



# Space Technology Mission Directorate Game Changing Development Program

John Fikes | FY18 Annual Review Presentation | 09.25.2018

## Composite Technology for Exploration (CTE)

# Technology Overview

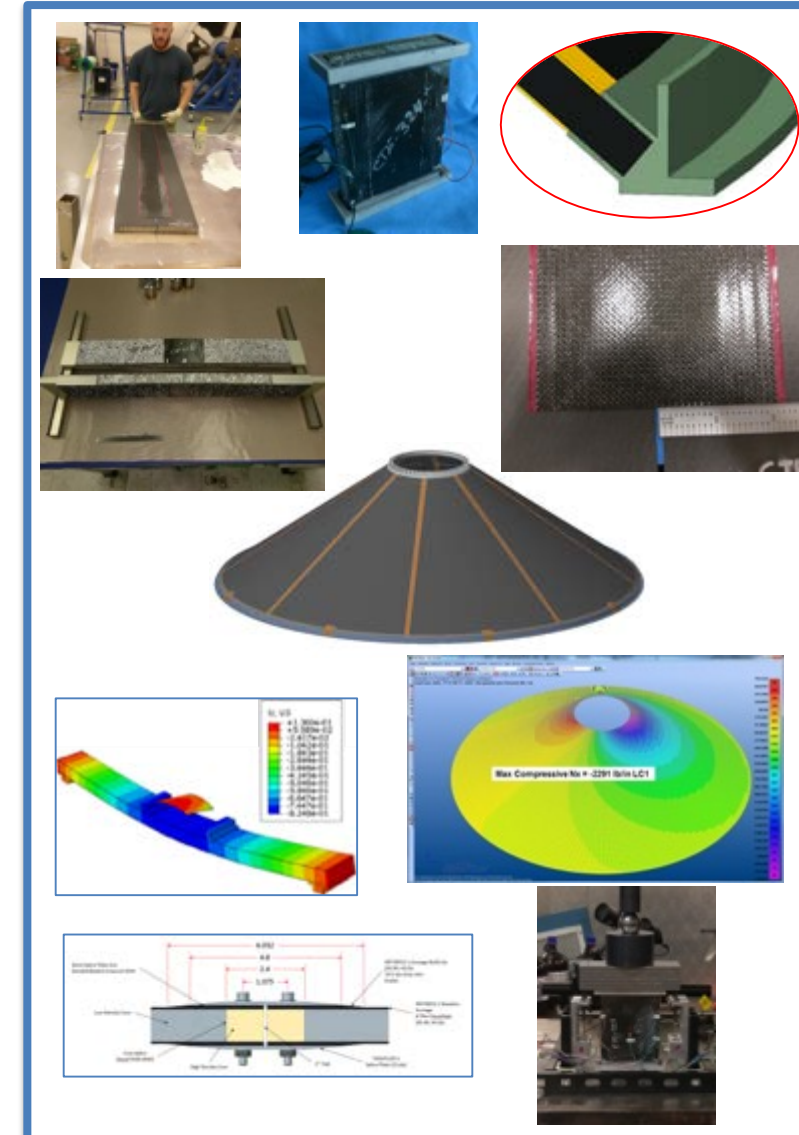


## ➤ Technology Product Capability

- The CTE project will develop and demonstrate critical composites technologies with a focus on weight-saving, performance-enhancing bonded joint technology for Space Launch System (SLS)-scale composite hardware to support future NASA exploration missions.
  - Improve the analytical capabilities required to predict failure modes in composite structures.
  - Support SLS payload adapters and fittings by maturing composite bonded joint technology and analytical tools to enable risk reduction.

## ➤ Exploration & Science Impact

- Lighter weight structures.
- Improved material predictive capabilities.
- Improved bonded joint failure load and mode predictions to help reduce knockdown factors; and improve predictability and reliability.
- Increase confidence of all bonded joint composite structures.
- Reduce reliance on expensive testing.



# Mission Infusion & Partnerships



- Infusion/transition plan
  - HEOMD – SLS.
  - Block upgrades. CTE will provide lighter weight structures for greater performance and increased payload capability.
  - Composite Bonded Joint Design and Analysis through the NESC PMC Community of practice.
  
- Contributing partners and/or stakeholders
  - HEOMD – SLS
  - OCE/NESC is helping capture CTE data for future project usage
    - Composite Bonded Joint Design, Analysis and Test data is being captured through the NESC Polymer Matrix Composite Community of Practice.

# CTE Technology Goals & Project Objectives



## Technology Goals

<b>Goal #1</b>	Develop and validate high-fidelity analysis tools and standards for predicting failure and residual strength of composite bonded joints.
<b>Goal #2</b>	Develop and demonstrate an analytical tailoring approach that enables the reduction of the baseline 2.0 safety factor for composite discontinuities.

**Notes:** Demonstrated CTE double lap longitudinal joint design, an out of autoclave cured bonded composite joint, through design, analyses, manufacturing, and test. Developed longitudinal joint detailed designs, test article designs and NDE standards. Evolved manufacturing process parameters to produced repeatable and reliable longitudinal joints and fabricated 12 jointed panels with these processes at MSFC. Manufactured 44 joints test articles at GSFC. Tested those 44 tests articles in primary loading conditions, in both pristine and damaged conditions, at Southern Research. Pristine and damaged joints met minimum CTE load requirements with 2.0 factor of safety. Evaluated cohesive zone and VCCT longitudinal joint specimen models for joint failure predictions. Established non-linear approach resulting in pretest predictions within 7% . Developing and evaluating a parametric FE-based joint design tool based on different analysis tools for rapid joint doubler preliminary sizing. Produced 3D woven flat panels through a contract with Bally Ribbon Mills. Initiated 3D weave material testing with NIAR to evaluate 3D weave predictive tools. Contract awarded with Bally Ribbon Mills to produce 3D weave circumferential joint concepts.

## Project Objectives

<b>Joint Configuration</b>	Identify low mass bonded joints for light-weight composite launch structures.
<b>Model Predictions</b>	Establish modeling capabilities that enable failure predictions with low engineering uncertainty.

**Notes:** The CTE project has designed a bonded (no fasteners) longitudinal joint. Joint test coupons fabricated and tested. Pristine and damaged joints met minimum CTE load requirements with 2.0 factor of safety. Completed four full-scale joints on the Payload Adapter Manufacturing Demonstration Article (PLA MDA). Next, the CTE project will design a bonded circumferential joint – much bigger challenge, but much bigger payoff.

The CTE project has down-selected several analytical programs and failure theories and is analyzing joint designs with the selected programs and theories. The results of the joint tests are being used to evaluate analytical approaches.

# CTE Performance



## Key Performance Parameters

### Composite Technologies for Exploration (CTE)

Performance Parameter	State of the Art (SOA)	Threshold Value	Project Goal	Estimated Current Value
Failure Prediction <sup>(1)</sup>	±25% of mean	±15% of mean	±5 of mean.	See #1 in Notes
Risk Reduction Factor <sup>(2)</sup>	2.0	1.8	1.4	SOA
Part Count <sup>(3)</sup>	100%	75%	50%	2% <sup>(4)</sup>
Weight <sup>(3)</sup>	100%	85%	75%	15% <sup>(4)</sup>

**Notes:**

1. Initial assessment of advanced tools by experienced analyst reflects reduction to threshold value of ±15% of mean.
2. Safety for joints in primary load path for an SLS-like composite structure Discontinuity Factor of Safety =  $J * 2.0$ , where  $J$  is a risk reduction factor based on new analytical techniques and test data.
3. State of art metal bolted joint in primary load path for 8.4 M diameter scale structure. Weight associated with metal/bolted joints (*e.g., 3 lb/ft metal bolted joint to lower weight per linear foot bondline*).
4. Longitudinal bonded joint, CTE point design. Highly loaded structure.

# CTE Technical Approach



- Plan to accomplish project objectives:
  - Develop and validate high-fidelity analysis tools/modeling and analysis standards for the prediction of failure and residual strength of composite bonded joints.
  - Design, fabricate, and test a suite of light-weight bonded joint concepts for SLS-like applications (for example, the Payload Attach Fitting, PAF).
  - Develop and demonstrate an analytical tailoring approach that enables the reduction of the baseline safety factor for composite discontinuities in NASA-HDBK-5001 from the current 2.0, which would subsequently reduce the baseline weight for bonded composite structures.
  - Deliverables include:
    - The design, analysis, fabrication, and test of one or more representative-scale bonded joints.
    - Material equivalency reports.
    - Validated analytical methodologies for the prediction of composite bonded joint behavior and behavior at/near discontinuities.
    - Post-test report to include a proposed strategy and infusion path forward.

# Composite Technology for Exploration (CTE)

## Complete Design, Analysis, Fabrication & Testing of Down Selected Longitudinal Bonded Joint Concept API Milestone Completion



**Objective:** Design, fabricate, and test longitudinal composite bonded joint concept for potential SLS-scale structures infusion, and use tests data to validate joint failure predictions and advance predictive modeling methodology and tools.

Date	
Scheduled	08/24/18
Actual	08/22/18

### Key Accomplishments:

- CTE team successfully designed, fabricated and tested a 4-ply bonded joint concept for SLS-class structures.
- CTE manufacturing team developed and demonstrated joint processing with repeatable, predictable performance.
- CTE analyses team evaluated different tools and methods to predict initial failure and determined a viable approach to predict longitudinal double lap bonded joint performance.

### Technology Advancement:

- CTE project shows reduced joint mass by 85% while reducing part count by 98% with respect to metallic bolted joints. (based on CTE point design and loads)
- Additionally CTE screened, evaluated and found best analyses tools and methodologies resulting in composite longitudinal joints failure prediction within 5% of test average values.

CTE Point Design

CTE Joint Concept

Global Analysis

Fabricated Joint Panels

Payload Adapter

Bonded Joint (during cure)

Hot Bonder

SLS Manufacturing Demonstration Article

Joint Failure Analysis

Failure

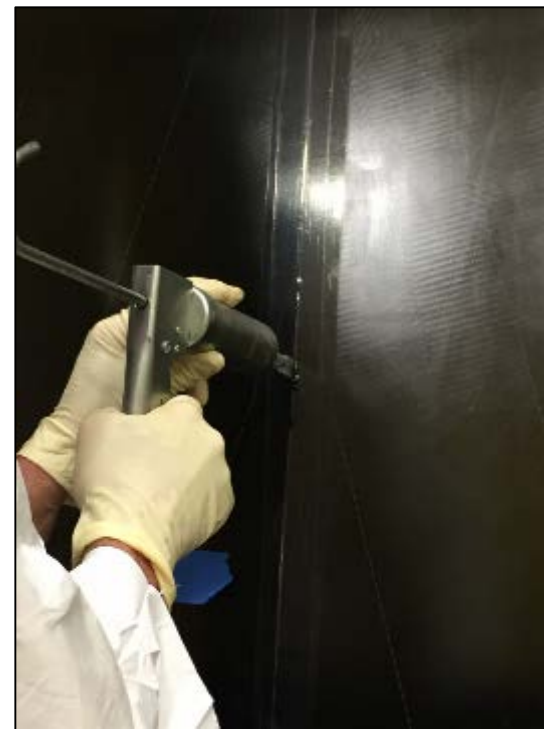
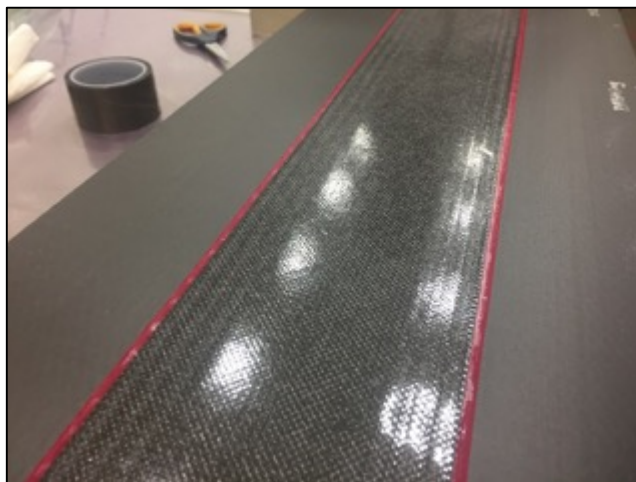
Joint Testing

