • Demonstrate Acceptable B-basis Allowables With Z-fiber

• **Load Induced Delaminations Are Allowed... Provided:**
  • Delams Do Not Extend Over .75” Into the Joint
  • Any Delams Must Not Grow for 3 Lifetimes After Initiation
  • Delams Must Not Compromise Joint Static Capability After Fatigue Limits Are Met
Manufacturing Certification

- Developed New Manufacturing Process for Co-cured Hats
  - Verified Through Inspection/Dissection of 8 Full Scale Articles, 4 Part Numbers
  - Created Appropriate Control Documents ie.. PCD, MMS, PS
- Developed Production Insertion Plan to Smooth Implementation
- **Produced 100% Acceptable DD63 Tear Down Articles for All Part #’S**
Benefits To F/A-18 E/F

- **Reduced Cost by $85K Per Ship-Set**
  - Composite Part Touch Labor Reduction

- **Weight Reduciton of 34 Lbs Per Ship-Set**
  - Elimination of More Than 4,800 Fasteners Per Ship-Set
  - Eliminates Nylon Channels Covering Fuel Tank Fasteners

- **Reduced Engine FOD Potential**
  - Eliminates 4,800 Fasteners Per Ship-Set in Inlet Duct

- **Reduced Assembly**
  - Improved Quality And Part Fit-up

- **Reduced O&S Costs**
Typical Fixed N-UCAS Skin Panel

- **Fixed skins baseline:**
  - Skins IM7 composite, some titanium
  - Pre-cured composite hat stiffeners bolted on
    Some clipped to sub-structure (highly loaded) Otherwise panel breakers

Air Data Ports

View A
Typical N-UCAS Fixed Skin Panel, Detail View

- Hat Stiffeners
  - Total Quantity: ~ 400
  - Total Linear Feet: ~520 ft
Design Criteria Evolution

**F/A-18 Application Demonstrated:**
- Cost savings
- Weight Savings
- Reduced Part Count
- Improved Quality

**Expanding Applications**

**Technology Revolution for Broader Usage of Composites:**
- Damage Tolerant Structure
- Allows Load Induced Delams
- Enables Integrated Structures

**Enabling Additional Applications:**
- UCAV-N Integrated Structure
- Fastener-less Inlet Designs
- Integrated Thermal Protection for B-2 and Space Applications

Z-pins™ Provided Significant Benefits to the F/A-18E/F Program. Will be Considered in Applications That Solve Existing Technical Problems.
Several attempts to automate the Z-pinning process

- Example: Limited success using load cells to replicate the hand “touchy-feely” sensitivity needed
- Research continues
Questions? Comments?
Unified Structure
Large Scale Composite Space Structures

- Altair Lunar Lander
  - Ascent Module
  - Descent Module

- Ares V Heavy Lifter
  - Payload Shroud
  - EDS
  - Core Stage
  - Avionics Skirt

- Lunar Surface Systems
  - Habitats
  - Rovers
Unitization

• Reduces Mass
  • Eliminates Longitudinal Joints
  • Integrates Assembly and Separation Joints
  • Reduces Minimum Gauge Penalty
• Reduces Cost
  • Reduces Part Counts
  • Reduces Supply Chain
  • Reduces Assembly Operations

Unitization Reduces Mass And Cost
Ares V Composite Structures Unitization Candidates

Payload Shroud
EDS Fwd Skirt
EDS Intertank
EDS Loiter Skirt
EDS Interstage
Core Fwd Skirt
Core Intertank
Core Aft Skirt
Altair BAA Configuration Composite Structures
Unitized Structure
1500 Pounds Weight Reduction
Improved Metal Tank Studies

1. Fit in 5m Fairing
2. Refuel after LOI
3. Min Surface Area

Altair TAC0 Structural Arrangement
- AM Crew Cabin
- Habitat Airlock
- DM LOX Tank
- DM LH2 Tank
- EDSA

Altair Configuration Studies
- Min Surface Area
- Refuel after LOI
- Fit in 5m Fairing

Strut & Truss Node Studies

Propellant Depot Studies
- Patent Pending End Ftg
- Tank Size vs Launch Opt

EDS Configuration Studies

Air-launched Crew Transport System
- MLAS Crew Escape System
- Common Tooling Core & Upper Stage LOX & LH2 Tanks

Common Bulkhead Potential

Improved Metal Tank Studies
- More Unitized Orthogrid vs Optimized Skin Stringer
Win Strategy: Low Cost Wins

Composites
Cost and Drivers

Autoclaves
Floor Space
Rigid Sequential Manufacturing
Material Distribution (Layup) Rates
“...here I opened wide the door ... darkness there and nothing more. Deep into that darkness peering, long I stood there, wondering, fearing, doubting, dreaming dreams no mortal ever dared to dream before;”

_Edgar Allan Poe_ “The Raven”
First...Some Useful Definitions

*Out of autoclave composite manufacturing* is an alternative to the traditional high pressure/elevated temperature autoclave curing process commonly used by the aerospace industry for manufacturing composite material. Out of autoclave (OOA) is a process that achieves *the same quality* as an autoclave.

