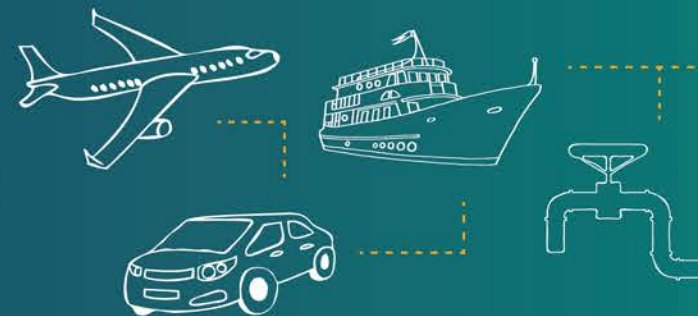




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SEPTEMBER 23-26

ANAHEIM, CA, USA

2019



Manufacturing Process Development for Adhesively Bonded Joints in Large-Scale Space Structures

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CAMX
THE COMPOSITES AND ADVANCED MATERIALS EXPO

Anaheim Convention Center | Anaheim, CA, USA

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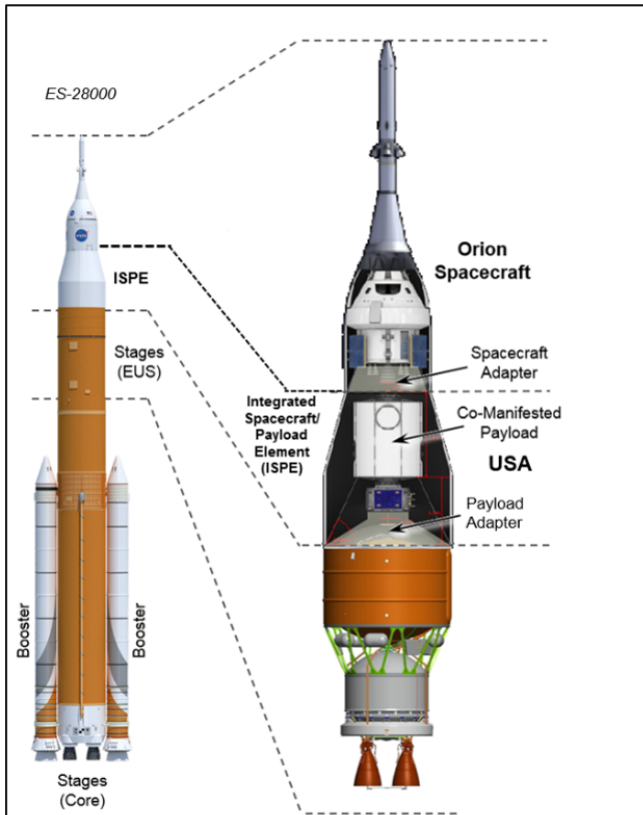
NASA Glenn Research Center

Sandi G. Miller



Space Launch System Block 1B Payload Adapter

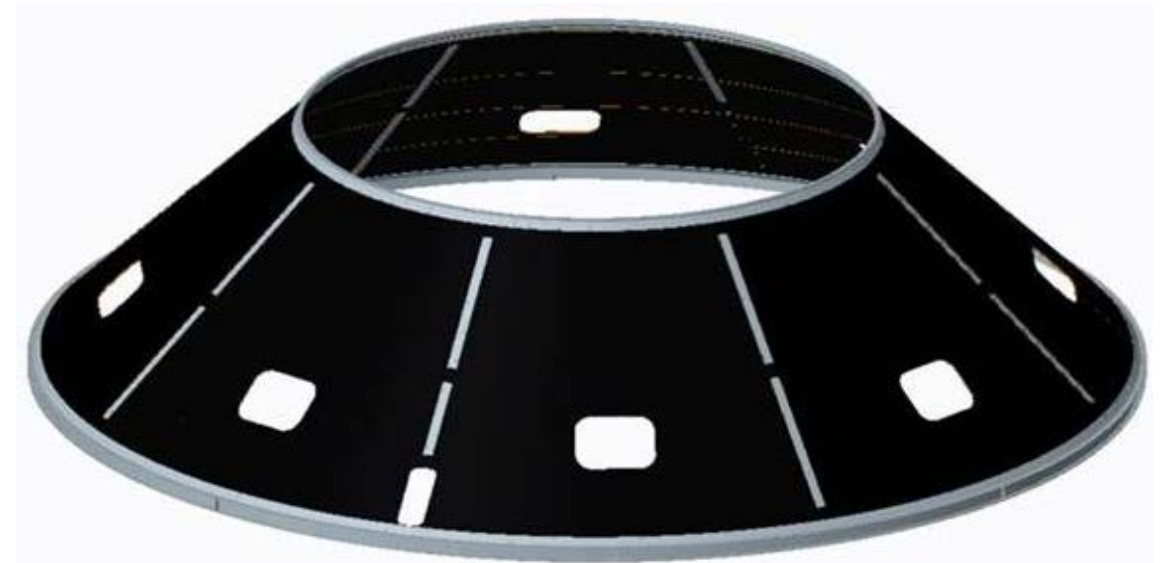
PLA Launch Vehicle Location



PLA aft ring interfaces with the Exploration Upper Stage (EUS) and the Universal Stage Adapter (USA) or the Cargo Fairing