# Technical Status: Manufacturing



## ➤ Successfully completed fabrication:

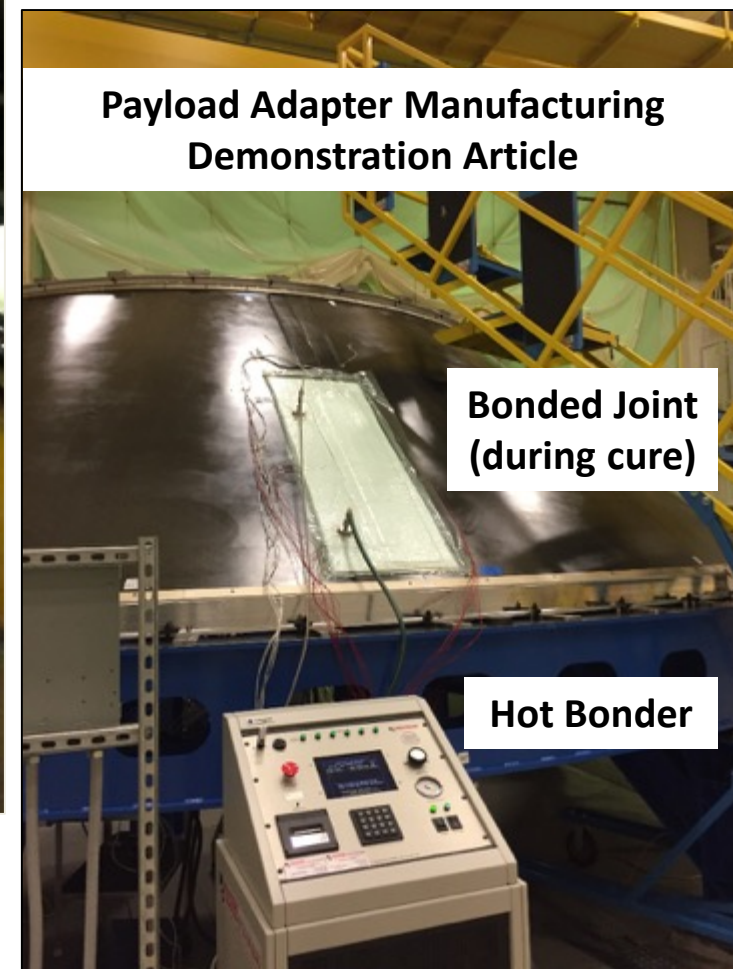
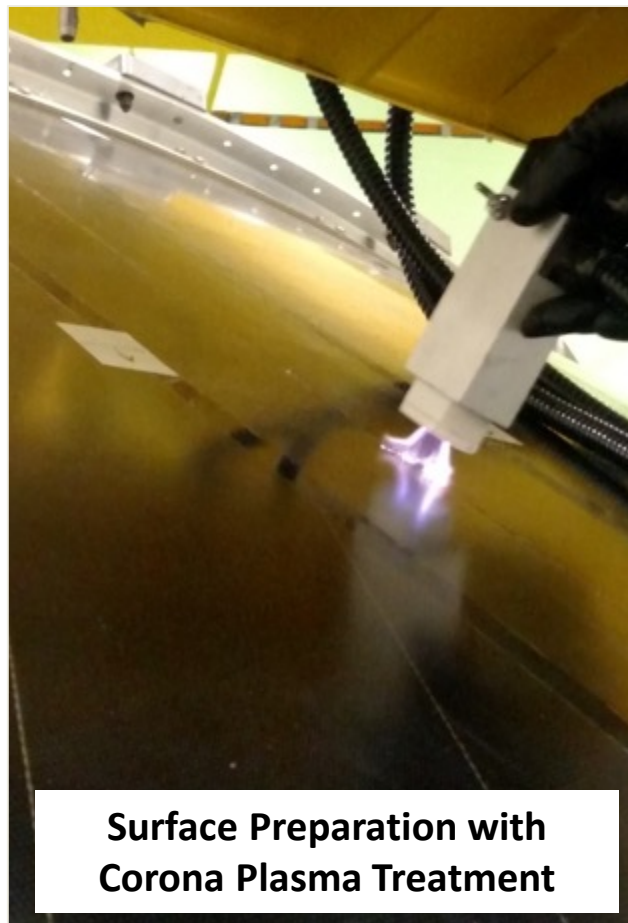
- For Coupon Testing
  - Surface preparation lap joints
  - Strain energy release rate coupon panels
- For Longitudinal –Joint Sub-Element Testing
  - NDE standard panels
  - Small and large-scale acreage panels
  - Small and large longitudinal bonded joint panels



# Technical Status: Manufacturing



- Procured process equipment for large-scale bonding operations.
  - Corona plasma treatment system for high performance, consistent surface preparation.
  - Multi-zone longitudinal heating blankets for improved scale-up bonding operations.
- Developed process parameters for out-of-autoclave bonded joint cures with hot bonder.
- Completed four full-scale joints on the Payload Adapter Manufacturing Demonstration Article (PLA MDA).

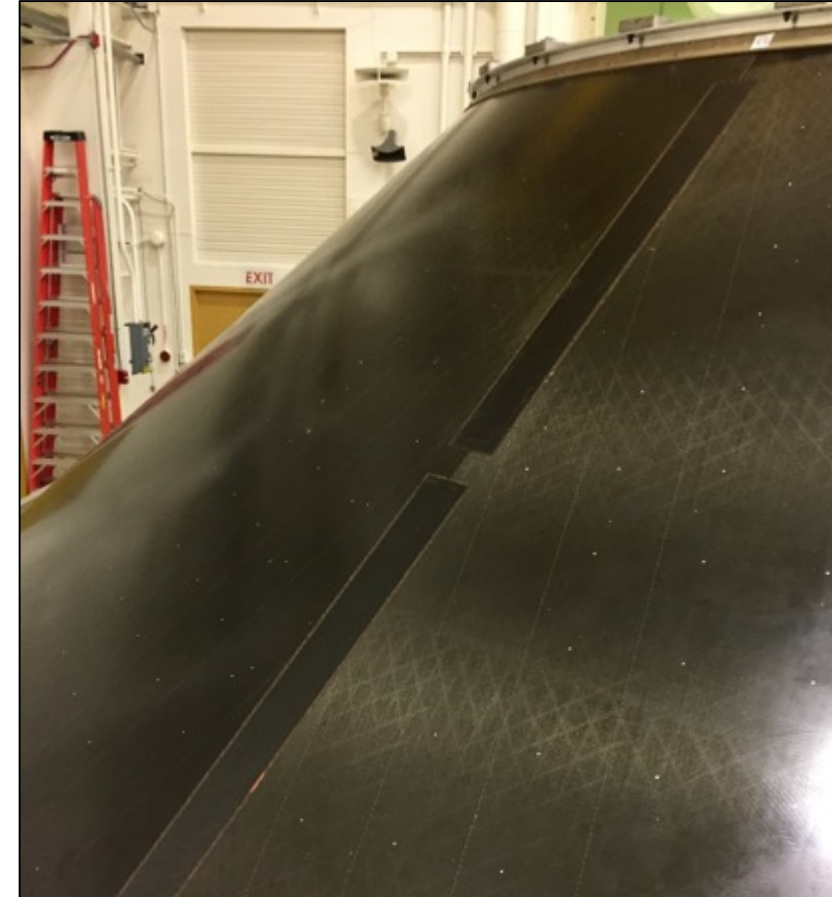


# Applying Longitudinal Joint Work to SLS



## ➤ Completed four full-scale longitudinal bonded joints on the Payload Adapter Manufacturing Demonstration Article

- Completed four joints in eight cures. (two cures per joint)
- Incorporated co-cured and pre-cured doublers. (two joints per method)
- Used materials, layup, and process controls selected and developed under the CTE project.
  - Used corona plasma surface treatment process.
  - Used surface analyst to verify bond readiness.
  - Used hot bonder and heater blankets procured and evaluated under the CTE project.



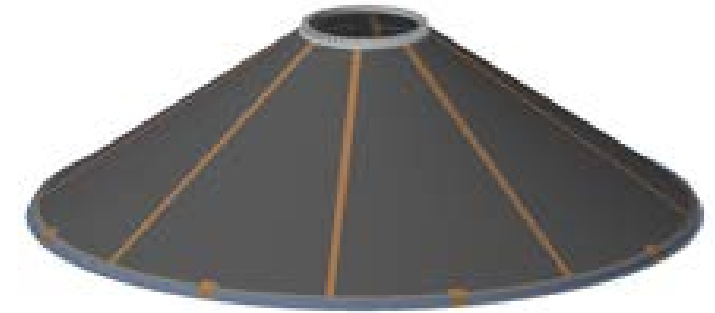
Payload Adapter Manufacturing  
Demonstration Article  
Bonded Joint (after cure)

# Applying Longitudinal Joint Work to SLS



➤ **The SLS Payload Adapter team is considering longitudinal bonded joints as a part of a mass savings opportunities evaluation.**

- Drawing on the proof of manufacturability at scale on the Manufacturing Demonstration Article, aided by development work completed through the CTE project.
- If the design is re-baselined to incorporate longitudinal bonded joints:
  - Longitudinal bonded joints will be used on the Development Test Article.
  - Surface preparation procedures and scale-up manufacturing development work developed through the CTE project will be utilized.
  - Hot bonder, improved heater blankets, corona plasma surface treatment, and surface analyst procured through the CTE project will be utilized.



# Technical Status: Manufacturing



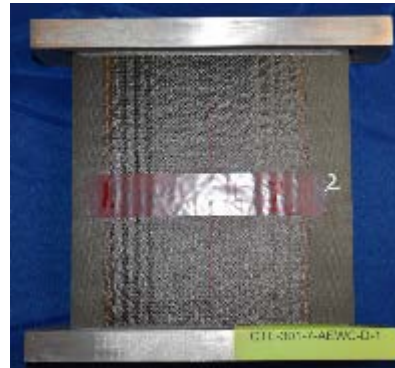
## L-Joint Test Article Manufacturing: GSFC

- MSFC provided Jointed Panels were trimmed and assembled into Sub-Element test articles.

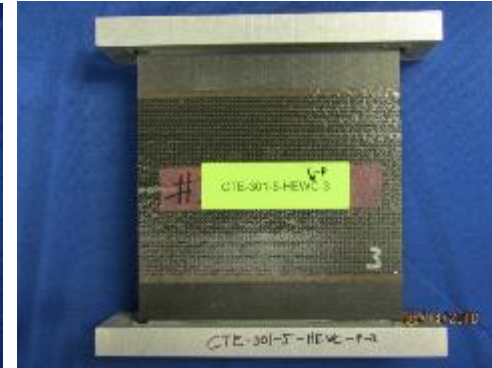
### Produced:

- 19 Axial edge-wise compression (AEWC) test articles.
- 17 Hoop edge-wise compression (HEWC) test articles.
- 20 Axial edge-wise compression (AEWC) test articles.

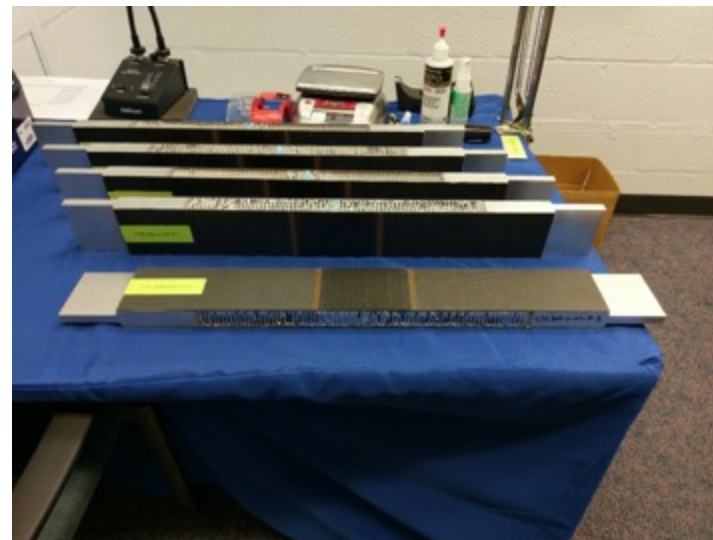
*Note: CTE made some spares, not tested.*



Axial EWC



Hoop EWC



Hoop Tension

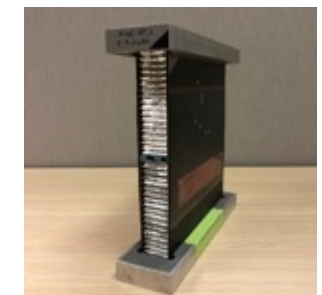
## Processing



Trim Panels



Bond Ends



Final Trim & Metrology

# Technical Status: NDE

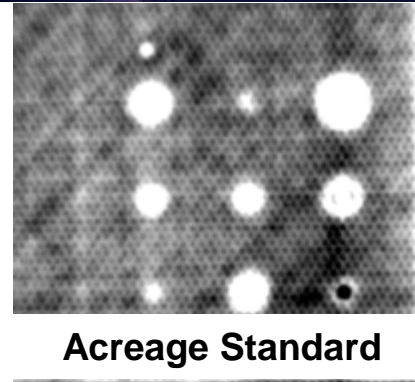


## ➤ Standards Panels – Developed and characterized to quantify defect detectability

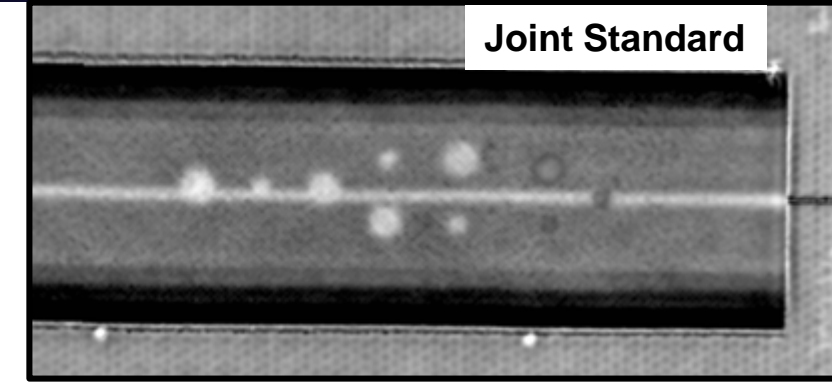
- Porosity
- Acreage areas
- Joint doublers

