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SCIENCE & TECHNOLOGY OFFICE

Composite Technology for Exploration (CTE)

Briefing to SLS USA Team

Dec 13, 2018

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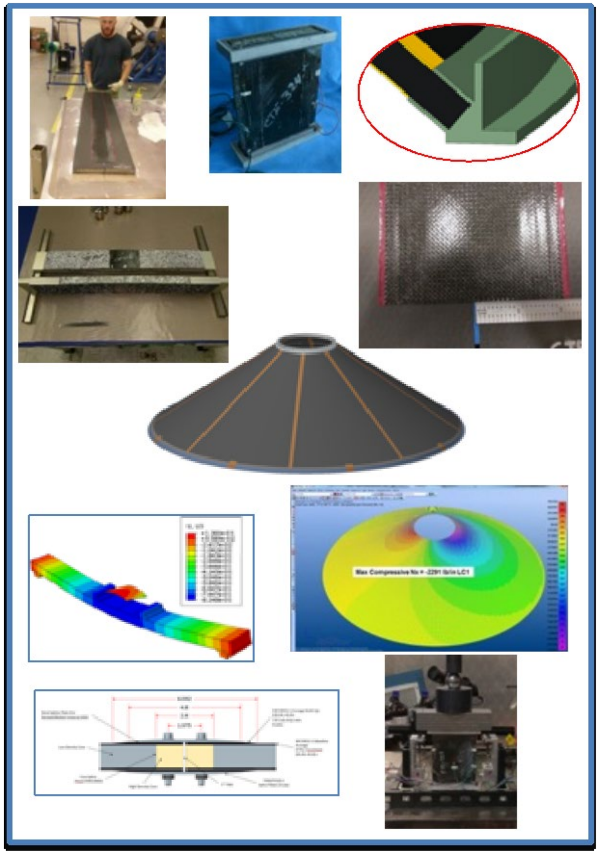
Agenda

- CTE Overview
- L- Joints Update
  - Design Review
  - Materials Testing
  - Joint Testing
  - Joint Analyses
- 3D Woven Joints
  - The potential
  - The approach

CTE Overview

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.



Technology Goals

Goal #1	Develop and validate high-fidelity analysis tools and standards for predicting failure and residual strength of composite bonded joints.
Goal #2	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 9% . 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.

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Level 1 Project Goals

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Composite Technologies for Exploration (CTE)	
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Goal #2	Develop and demonstrate an analytical tailoring approach that enables the reduction of the baseline 2.0 safety factor for composite discontinuities.
Notes: The CTE team established the design criteria working with SLS SPIE and selected a point design as the baseline for CTE joint development and analysis comparisons. This point design was chosen based on challenging loads and geometries relevant to SLS-scale composite structures. The CTE longitudinal joint design was selected to be a double lap, out of autoclave/out of oven cured bonded composite joint. Utilized Digimat, a material modeling and analysis software tool, to predict composite material allowables by analysis with limited physical tests. The analysis team has performed a preliminary assessment of our tools for the failure prediction of composite bonded joints using data from previous NASA projects. The CTE team has developed test matrices and plans to demonstrate potential reductions in 2.0 safety factor.	

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Key Technical Challenges

Key Technology Challenges	
Composite Technologies for Exploration (CTE)	
Title	**Description**
Joint Configuration	Identify low mass bonded joints for fiber composite launch structures
Model Predictions	Establish modeling capabilities that failure predictions of empirical data with low engineering uncertainty.

Notes: The CTE project has designed a bonded (no fasteners) longitudinal joint. Joint test coupons will be fabricated and tested and full-scale joint tests will follow. 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. The project is currently analyzing joint designs with selected programs and theories. Results of joint tests will be used to evaluate analytical approaches.

Key Performance Parameters

Key Performance Parameters				
Composite Technologies for Exploration (CTE)				
Performance Parameter	**State of the Art (SOA)**	**Threshold Value**	**Project Goal**	**Estimated Current Value**
Failure Prediction (1)	±25% of mean	±15% of mean	±5 of mean.	See #1 in Notes
Risk Reduction Factor (2)	2.0	1.8	1.4	SOA
Part Count (3)	100%	75%	50%	2% (4)
Weight (3)	100%	85%	75%	15% (4)

Notes:

1. Initial assessment of advanced tools by experienced analyst reflects reduction to threshold value of ±15% of mean. Current failure prediction is ±9% of mean pre-testing and ±5% of mean post-tests.
2. Safety for joints in primary load path for an SLS-like composite structure Discontinuity Factor of Safety = Ɉ * 2.0, where Ɉ 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.