PLA forward ring interfaces with the Co-Manifested or Primary Payload via a Payload Separation System

PLA Configuration



Forward ring
Aluminum forging
Single-piece

Aft ring
Aluminum plate
Segmented
Single-flange

Forward and aft attachments
Separable clevis
Mechanically fastened

Panels
Eight panels
Carbon fiber / epoxy composite facesheets
Closed cell structural foam core

Panel to panel attachments
Bonded longitudinal joints



PLA Development Approach

Pathfinder Panels

- Demonstrate in-house manufacturing viability
- Full-scale panel manufacturing development
- Preliminary processing parameters development

Manufacturing Demonstration Article

- Refine panel fabrication processing parameters
- Develop in-process inspection techniques
- Develop flight-like work tracking processes (Solumina)
- Demonstrate and evaluate full-scale article assembly processes

Development Test Article

- Full-scale proof test
- Modal test to verify natural frequency and mode shapes
- Limited damage tolerance test
- Test to failure to determine critical failure modes
- Data acquisition for dynamic model and strength model correlation
- Full-scale evaluation of bonded longitudinal joints

Qualification Article

- Full-scale proof test
- Ultimate load test to verify strength and stability



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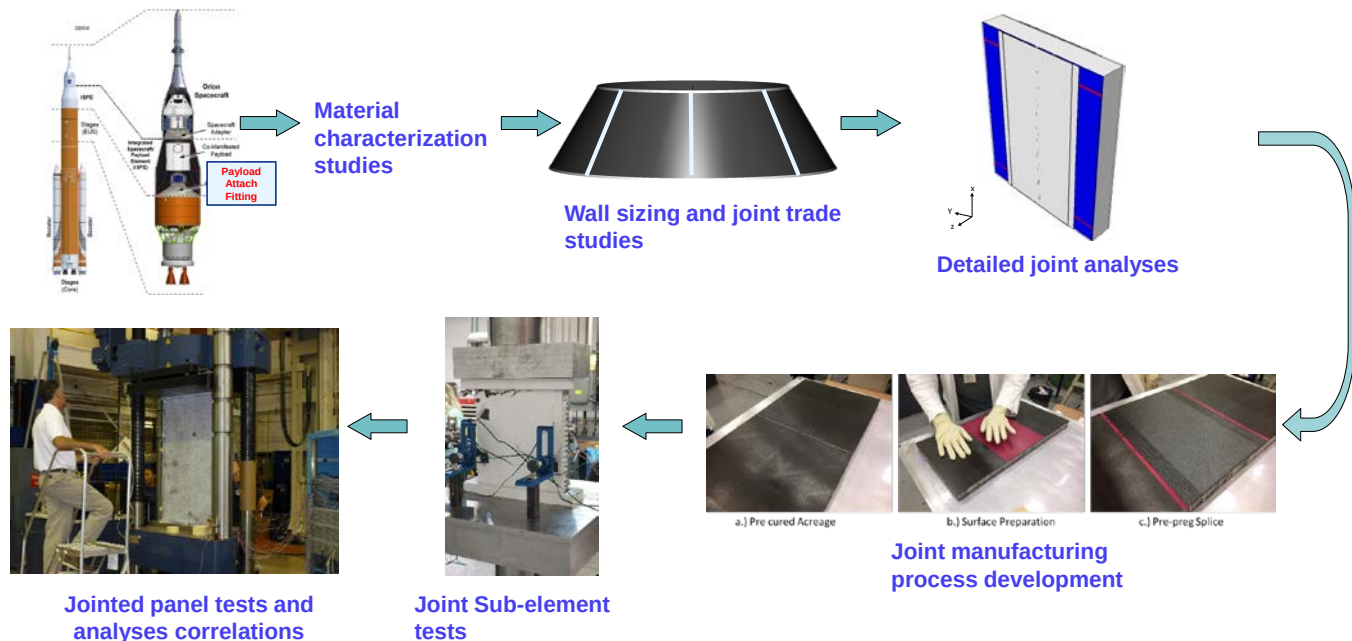
Composite Technology for Exploration Project