## ➤ Inspections

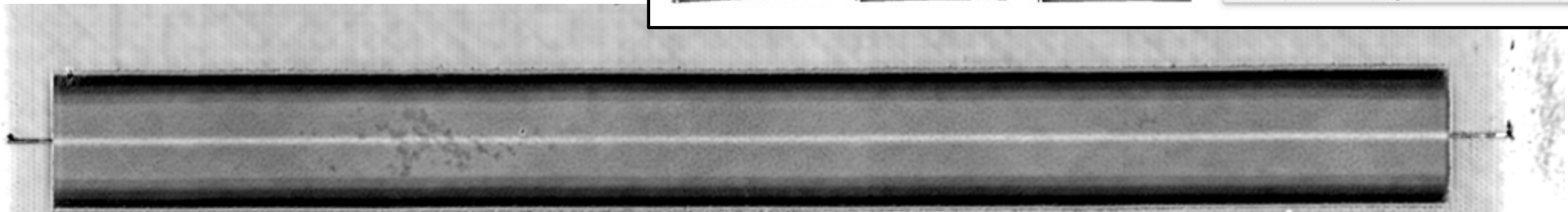
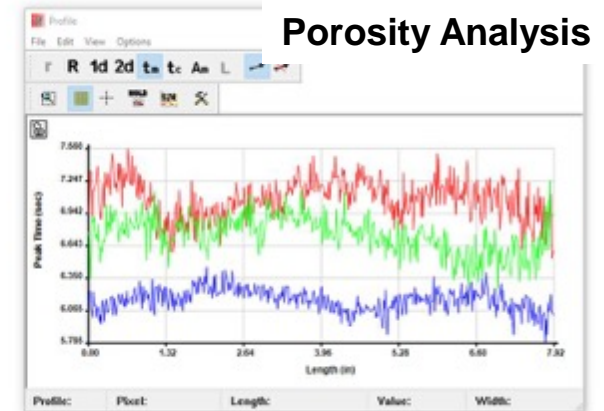
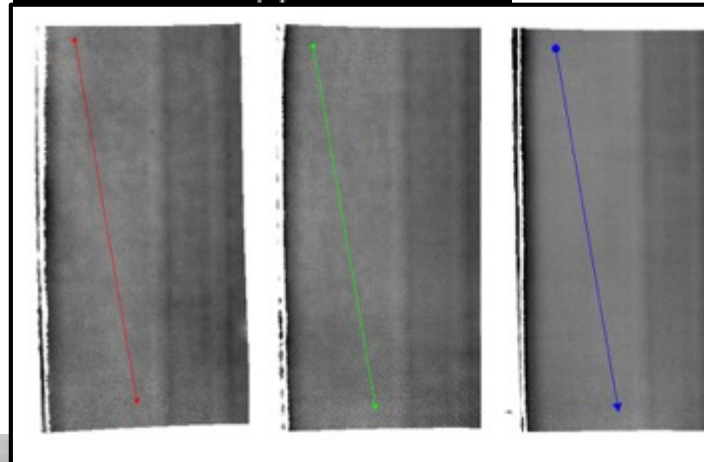
- 50+ panels and coupons inspected at various stages of manufacturing and testing
- Porosity detected in several joint panels



Acreage Standard



Joint Standard

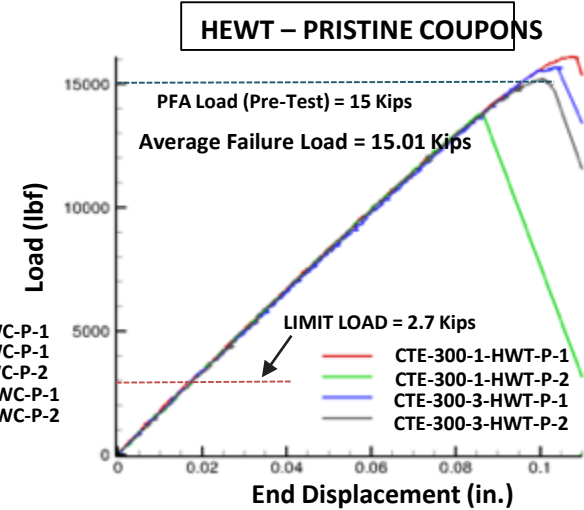
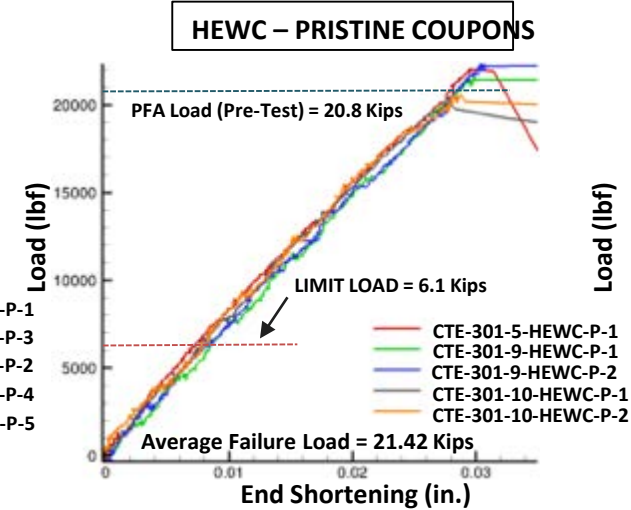
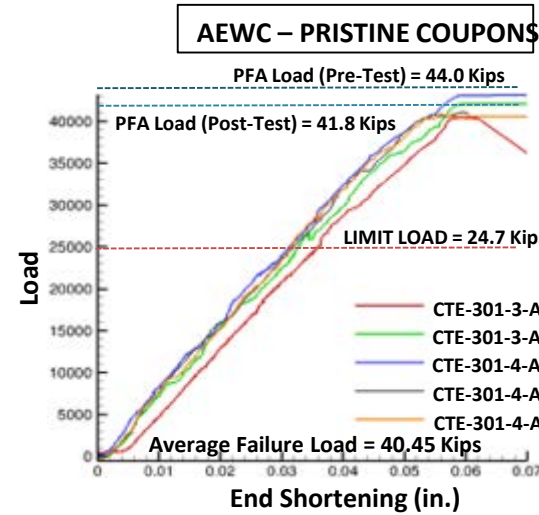


Porosity Detected in Joint Doubler

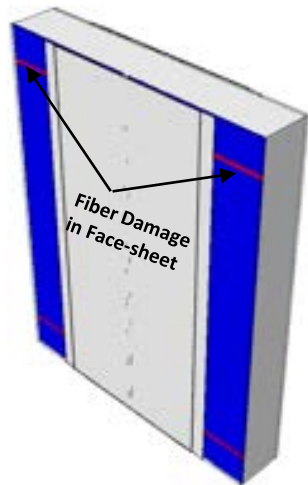
# Technical Status: Test and Analysis Longitudinal Joint Test/Analysis Correlation



- Tested 28 pristine coupons at Southern Research.
- All coupons (pristine) failed above CTE Point Design required strength with 2.0 FS.
- Progressive failure analysis (PFA) using cohesive zone and COSTR damage model used to predict joint failure.
- Post-test correlation achieved within 5% of test data for all tests.



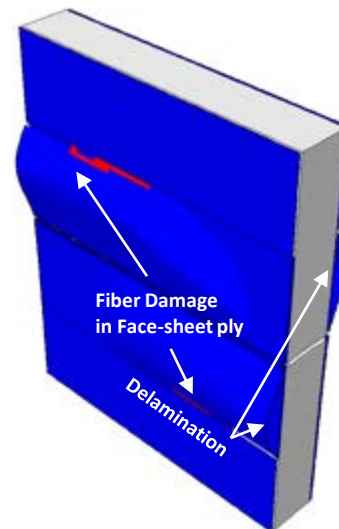
Failed AEWc Coupon



PFA of AEWc Coupon



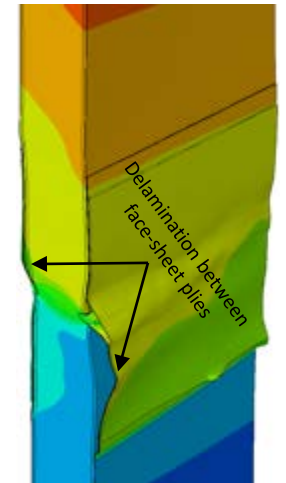
Failed HEWC Coupon



PFA of HEWC Coupon



Failed HT Coupon



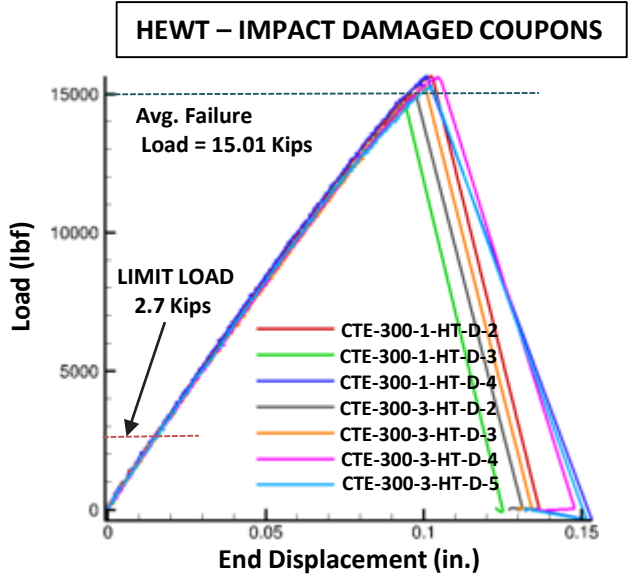
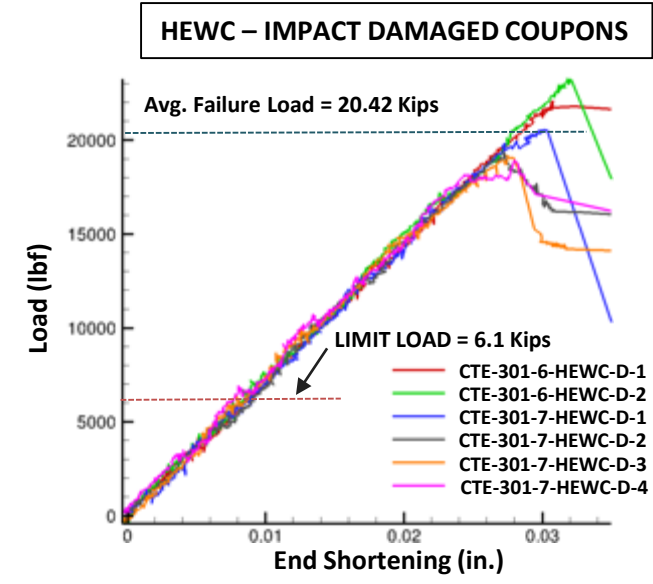
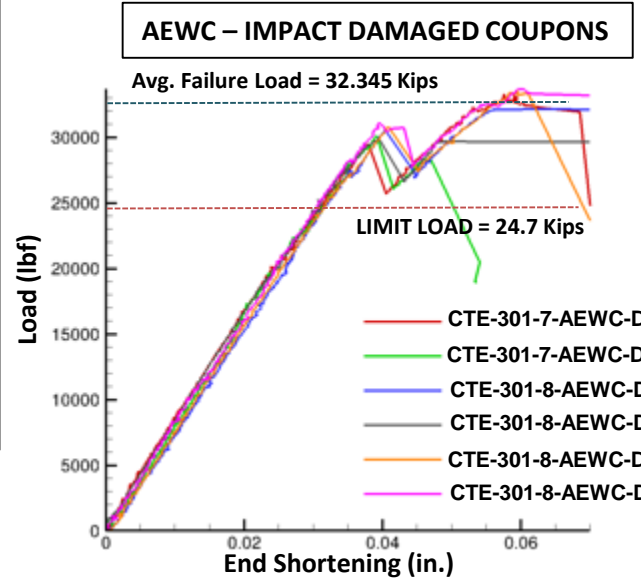
PFA of HEWT Coupon

# Technical Status: Test of Impact Damaged Coupons

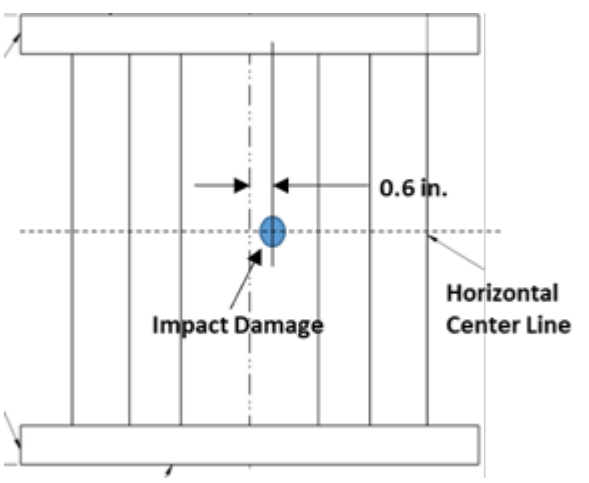
## Longitudinal Joint Test Data



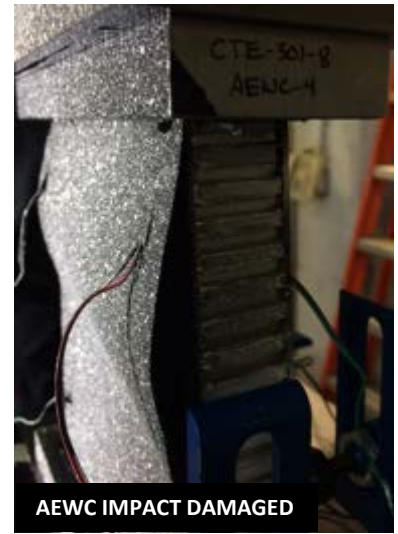
- Tested 21 impact damaged coupons at Southern Research.
- All coupons (impact damaged) failed above CTE Point Design required strength with 2.0 FS.