*Autoclave* is a high pressure (100+ psi) and elevated temperature (750° F +) vessel used for consolidating and curing prepreg composite laminates

OOA is any composite fabrication that is not performed with an autoclave

1. Wet Lay-up
2. VARTM
3. Compression Molding
4. RTM
5. SQRTM
6. VBO prepreg
Part designs not limited to autoclave size
Autoclave costs increase exponentially with increasing diameter
Reduced risk for vacuum bags leaks/failure at high pressure
Lower potential for core migration and skin dimpling
Lower recurring operating costs
Oven configurations are more flexible & less expensive
  - Options to consider portable/pop-up ovens
  - Simplify handling/transport of large/heavy tools in/out of autoclave
Larger industry base due to lower asset requirements
Increased ability for large structural integration
Built by Scaled Composites for Virgin Galactic

- One of the largest aircraft built and flown to date and fabricated primarily with out-of-autoclave cure materials
- Wingspan: 141 ft
Burt Rutan-Voyager
1st around the world nonstop, non-refueled flight

Scaled Composites-SpaceShipOne
First manned private spaceflight

Northrop Grumman-X-47B (Modified Demo)
Complex bonded composite CRAD

Northrop Grumman
Bonded Wing Box Demonstration Article
Disadvantages
Complex Tooling
The travel is longer than the different in thickness
Maximum pressure: 29 psi (2 Kg/cm²)

Laminated Skin

0.2 to 0.4% elongation
Win Strategy: Low Cost Wins

In Situ Manufacturing System (IsMS)
Basic Manufacturing Flow
Example: Ares V Interstage: 10 Meter Ø, 14.6 Meter Long

• Traditional Manufacturing Flow:
  • 6 Manufacturing Stations
  • 6 Moves

• IsMS Manufacturing Flow:
  • 1 Manufacturing Station
  • 1 Move

The IsMS Reduces Facility Requirements By Consolidating Processes Into A Single Station And Eliminating Required Moves
What Is The In-situ Manufacturing System?

• Multiple Variants:

  - Unitized Composite Structure Fabrication
  - Segmented Composite Structure Assembly
  - Metallic Friction Stir Welding Structure Assembly

IsMS Is a Flexible Manufacturing Technology For Large Space Structures Reducing Cost and a Northrop Grumman Discriminator
Unitized Composite Structure Fabrication

- Single footprint system with multiple processing heads
  - Automated Tape Placement head
  - Drill head
  - Non-Destructive Inspection head

- Cures components via Out-of-Autoclave technologies

Automated Lay-up
Non-Autoclave Cure
Drill, NDI & Extraction
Segmented Composite Structure Assembly

Segmented Panel Assembly

Major Assembly and NDI

Component Extraction
Metallic Friction Stir Welding Structure Assembly

Segmented Panel Assembly

Friction Stir Welding and Drilling

Component Extraction
IsMS Handling & Assembly Fixture

- Indexes mandrels and assembly fixtures onto IsMS
- Extracts components from mandrel/fixture and locks component’s geometry
- Rotates components for Secondary Operations
- Indexes to additional Handling Fixtures for component splice operations
The IsMS8 is scaleable to Ares V class structures.

Would mitigate current composite cost and complexity to bring it on par with aluminum.
Summary

• Lower Mass
  • Reduce or Eliminate Dome Parasitic Mass from Natural Path Lamination
  • Unitize Barrels, Domes and Cones Eliminate Longitudinal Joints
  • Integrate Assembly and Separation Joints

• Lower Cost
  • Not Slave to Large Fixed Asset (Autoclave)
  • Reduce Facility Requirements (Single Footprint)
  • Reduce Supply Chain, Processes and Parts

• Demonstrated Capabilities
  • 8 Foot Diameter Pathfinder In-situ Manufacturing System
    • Scaleable to Constellation Class Structures

• Workforce Development
  • Hands on Growth Opportunities for Young Engineers
  • Hands on Opportunities for Interns
Conclusion

• Composites Enables Unified Structure
  • Size Constraints

• The Joining of Composites Is Complex
  • Fasteners
  • Adhesives
  • Automation

• Future Composite Material Advances
  • Will Challenge Manufacturing Technology
Questions?
Thank you!

George N Bullen
Nick

Contact Information
georgebullen@aol.com