Multi-center technology development program

- Joint funding by the Game Changing Development Program in the Space Technology Mission Directorate and the Spacecraft Payload Integration and Evolution Office in the Space Launch System Program
- First phase (complete) focused on longitudinal composite bonded joints for a generic launch vehicle payload attach fitting: the CTE point design
- Second phase (in-work) focused on 3D woven composite circumferential rings with a bonded attachment

Included disciplines:

- Materials
- Design
- Analysis
- Manufacturing
- Testing
- Repair



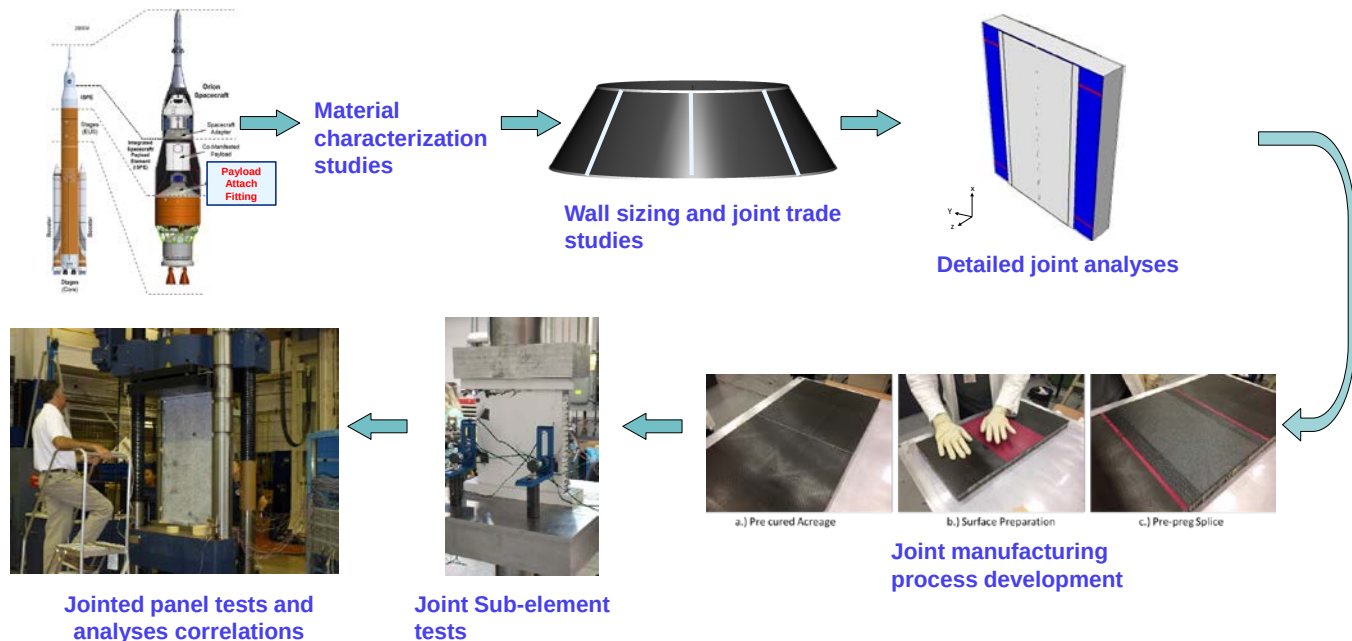
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Development Work Through CTE

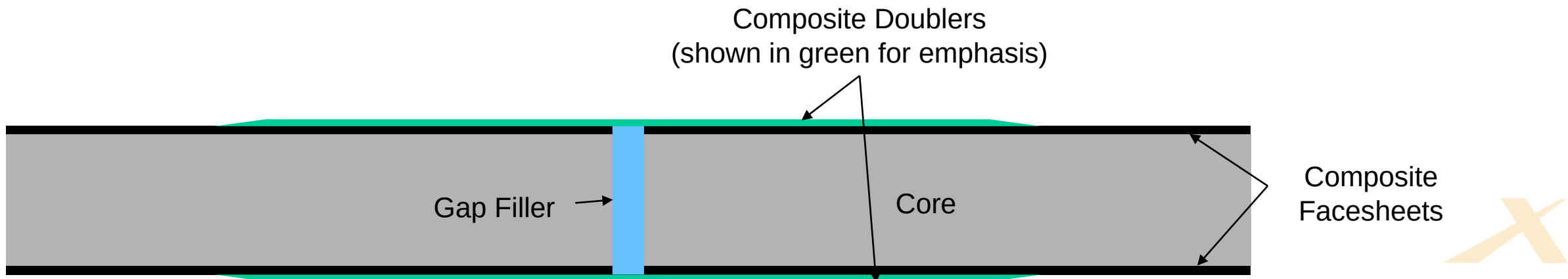
The longitudinal bonded joint design used in this effort was leveraged from NASA's Composite Technology for Exploration (CTE) project

Consists of...