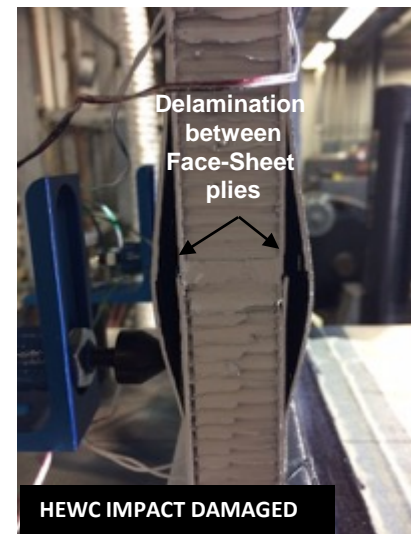
Test Setup of AEWC & HEWC Coupons



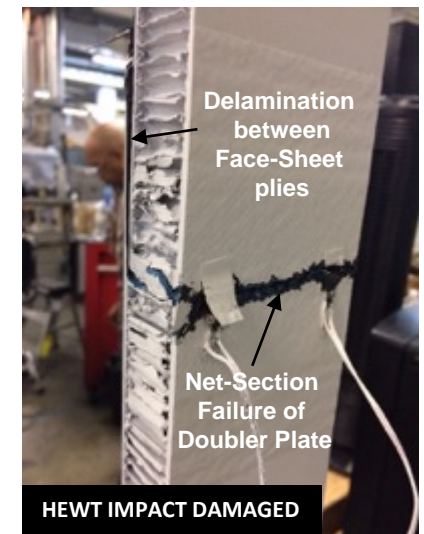
Average Impact Damage Location



Failed AEWC Coupon



Failed HEWC Coupon

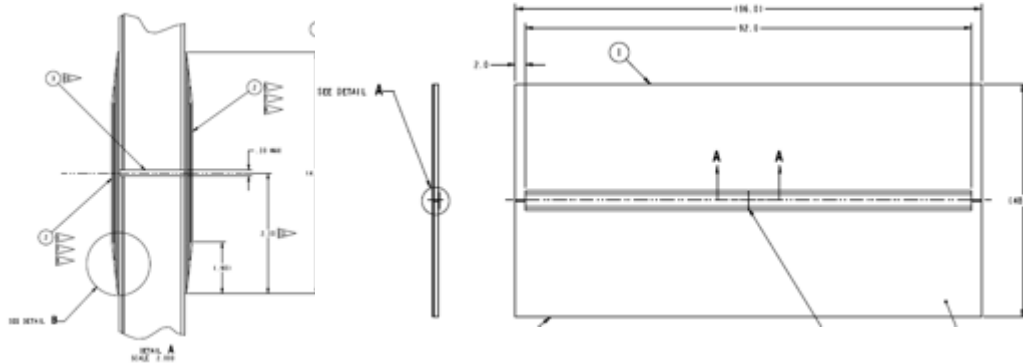


Failed HT Coupon

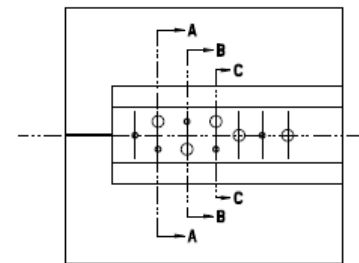
# Technical Status: Longitudinal Joint Design Accomplishments



Designs and drawings produced for all CTE development activities



Longitudinal Joint (L-Joint) Detailed Designs

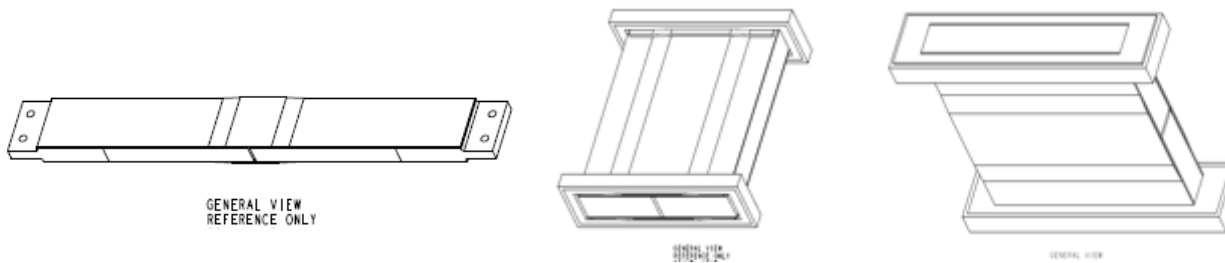


NDE Standards



Large Scale Test - Buckling Panel

Future L-Joint Design:  
Complete combined load test panel

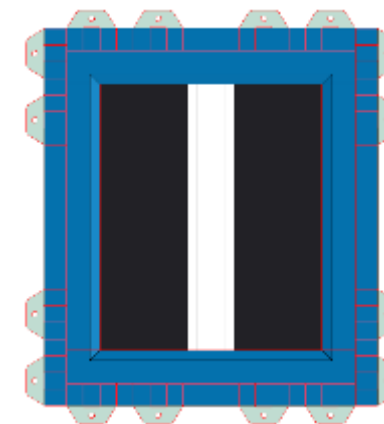


L- Joint Test Article Designs



3D Woven Composite Test Panels

GENERAL VIEW



Combined Load Test Panel – in Progress

# Technical Status: Analysis

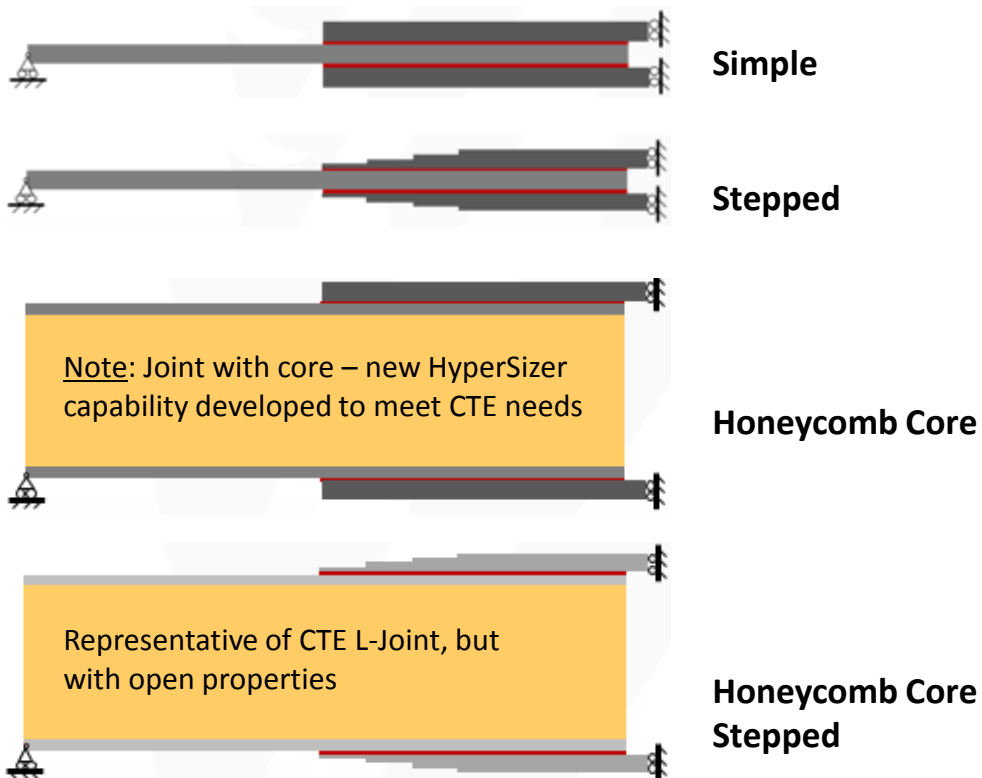
## Assessment of Rapid Bonded Joint Design Tools



- Rigorous comparison of common joint design tool predictions with FEA and experiment.

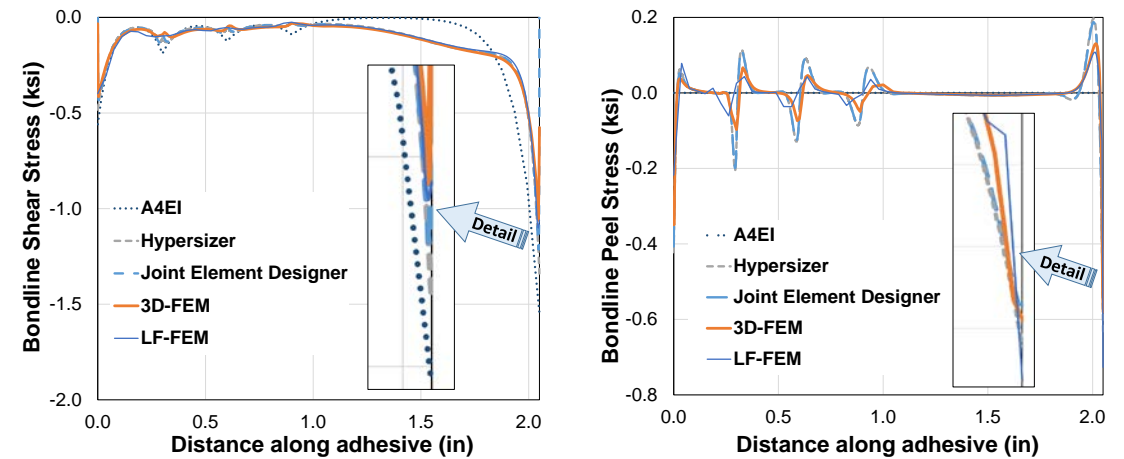
A4EI ■ HyperSizer ■ Joint element designer ■  
 Low fidelity FEA ■ 3D FEA

- Consider a range of joints from simple to more complex:

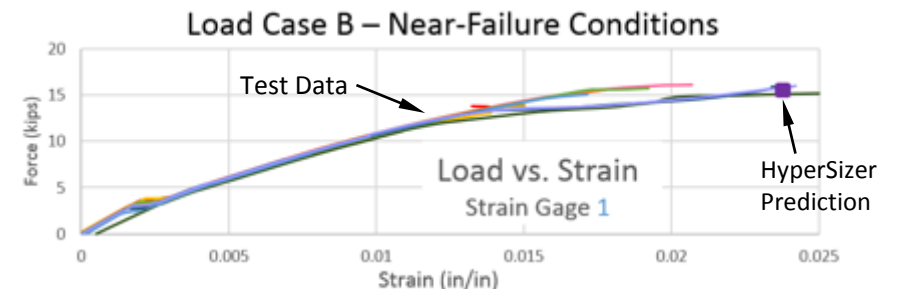


- Comparison of bondline stresses as well as full stress contours.
  - Stresses commonly used for joint margin calculation.

Bondline Stress Comparison for Representative (open) CTE L-Joint



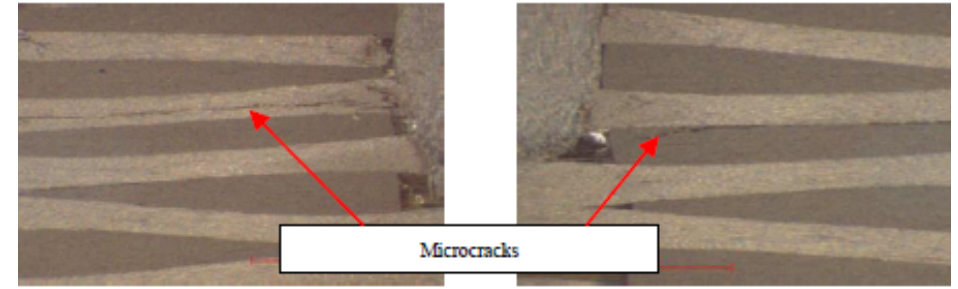
- Results to be presented at AIAA SciTech Forum, Jan. 2019.
- For actual CTE L-Joint (restricted properties), tools validated vs. CTE test data:



# Technical Status: Materials



- Established a flat panel study
  - Evaluation of resin micro-cracking in the 3D woven architecture.
  - Enable resin down-selection based on panel test data.
  - Risk reduction by providing material data to design and analysis.
  - Bally Ribbon Mills manufactured 3D woven flat panel preforms.
  - 3D woven panels were infused at North Coast Tooling in Cleveland, OH with 4 separate resins to evaluate micro-cracking and mechanical properties.
  - Panels were shipped to NIAR for machining and mechanical testing. Coupons will be returned to Glenn for optical microscopy and fiber volume fraction measurement. Additional coupons will be sent to Goddard for X-ray CT.



Reference: Poulaert, B. et. al, "Composite Ring Made of 3D Woven Preform Injected by RTM: From Design to Full Scale Testing", SAMPE, Long Beach, 2016

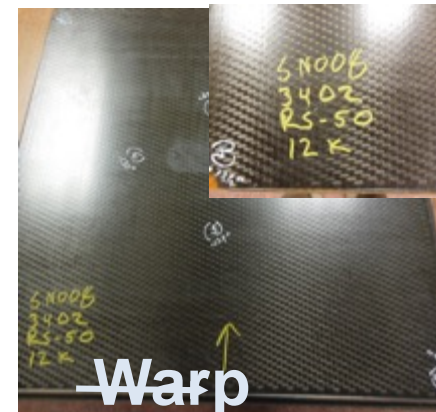
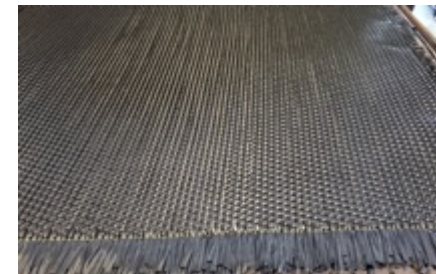


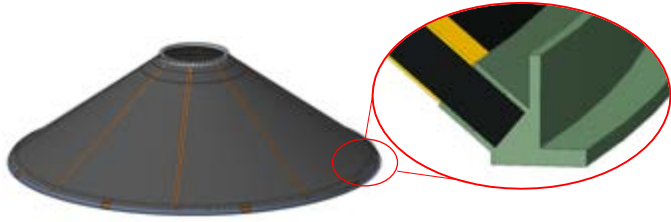
Photo of mechanical testing 3D woven coupon at GSFC.

# Technical Status: 3D Weave Team

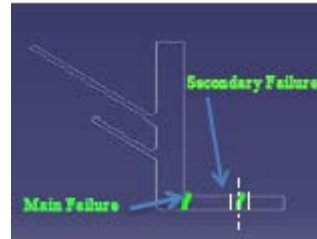


**Concept Starts**

NASA / MSFC and GSFC



BRM (ESA-Sonoca)  
*Prior Work*

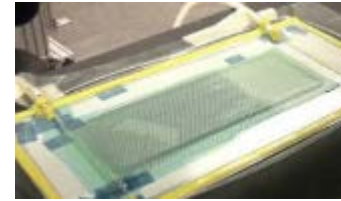


BRM: *Design Inputs*

BRM  
*Weave flat panels*



Northcoast  
*RTM panels*



NASA/ GRC and NIAR  
*Properties testing*

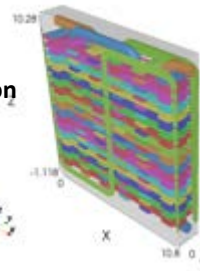


"Predicted" Elastic Properties  
w/ Modeling & Test Correlation

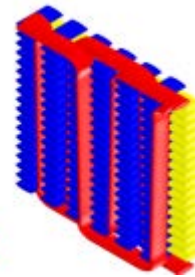
Ex	42.28	GPa
Ey	67.29	GPa
Ez	15.63	GPa
nu12	0.037	-
nu13	0.195	-
nu23	0.188	-
Gxy	2.5	GPa
Gxz	2.32	GPa
Gyz	2.34	GPa

NASA/ GSFC & GRC and MSC Software: *Modeling Development*

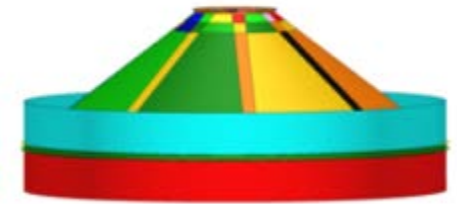
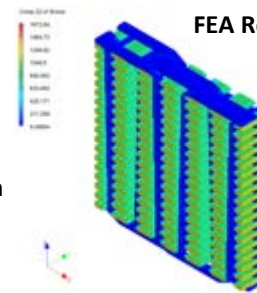
TexGen  
Illustration



Modeled in  
Digimat



FEA Results



NASA / TBD  
Joint Verification Testing

**3D Weave Design  
Cycle Iteration  
Complete**

NASA/ MSFC Joint Assembly

CRG: RTM End Ring



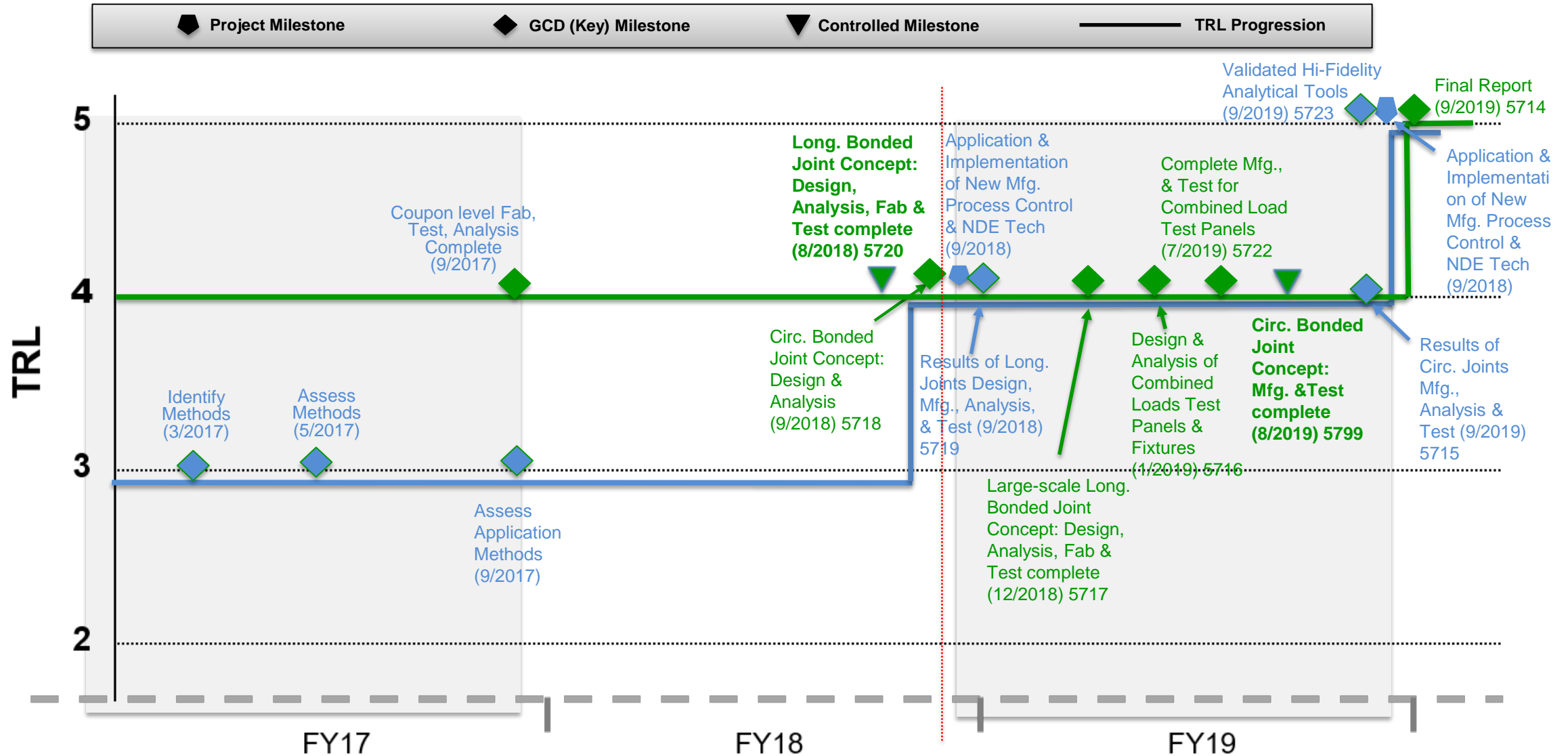
BRM: *End Ring Weaving*



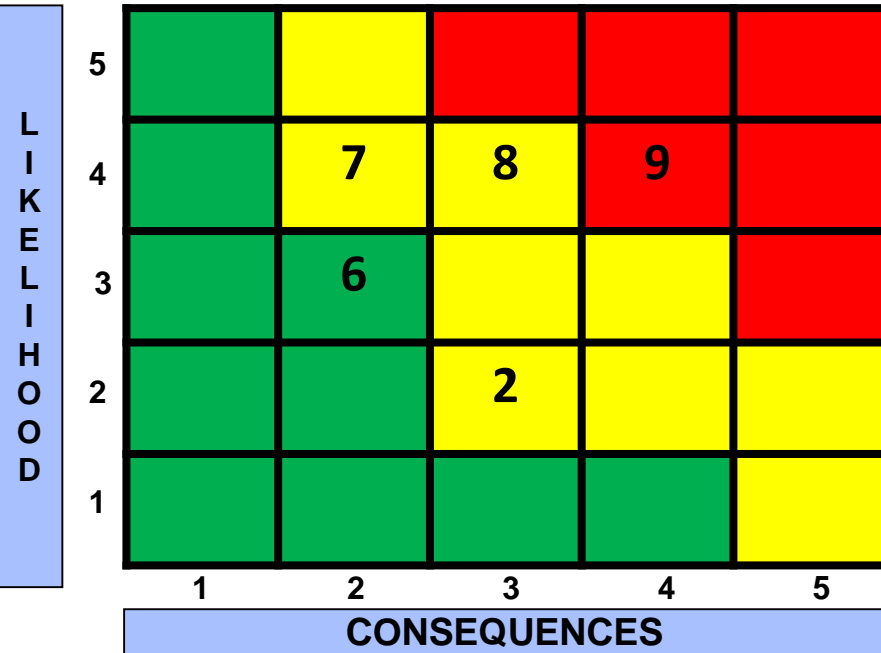
CRG: *Tool design and Fab*



# CTE IMS/TRL Alignment



# CTE Risk Summary



Risk ID	Affinity	Description/Status	Trend
2	M/T,Sc,C	Limited Verification of Structural Capability	⇨
6	W/Sc	Facility Availability	⇨
7	W/T,Sc	3D Woven Joint Lead-Time	⇨
8	M/T	NDE Acceptance Criteria	⇨
9	M/T	Scale-Up	⇧

NOTE: Risk 9 increased to 4x4, and approach changed from Watch to Mitigate. Details in backup

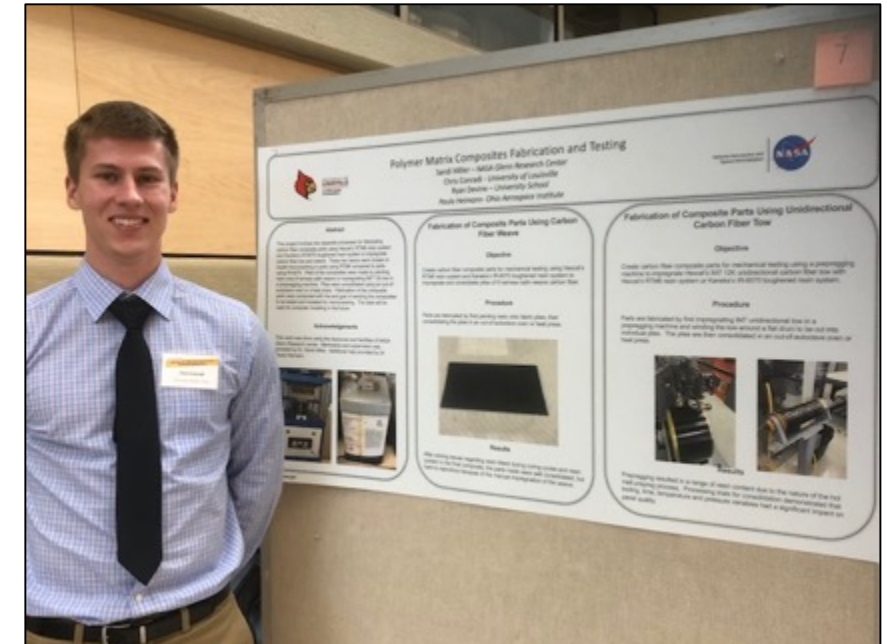
<b>Criticality</b>	<b>L x C Trend</b>	<b>Approach</b>
High (Red)	⇩ Decreasing (Improving)	M - Mitigate
Med (Yellow)	⇧ Increasing (Worsening)	W - Watch
Low (Green)	⇨ Unchanged	A - Accept
	☐ New Since Last Period	R - Research
<b>Affinity:</b> T-Technical C-Cost Sc-Schedule Sa-Safety		

# EPO Summary Chart



## ➤ Summary of Education and Public Outreach

- 2018 AIAA SciTech Forum (Kissimmee, FL) – January 8-11, 2018
- SAMPE 2018 (Long Beach, CA) – May 21-24, 2018
- NSMMS / CRASTE: National Space & Missile Materials Symposium (Madison, WI) – June 25-28, 2018
- Northeast Ohio Undergraduate Research Symposium held at Kent State University, August 2, 2018.
- Structures, Loads and Dynamics, and Mechanical Systems (SLaMS) Young Professionals Workshop (NASA/GSFC) – August 21-24, 2018



CTE materials work was presented at the Northeast Ohio Undergraduate Research Symposium held at Kent State University, August 2, 2018. Chris Conradi is a summer intern at GRC. He attends the University of Louisville.

# Annual Summary



- Completed the CTE API Milestone **”Complete Design, Analysis, Fabrication & Testing of Down Selected Longitudinal Bonded Joint Concept”**.
- Demonstrated CTE double lap longitudinal bonded joint design through design, analyses, manufacturing, and test.
- Tested 49 longitudinal bonded joint sub-element specimens in primary loading conditions. **Pristine and damaged joints met minimum CTE load requirements with 2.0 factor of safety.**
- Developed manufacturing process parameters to produced repeatable, reliable and predictable longitudinal joint performance.
- Evaluated cohesive zone in-plane continuum damage model (COSTR) for longitudinal joint specimen failure predictions. **Established non-linear approach resulting in pretest predictions within 7% .**
- Advanced 3D woven joint design methodology learning how to communicate design intent between designer, manufacturer, and analyst to received 3D woven parts as needed to structurally perform.