- double strap configuration where tapered doublers are bonded to the primary structure with film adhesive.

Maximizing Use

- out-of-autoclave material systems were used for both the doublers and the film adhesive.



Surface Preparation Overview

Common Surface Prep Methods

- Solvent wipe
- Manual abrasion
- Peel ply
- Plasma treatment

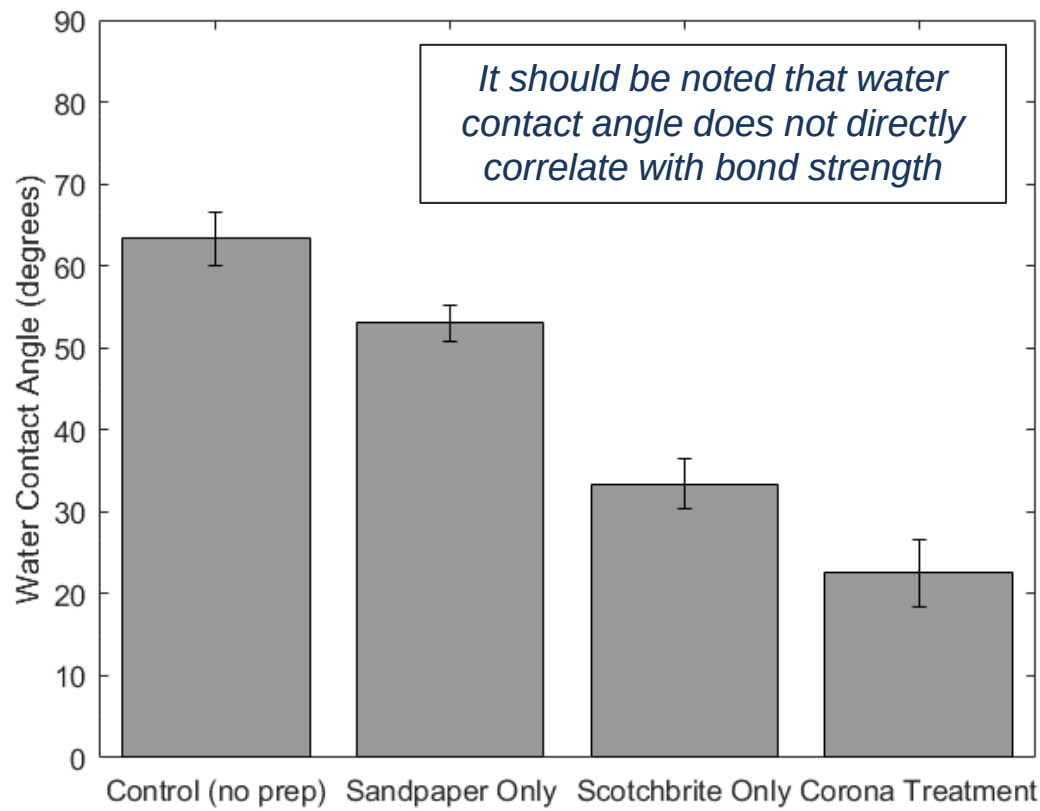
MDA Limitations

- Location constraints
 - Class 100k clean room
 - Flight hardware processed concurrently in same area
- Phased scheduling
 - Panel fabrication began prior to bonded joint development
 - No peel ply – tool & bag surfaces only
- Equipment availability
 - Corona treatment system vs preferred atmospheric plasma