# Annual Assessment Summary



Technology	Mid Year				Annual Performance				Comments
	C	S	T	P	C	S	T	P	
TRL Element #1	Yellow	Yellow	Green	Green	Green	Green	Green	Green	Technical, schedule, and cost continue to be green. Completed the CTE API Milestone <b>"Complete Design, Analysis, Fabrication &amp; Testing of Down Selected Longitudinal Bonded Joint Concept"</b> on schedule.

# EPO Summary Chart



## ➤ Conferences attended

Conference Name	Papers/Posters/Panel Discussions
2018 AIAA SciTech Forum	1 Paper
SAMPE 2018	1 Paper
NSMMS / CRASTE (National Space & Missile Materials Symposium)	1 Presentation

## ➤ Academic involvement

# of Students	Education Level	School Name
1	Sophomore	University of Maryland, College Park
1	Senior	University of Louisville
1	Highschool Junior	Shaker Heights, OH
1	Grad student	University of Connecticut
1	Grad student	University of Massachusetts Lowell
1	Summer Faculty Fellow	Wichita State University

# GCD Project Performance Evaluation Criteria



Technical/Performance	
<b>Green</b>	Project is demonstrably making progress on the Learning Trajectory (e.g. milestones met, knowledge advanced) or advancing TRL. Project is on track to meet L1 requirements.
<b>Yellow</b>	Project is making progress on the Learning Trajectory or advancing TRL with issues. Project is on track to meet L1 requirements but issues exist that may threaten achievement.
<b>Red</b>	Project has ceased to make progress on the Learning Trajectory or advance TRL. Project is unable to meet one or more L1 requirements.

Cost	
<b>Green</b>	Project can meet its commitments with its planned/allocated budget.
<b>Yellow</b>	Project cannot meet its commitments within its planned/allocated budget but will not be requesting additional budget from Program. Mitigation plans have been developed.
<b>Red</b>	Project cannot meet its commitments within its planned/allocated budget and will be requesting additional budget from Program.

Schedule	
<b>Green</b>	Project can meet its commitments within its planned/allocated schedule baseline for critical milestones.
<b>Yellow</b>	Project cannot meet its commitments within its planned/allocated schedule baseline but mitigation plans have been developed to pull it back in.
<b>Red</b>	Project cannot meet its commitments within its planned/allocated schedule baseline.

Programmatic (Institutional, Internal/External Dependencies **)	
<b>Green</b>	Relevance of technology to stakeholders and/or technology infusion path is maintained. Mission sponsor still actively interested. No issues exist with workforce, test facilities, etc.
<b>Yellow</b>	Relevance of technology to stakeholders and/or technology infusion path are threatened. Mission sponsor backing off. Issues exist with workforce, test facilities, etc. but plans to mitigate are available.
<b>Red</b>	Relevance of technology to stakeholders and/or technology infusion path are not projected to be met, or has lost relevance to stakeholders. Mission sponsor cancelled interest. Issues pertaining to workforce, test facilities, etc. are preventing progress along the Learning Trajectory.



# CTE Risk: Scale Up

**9**

**Trend**



**Criticality**

**High**

**Current LxC**

4x4

**Affinity Group**

Technical

**Planned Closure**

Final structural test

**Open Date**

2/10/2017

Risk Statement: Bonded joint manufacturing processes developed at the laboratory scale may present challenges at full scale.

Approach: **Mitigate**

1. For processes developed at the laboratory scale, continue to develop said processes with a focus on application at full scale.
2. Use opportunities on SLS Payload Adapter Manufacturing Demonstration Articles (MDA) to trial bonded joint manufacturing processes at full scale and apply lessons learned to laboratory scale development work.

Context

Bonded joint manufacturing processes have been developed by the CTE team at the laboratory scale. This effort has focused on applicability to full scale (i.e. SLS vehicle scale), but challenges that could potentially arise upon scale-up are likely unavoidable. In particular, precise control of heat input into the bonded joint assembly (which is required to cure the out-of-autoclave materials) could be a challenge on full scale hardware.

Status:

2/5/18 – Longitudinal joint design concepts that can be fabricated in 4 foot sections being evaluated to enable scale-up to effectively any size.

5/21/18 – Preliminary bonded joint work on the SLS Payload Adapter MDA has begun. Development work at full scale will be used to inform continued CTE development work and further mitigate risk.

5/29/18 – A scalable bonded joint concept (4 foot section) has been designed and analyses show low risk. A test program has been suggested to mitigate risk associated with this concept.

**8/29/18 – Four bonds on SLS Payload Adapter MDA were completed; significant heat loss was experienced during cure resulting in variation from target cure temperatures**

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
Continue laboratory scale development work with a focus on application at full scale.		Ongoing			
Continue full scale development work on SLS Payload Adapter MDA.		5/31/18			
<b>Purchased multi-zone heater blankets to reduce edge heat loss issues; will perform cure cycle variability checks to compare with historic cure cycle data with older heater blanket</b>		<b>8/29/18</b>			

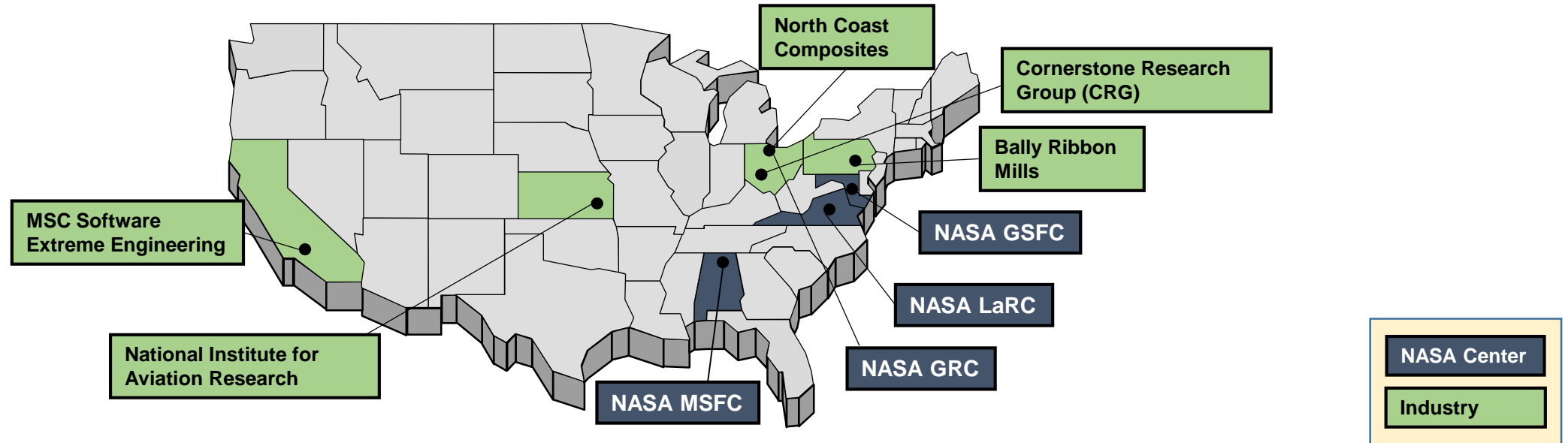
# Bolted vs Bonded Process Comparison


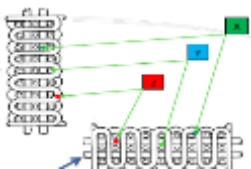
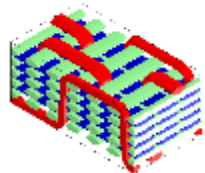



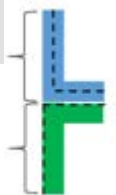
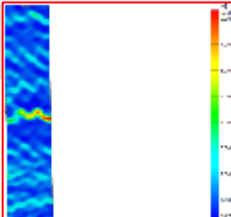
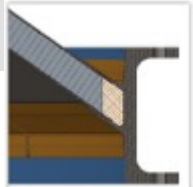


## Longitudinal Joint Comparison; PLA-like Structure

	Bolted		Bonded		Caveats
	Match-drilled	Pre-drilled	Co-cured	Pre-cured	
<b>Equipment needed (1)</b>	Drill templates; drill	CNC	Hot bonder; heater blankets; plasma treatment; vacuum pressure only	Oven; hot bonder; heater blankets; plasma treatment; vacuum pressure only	1. Does not include all possible equipment, just major items
<b>When design &amp; analysis is needed</b>	Prior to design & fabrication of drill templates Up to 6 months prior to assembly start	Prior to individual panel machining Two months prior to assembly start (1)	Prior to layup of doublers One week lead time	Prior to layup of doublers At least one month lead time	1. Assumes block assembly approach. If waterfall assembly approach, lead time will decrease to 1 month
<b>Time to complete attachment operations on-part (1)(2)</b>	3 weeks	1 week	8 weeks (3)	8 weeks (3)	1. Assumes block assembly approach, i.e. all other items needed for assembly are ready (all composite panels, all metallic components, etc.) 2. Does not include other assembly items such as loading panels, attaching rings, or drilling and assembling the forward and aft rings and splice plates. 3. Assumes two cures per joint and 8 joints
<b>Time to complete off-part</b>	---	Included in panel trim process	1 week	4 weeks (1)	1. Assumes flat doublers rather than using a curved cure surface. Dedicated layup surface increases time to complete off-part.

# Technical Status: 3D Weave Team



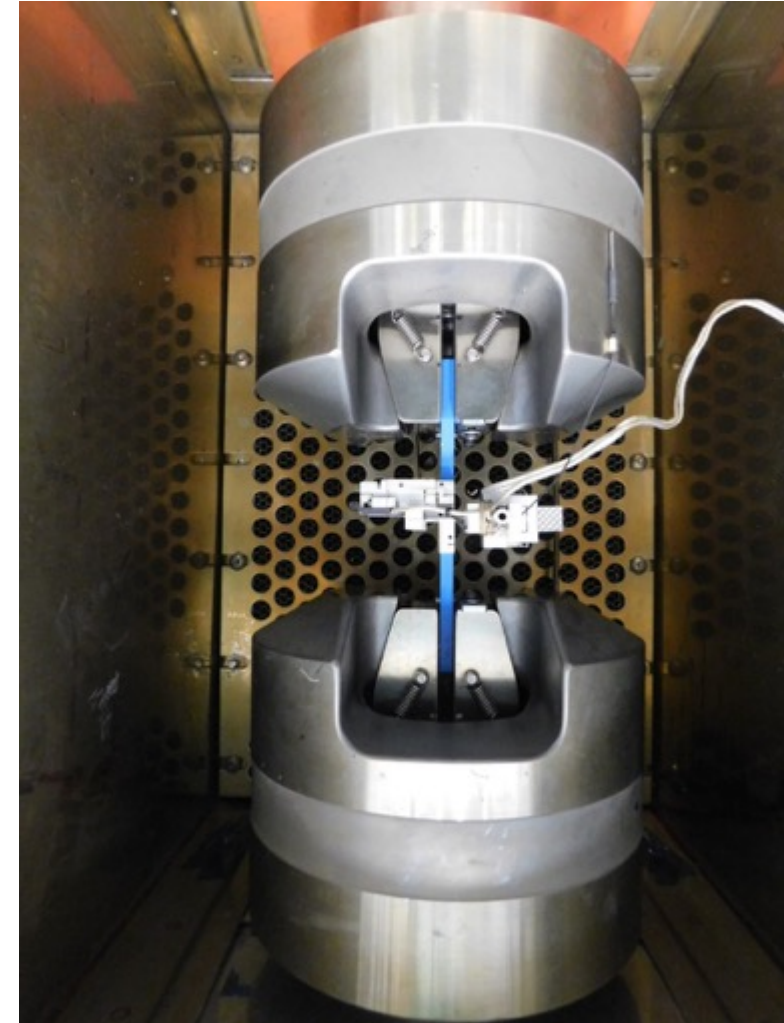
NASA/ GRC	NASA/ GSFC	MSC Software Extreme Engineering	Bally Ribbon Mills	North coast Composites	Cornerstone Research Group (CRG)	NASA/ LaRC	National Institute for Aviation Research (NIAR)	NASA/ MSFC
Cleveland, OH	Greenbelt, MD	Santa Anna, CA	Bally, PA	Cleveland OH	Miamisburg, OH	Hampton, VA	Wichita, KS	Huntsville, AL
Material Modeling, and Testing	Material Modeling	Material Model Support	3D Weaving	Panel-Resin Transfer Molding	C-Joint -Tooling and RTM	Joint Sizing Analyses	Material Testing	Project Management and Joint Assembly
								

# Technical Status: Materials



## ➤ Mechanical Tests to Support Longitudinal Joint Analysis

- Mode I, Mode II and Mixed Mode Strain Energy Release Rate tests were performed at NIAR on panels prepared from acreage material and acreage/ joint material.
- Completed testing of FM209-1M adhesive to determine its material properties used in structural analysis models for joint failure prediction.
  - Thick adherend shear tests. (Element Labs)
  - Tensile test of cured film adhesive. (NIAR)
  - Tensile test of core splice material completed at NIAR.



# Technical Status: Materials



## Test Matrix for Micro-Cracking Panels

Test	Coupon Thickness	Standard
Single Shear Bearing	0.125"	ASTM D5961
Short Beam Shear	0.125"	ASTM D2344
Compression	0.125"	ASTM D6641
Tension	0.125"	ASTM D3039

### Each Material Tested Under the Following Conditions:

Room Temperature Ambient (RTA)  
RTA/ After Thermally Cycled\*  
Elevated Temperature Wet (250°F)

### *\*Thermal Cycling Profile*

15 min ramp to -55°C  
Hold 15 min  
15 min ramp to 80°C  
Hold 15 min  
Repeat for 400 cycles.