Surface Prep Evaluation and Downselect

Initial Screening w/ Surface Analyst



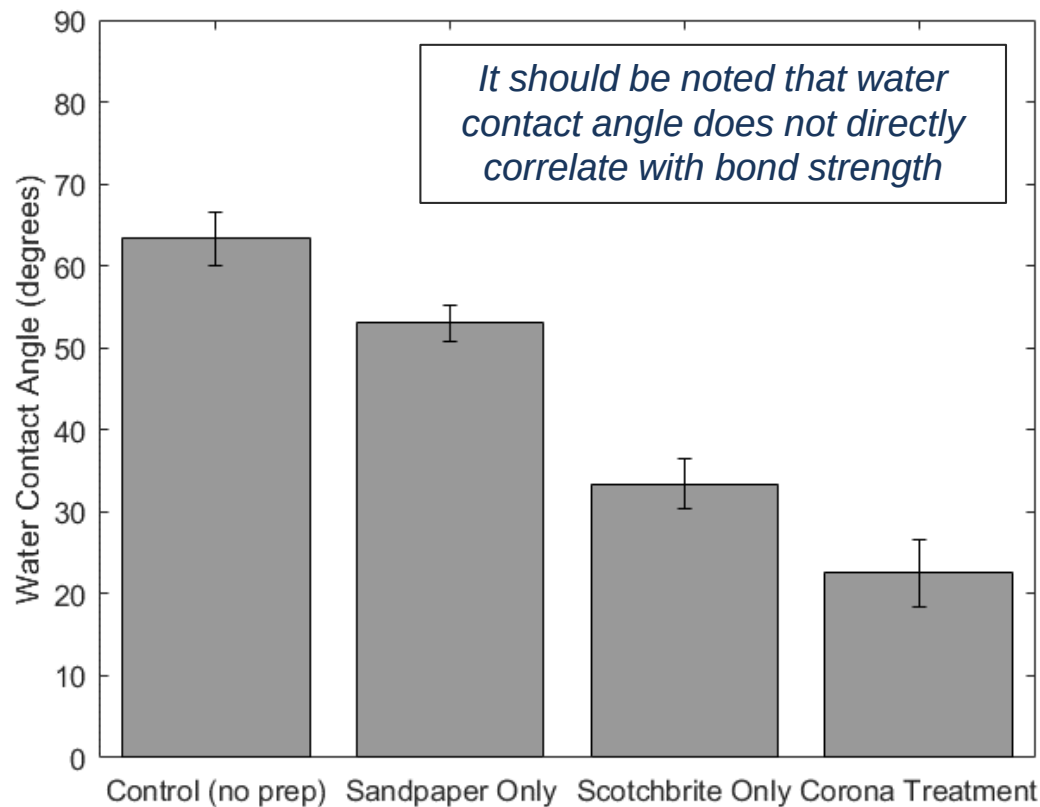
Plasma Treatment System

- Allows for chemical bonding due to creation of surface functional groups
- Provided consistent results between operators
- No FOD created during operation
- Some degree of surface cleaning prior to bond
- Scalability
 - Allows for full automation in future work



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Selected approach: Solvent wipe → Corona treatment → In-situ WCA measurements



Surface Prep Validation

Single Lap Shear Fabrication and Testing

- Fabricated single lap shear test coupons using selected surface prep approach
- Post-failure images examined via digital image analysis to determine relative percentages of each failure mode
 - Single image containing both mating fracture surfaces
 - Pixel counts of failure modes compared to original bond area

Failure Mode

- Adhesive: failure at the bonding interface
- Cohesive: failure in the bulk adhesive
- Substrate: interlaminar failure within the adherend

Single Lap Shear Failure Modes

Specimen	Failure Mode (relative %, based on area)		
	Adhesive	Cohesive	Substrate
1	0	99	1
2	0	53	47
3	0	72	28
4	0	81	19
5	0	73	27
6	0	17	83
7	0	50	50
8	0	100	0

*Single lap shear testing
per ASTM D3165*

No adhesive failure was observed; failure did not occur at bonding interface.



Process Validation In-Oven

- A series of panels were fabricated in-oven and tested at NIAR for various mechanical properties
- Properties obtained were compared to previously validated data on-hand at NIAR
- Processes validated:
 - Material handling
 - Breathing scheme
 - Bagging procedure
 - Cure cycle

Comparison of mechanical properties used to validate processing approach.

Property	Normalized Mean Values (% of baseline)	
	NIAR	NASA MSFC
Longitudinal Tensile Strength	100	103
Longitudinal Tensile Modulus	100	101
Longitudinal Comp. Strength	100	110
Longitudinal Comp. Modulus	100	100
In-plane Shear Strength	100	96
In-plane Shear Modulus	100	100
Short-beam Shear	100	105

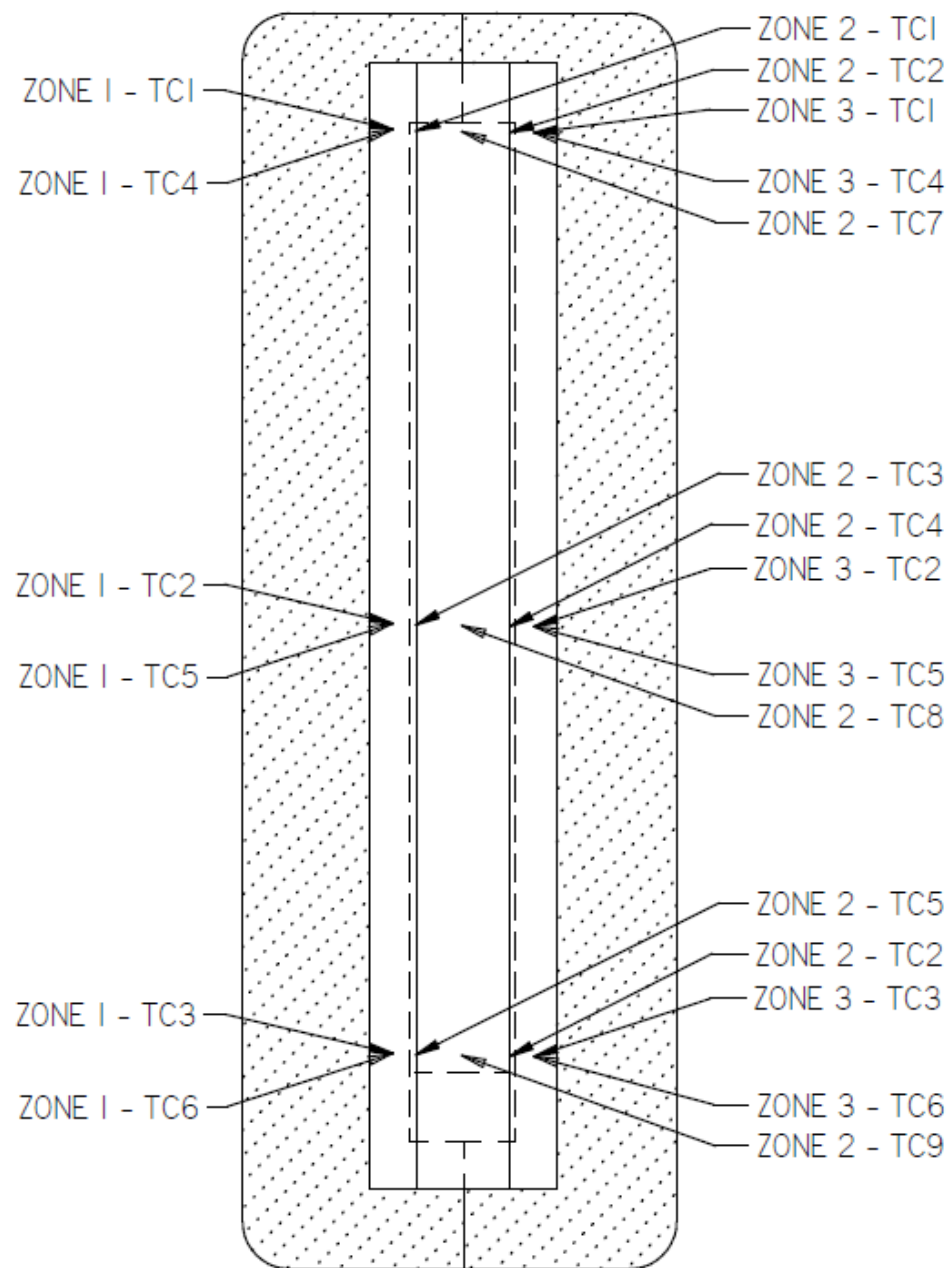
Out-of-autoclave material systems can be particularly sensitive to processing variation



Cure Process Scale-Up

- Hardware scale of MDA dictated the need for a hot bonder and heat blankets
- Sub-scale cure trials were performed on mock-up assemblies
- Heat blankets on-hand were modified to accommodate required cure region
- Thermocouples placed on top of doubler and on top of heat blankets
 - Blanket and part temperature lag used to configure hot bonder for cure
 - Hot bonder blanket set points were configured to compensate for part lag





TC Locations for Doubler A & Doubler C

Group	Zone	TC	Placement	Location (from FWD end of doubler)
1	1	1	Part	1"
1	1	2	Part	20"
1	1	3	Part	40"
1	1	4	Blanket	1"
1	1	5	Blanket	20"
1	1	6	Blanket	40"
2	2	1	Part	1"
2	2	2	Part	1"
2	2	3	Part	20"
2	2	4	Part	20"
2	2	5	Part	40"
2	2	6	Part	40"
2	2	7	Blanket	1"
2	2	8	Blanket	20"
2	2	9	Blanket	40"
1	3	1	Part	1"
1	3	2	Part	20"
1	3	3	Part	40"
1	3	4	Blanket	1"
1	3	5	Blanket	20"
1	3	6	Blanket	40"



Key Focus Areas

Continuous Doublers

- Doublers extend uninterrupted from the forward to the aft end

Segmented Doublers

- Multiple doubler segments separated by a gap

Co-bonding

- Doublers and film adhesive are cured and bonded to the primary structure in the same process