An infusion resin will be selected based on data generated in this study. Additional panels manufactured with the selected resin will provide coupon data to the circumferential joint design and analysis.

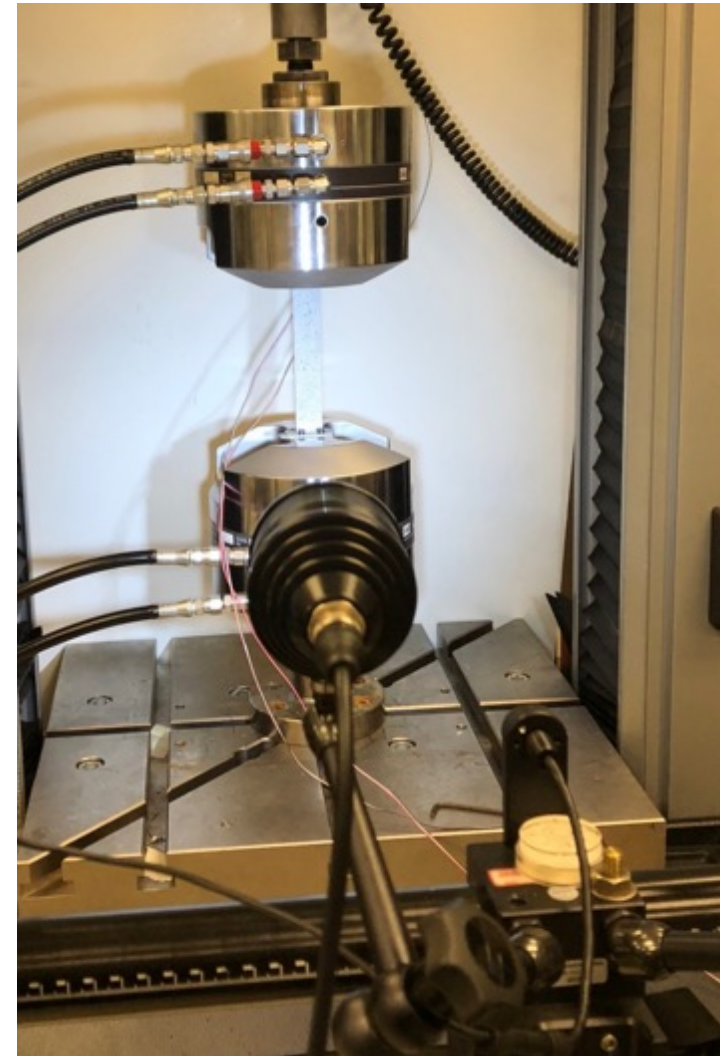


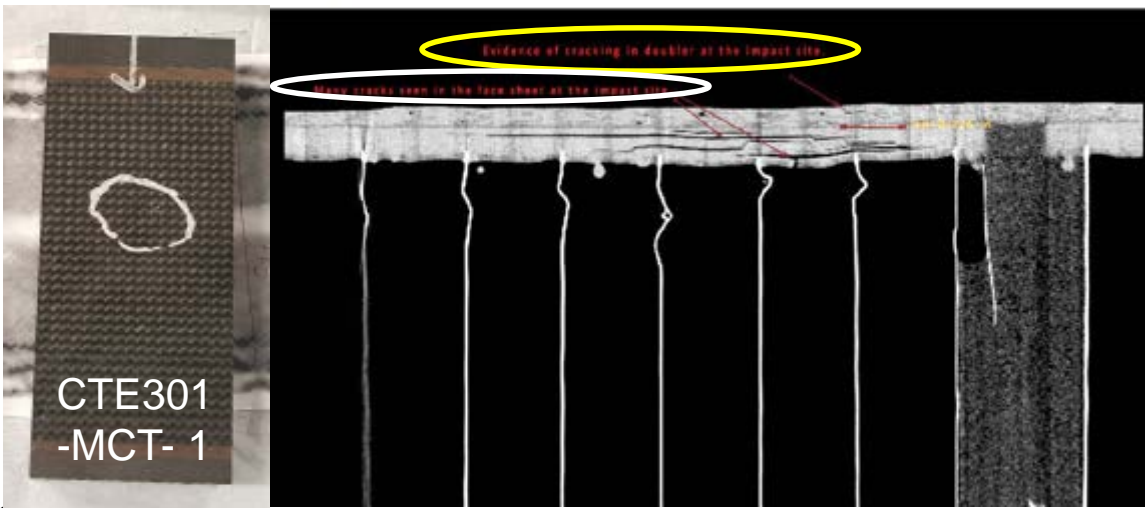
Photo of mechanical testing 3D woven coupon at GSFC.

# Technical Status: NDE

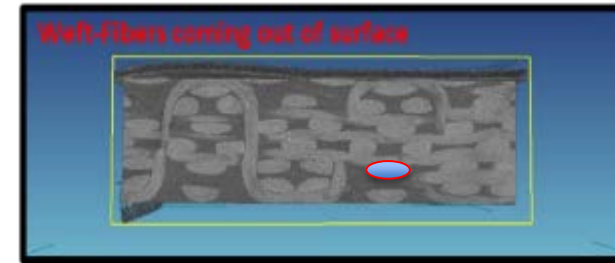


## ➤ L-Joint Barely Visible Impact Damage (BVID) Characterization

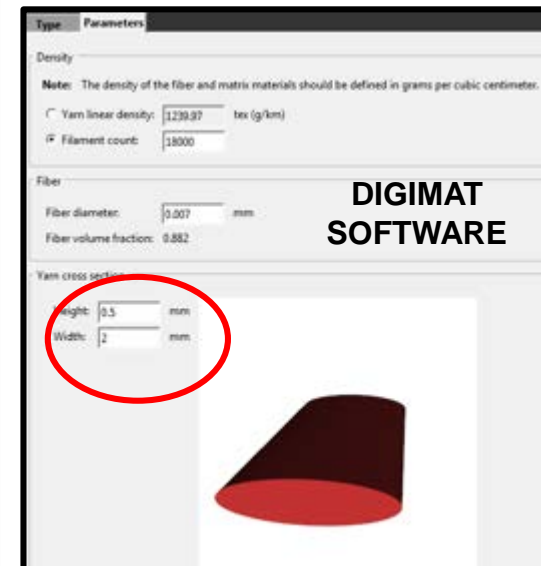
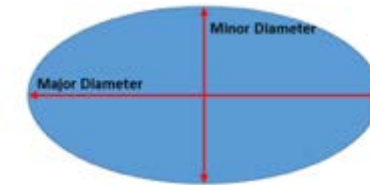
- Inspected with X-Ray Computed Tomography at GSFC.
- Joint impacted (6 ft-lbs) at MSFC.
- Captured:
  - Facesheet laminate damage.
  - Doubler damage at facesheet interface and at impact location. (very small compared to facesheet damage)
  - Local Core Crush.



## ➤ 3D Weave Characterization



X-ray CT captured geometry for fiber warp, weft, and Z tows



**Measured multiple fibers** and used dimensions as DIGIMAT Analysis inputs

# Technical Status: Damage and Repair

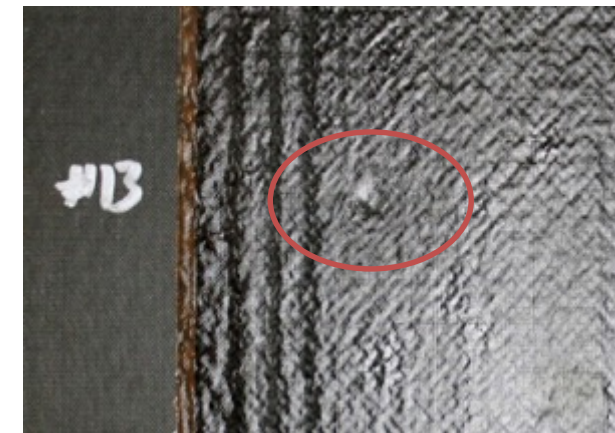


## Damage Testing

**Goal:** Test Barely Visible Impact Damage (BVID) panels to determine residual strength.

### Accomplishments:

- Performed 6 ft-lb Impact offset from the joint splice on test panels.
- Damaged panels were tested.

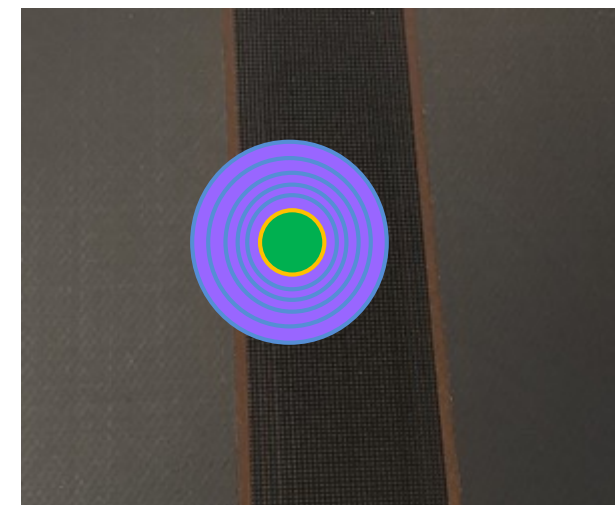


## Repair Process Development

**Goal:** Develop repair concepts and requirements for a launch site repair.

### Accomplishments:

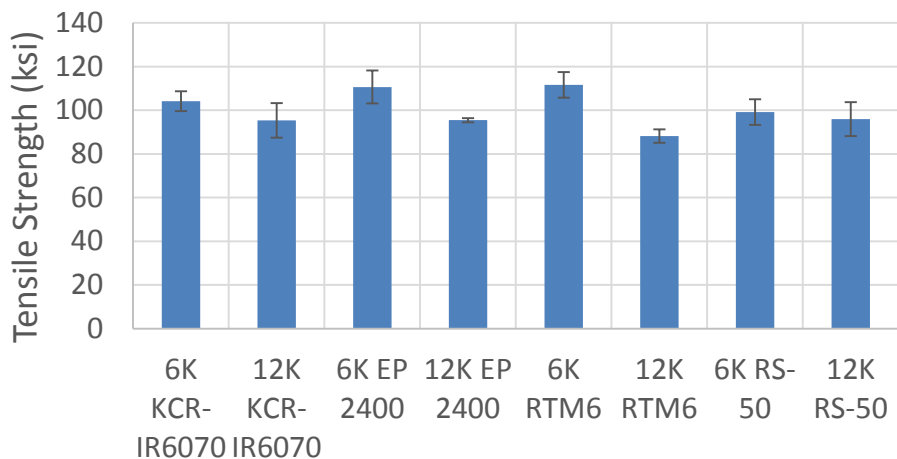
- Determined repair concepts based on observed impact damage to the joint.
- Performing repairs on test panels to demonstrate repair concept.



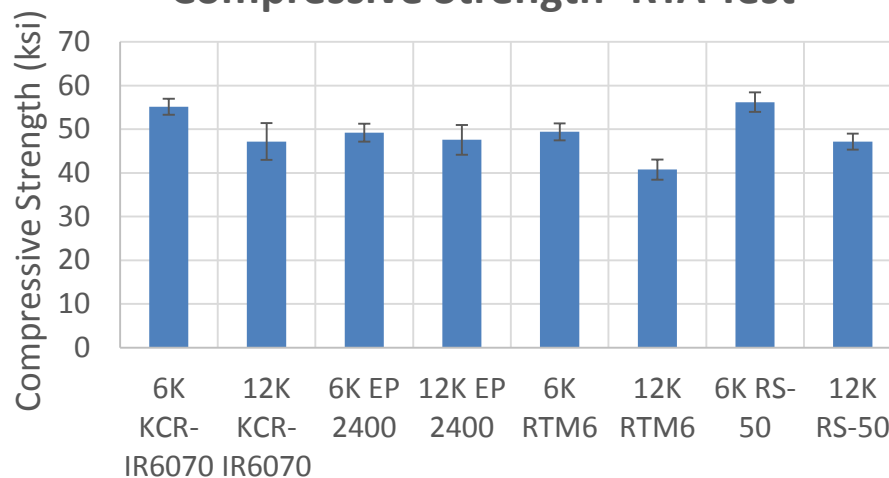
# Materials- RTA Data



### Tensile Strength- RTA Test



### Compressive Strength- RTA Test

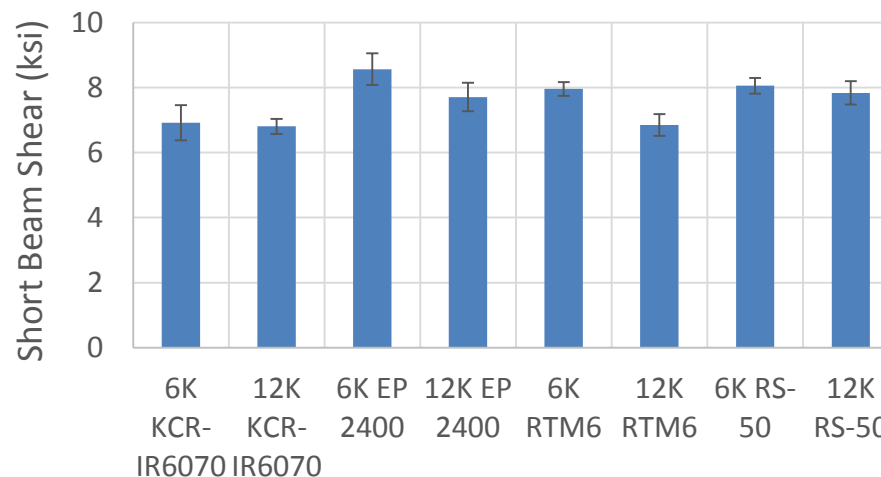


- Matrix resins show little statistical difference in ultimate strength following room temperature tests, however the variation in the linearity of the stress-strain curve was noted.