Secondary Bonding

- Pre-cured doublers bonded via film adhesive to the primary structure

Flat Doublers

- Doublers pre-cured on flat tooling

Curvature-matched Doublers

- Doublers cured on curvature-matched tooling



Configurations Considered on MDA

Config.	Description	Approach	Notes
1	Gap between doublers	Doublers co-bonded	— Gap between doublers demonstrates fracture control measure
2	Continuous doubler (via step-lap joint)	Doublers co-bonded	— Demonstrates ability to produce doubler larger than available heater blanket size
3	Doublers cured in oven on flat tool; gap between doublers	Doublers pre-cured, then secondarily bonded	— Allows doublers to be inspected after cure/prior to implementation on PLA — Allows for a lower temperature bonding process (by way of using 250°F curing film adhesive) — No specialized tooling needed for doubler layup/cure
4	Doublers cured in oven on curved PLA segment panel; gap between doublers	Doublers pre-cured, then secondarily bonded	— Allows doublers to be inspected after cure/prior to implementation on PLA — Allows for a lower temperature bonding process (by way of using 250°F curing film adhesive) — Precludes potential risk of internal stresses at bond interfaces (by more accurately matching curvatures)

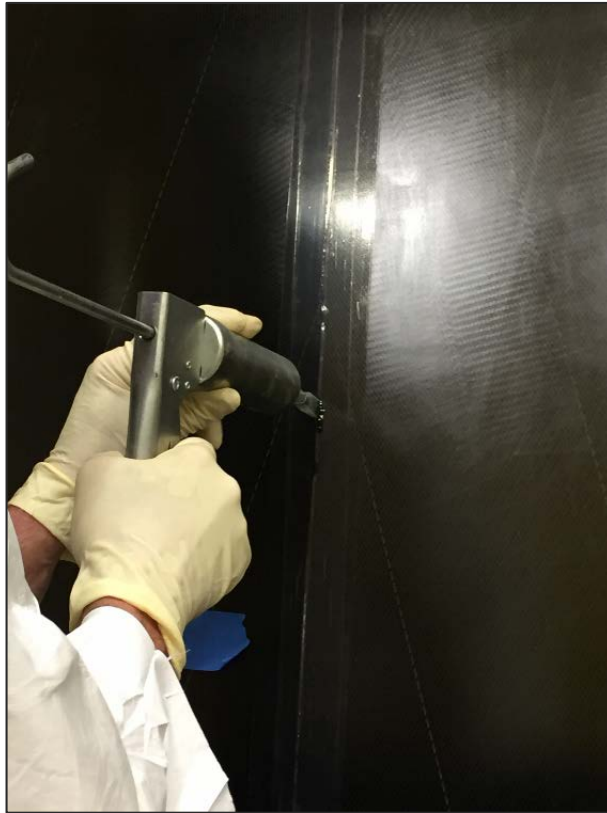


Full Scale Implementation on MDA

Step 1: Gap Filler

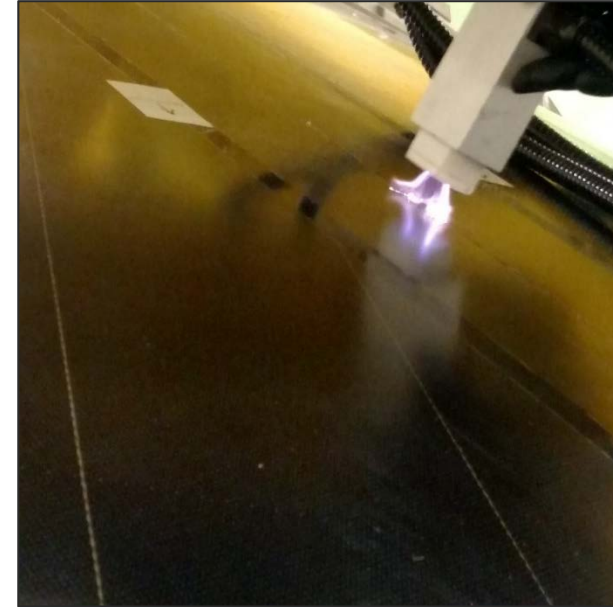
Room temperature curing epoxy injected in panel-to-panel gap and allowed to cure

- Enables even surface profile for doublers
- Enables vacuum integrity of bonding region



Step 2: Surface Prep

- (1) Delineated region ~2x the width of area to be bonded
- (2) Solvent wipe
- (3) Corona treatment (manually)
- (4) Water contact angle measurements taken at exterior edges of treated region (so as not to disrupt the area to be bonded)



Full Scale Implementation on MDA

Step 3: Doubler Installation

Doublers and film adhesive laid up prior to installation on primary structure

Doubler assembly placed

Processing materials, TCs, heat blankets, and vacuum bag applied



Step 4: Cure

OML and IML doublers of a given joint segment were cured concurrently to reduce heat loss



Full Scale Implementation on MDA

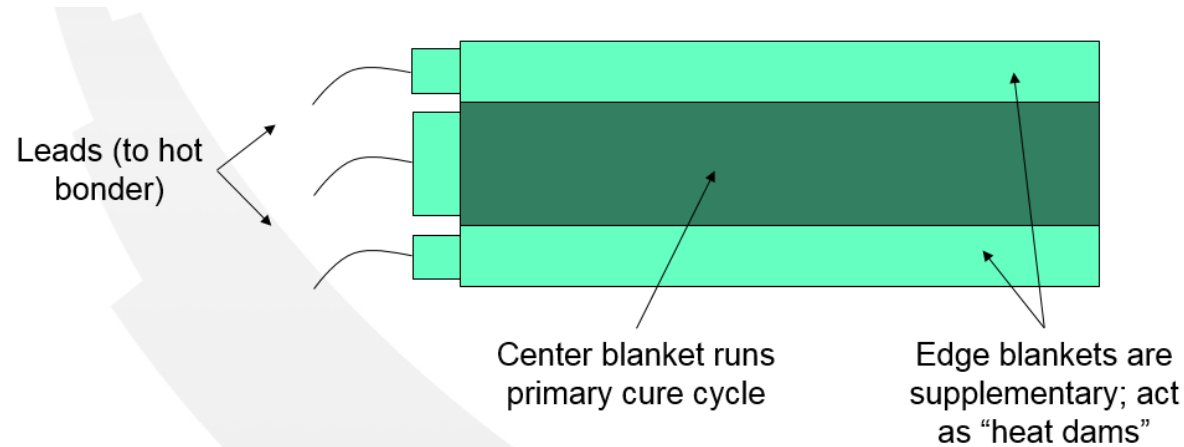


Lessons Learned

Surface Preparation

- Automation
 - Critical parameters (feed speed, offset distance)
 - Fully operator independent
- Atmospheric-pressure plasma treatment system outputs higher density plasma, altering the surface energy in a more significant manner

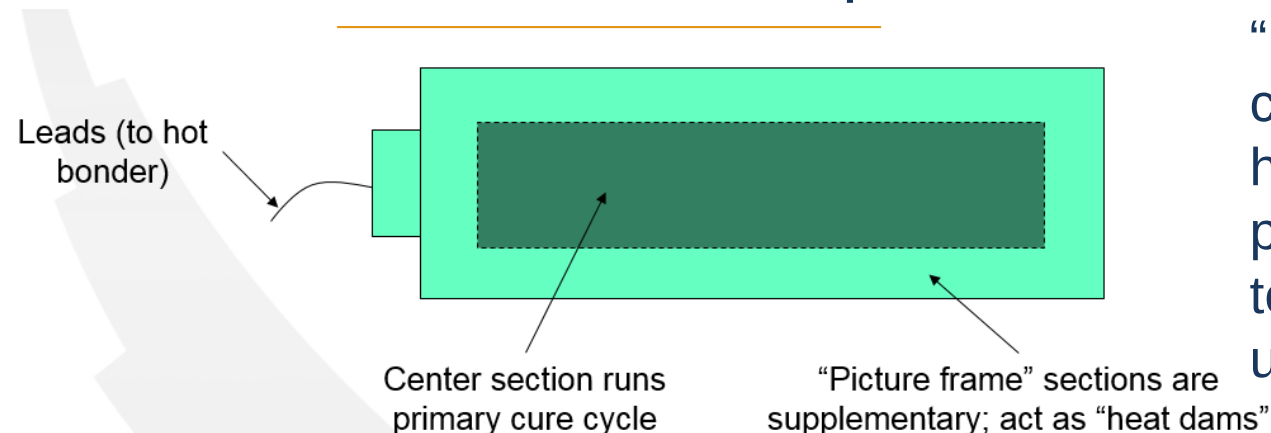
Config. Used on MDA



Heat distribution challenges:

- Part geometry
- Proximity to heat sinks
- Substrate thickness
- Core type

Multi-zone concept



"Picture frame" concept reduces heat loss at edge of part; promotes temperature uniformity



Lessons Learned: Bonding Method

Consideration	Co-bond	Secondary bond
Surface preparation	Required on one surface (primary structure)	Required on two surfaces (primary structure and doublers)
Doubler/bonding adhesive cure (where part scale exceeds size of available autoclave/oven)	Requires in-situ cure of prepreg material system for doublers and bonding adhesive (if used)	Requires in-situ cure of bonding adhesive only
Verification of doubler quality via NDE	Doubler quality can be verified only via post-cure NDE	Doubler quality can be verified via NDE prior to secondary bonding operation (i.e. ability to reject a doubler if quality is poor)
Verification of doubler quality via mechanical/thermal testing	Difficult to fabricate representative witness panels	Representative witness panels can be cured in same oven run as doublers; can verify material properties for each doubler produced
Bond integrity (in relation to as-built part geometry)	Co-bonding process allows doubler assembly to conform to as-built geometry of the primary structure	Must rely on film adhesive to compensate for irregularities in as-built primary structure geometry
Tooling	Does not require tooling	Requires tooling to match doubler form to that of the primary structure