### Single Shear Bearing- RTA Tests



### Short Beam Shear Strength- RTA Test



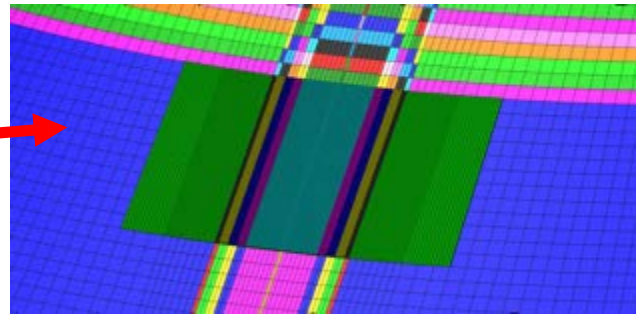
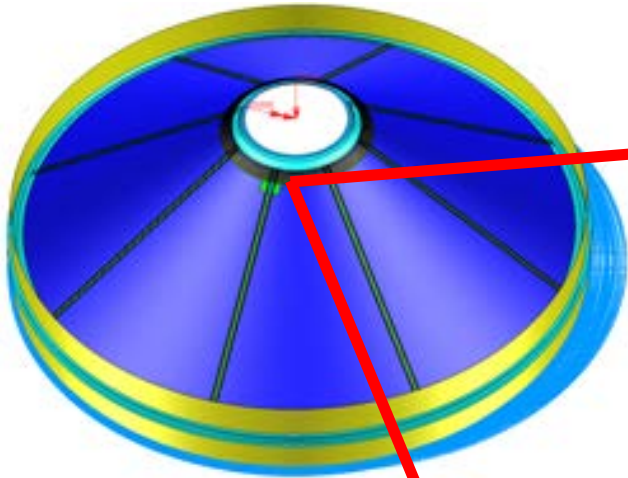
- Thermally cycled coupons will be run prior to a material selection.
- Coupons for optical microscopy, X-ray CT and acid digestion have been shipped to NASA from NIAR.

# Technical Status: Analysis

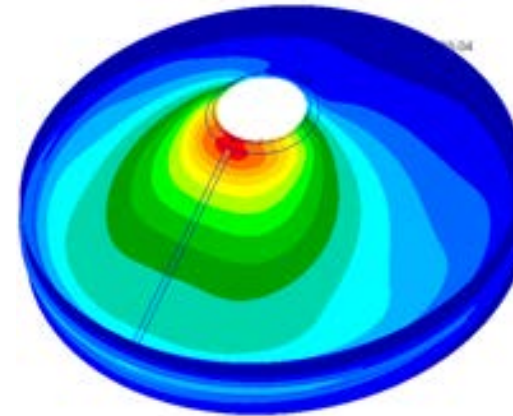
## CTE Longitudinal Joint Sizing Models and Results



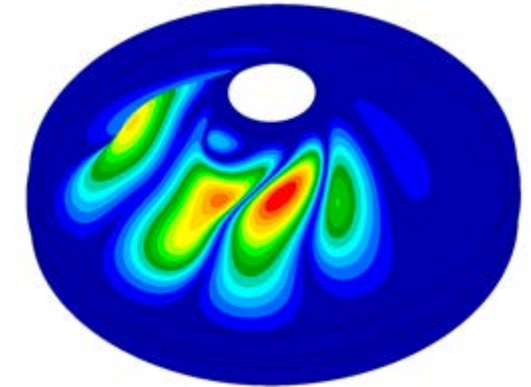
Global/Local Bonded Longitudinal Joint FEM



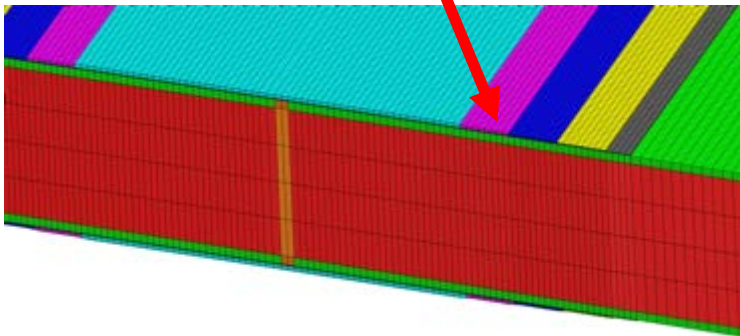
Detailed Local FEM  
(Overlaid on Global FEM)



Deformation



Buckling Mode Shape

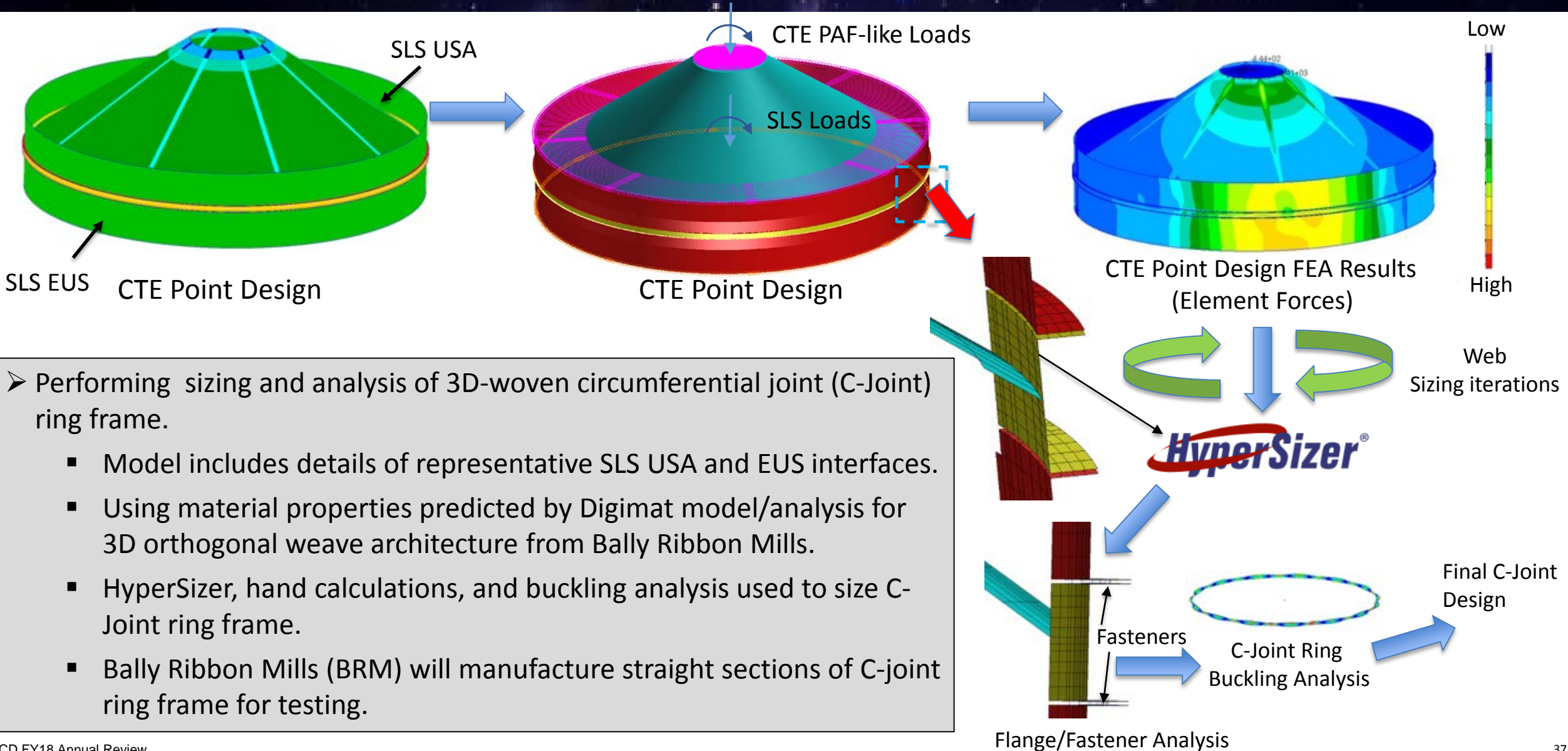


Local Joint Cross-Section

- Model used to perform detailed joint sizing and margin check for CTE longitudinal joint final design.
  - More accurate joint stresses and through-the-thickness stresses obtained from local model.
  - Nonlinear analysis performed for stress calculations.
  - 2.0 factor of safety assumed.
- CTE longitudinal final joint design later tested with sub-element testing for critical load cases. (axial compression, hoop compression, and hoop tension)

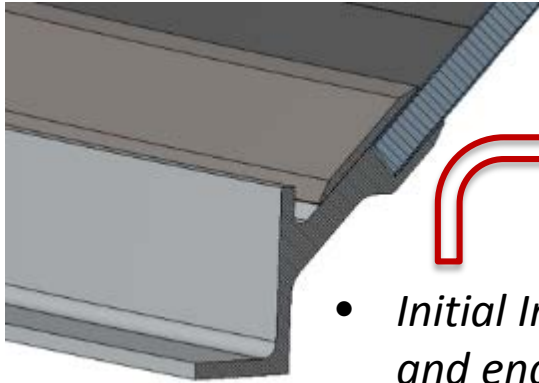
# Technical Status: Analysis

## CTE Circumferential Joint Sizing Models and Results



- Performing sizing and analysis of 3D-woven circumferential joint (C-Joint) ring frame.
  - Model includes details of representative SLS USA and EUS interfaces.
  - Using material properties predicted by Digimat model/analysis for 3D orthogonal weave architecture from Bally Ribbon Mills.
  - HyperSizer, hand calculations, and buckling analysis used to size C-Joint ring frame.
  - Bally Ribbon Mills (BRM) will manufacture straight sections of C-joint ring frame for testing.

# Technical Status: Circumferential Joint Design Accomplishments



- *Initial Interface and end ring*



CTE received interface information per SLS-ICD-029; 'SLS Stages to ISPE ICD'. Applied Interface information to CTE Point design and updated end ring configuration for CTE advancement



- *Updated Interface and end ring*

BRM contracted to weave C-Xsection and Pi-Preforms

Future Work:  
Design C-Joint test articles



*Harness ordered, due in October'18*

Other concepts studied. Curved acreage could save additional mass over other composite designs, considered too costly, too late to implement

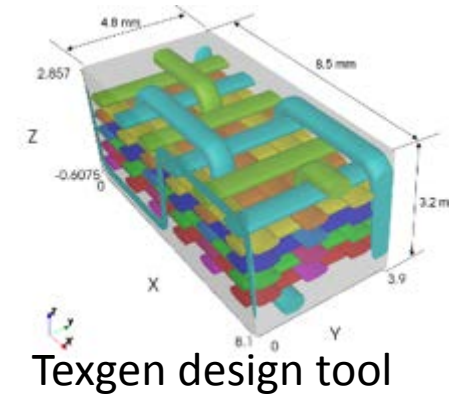
- Closed Sandwich Laminated and 3D Woven Designs
- Open End Sandwich Designs
- Highly Stiffened Design concepts

# Technical Status: Circumferential Joint Design Accomplishments- 3D Weave Designing

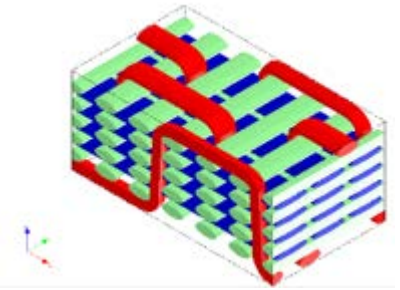


## 3D Weaves Design Lessons Learned

- Established Method to communicate 3D weave architecture between design, manufacturing, and analyses teams. Visualization software (Texgen) utilized.
- Weaver (BRM) is communicating design information via Fiber percentage in each direction and fiber volume amounts to achieve a part thickness and capability.
- NASA is converting that into analytical models for property predictions.



Texgen design tool



MSC DIGIMAT  
Design and  
Analyses Tool

Structural analyses need 3D Weave orientation to get right properties in the model. A part weaved can have two or more 'effective' planar properties. For example:

Weaving occurs in 3 directions, Warp (X), Weft (Y), and Binder (Z) directions. What CTE learned in this application is those effective orientations can switch in complex shaped parts, changing fiber loading, and changing properties.

For instance : Web X, Y, Z fiber loading - 40%, 40%, 20%

BRM weaves the part in the Web orientation with warp (X) in the long direction. A flange that is orthogonal will have planar properties are effectively a web rotated clockwise around the X axis, changing the flange effective fiber loading as shown transformed.

Flange X, Y', Z' fiber loading 40%, 20%, 40%

*Planar properties may vary. If a flange in this example is weft property dominated, Z to Y' and Y to Z' must be tracked, and the 20% fiber loading evaluated to see if it is a weakness.*

# Technical Status: Design & Analysis

## 3D Woven Modeling and Analysis