Design Start Point and Validation Approach

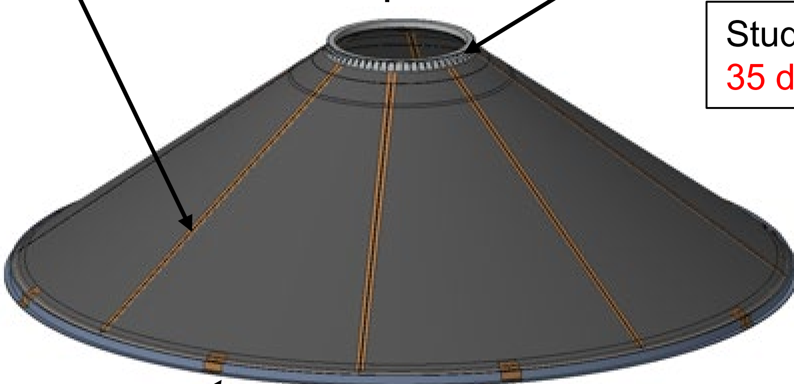
Composite Technology for Exploration (CTE)

Point Design

- REVIEW - CTE Point Design
  - Sized on ATLAS V loads, assumed off-sets, interfaces, and geometry relevant to SLS-scale composite structure.

FOCUS Today Longitudinal Joint work

To Payload



1.58 m Diameter (Bolt circle)
Based on Standard interface design SpaceX Falcon 9 User guide

Studied 35 to 45 degree cone angle
35 degrees results in highest line loads

Acreage Design
8 ply Facesheets : [45,90,-45,0]s
1" Core : 3/16 - 0.001 – P -5056
Film Adhesive : FM209-1M 0.06psf

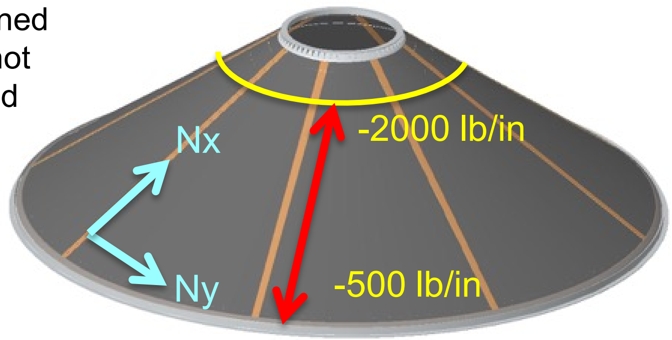
Region of local stiffening
Required for strength / buckling
~ 22" from top- Area not to be studied in detail

8.4 m Diameter
Based on SLS EUS Interface
https://www.nasa.gov/exploration/systems/sls/multimedia/images.html

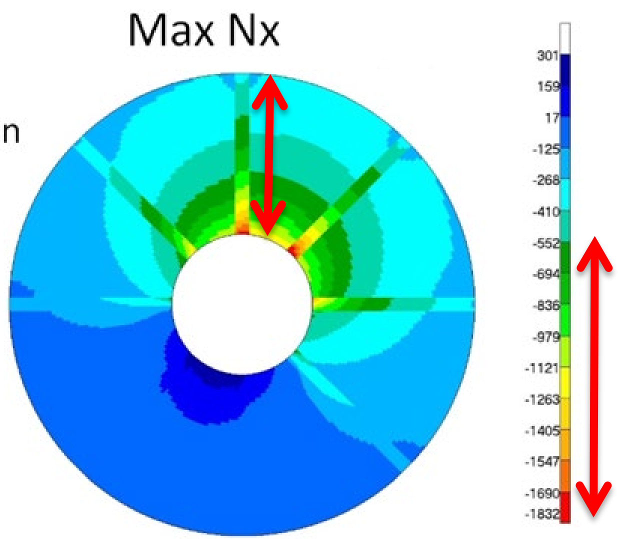
Composite Technology for Exploration (CTE)
Point Design Line Load

DESIGN : Longitudinal Joints Load Distribution

Upper ring area with stiffened acreage not considered



Max Nx = lb/in compression



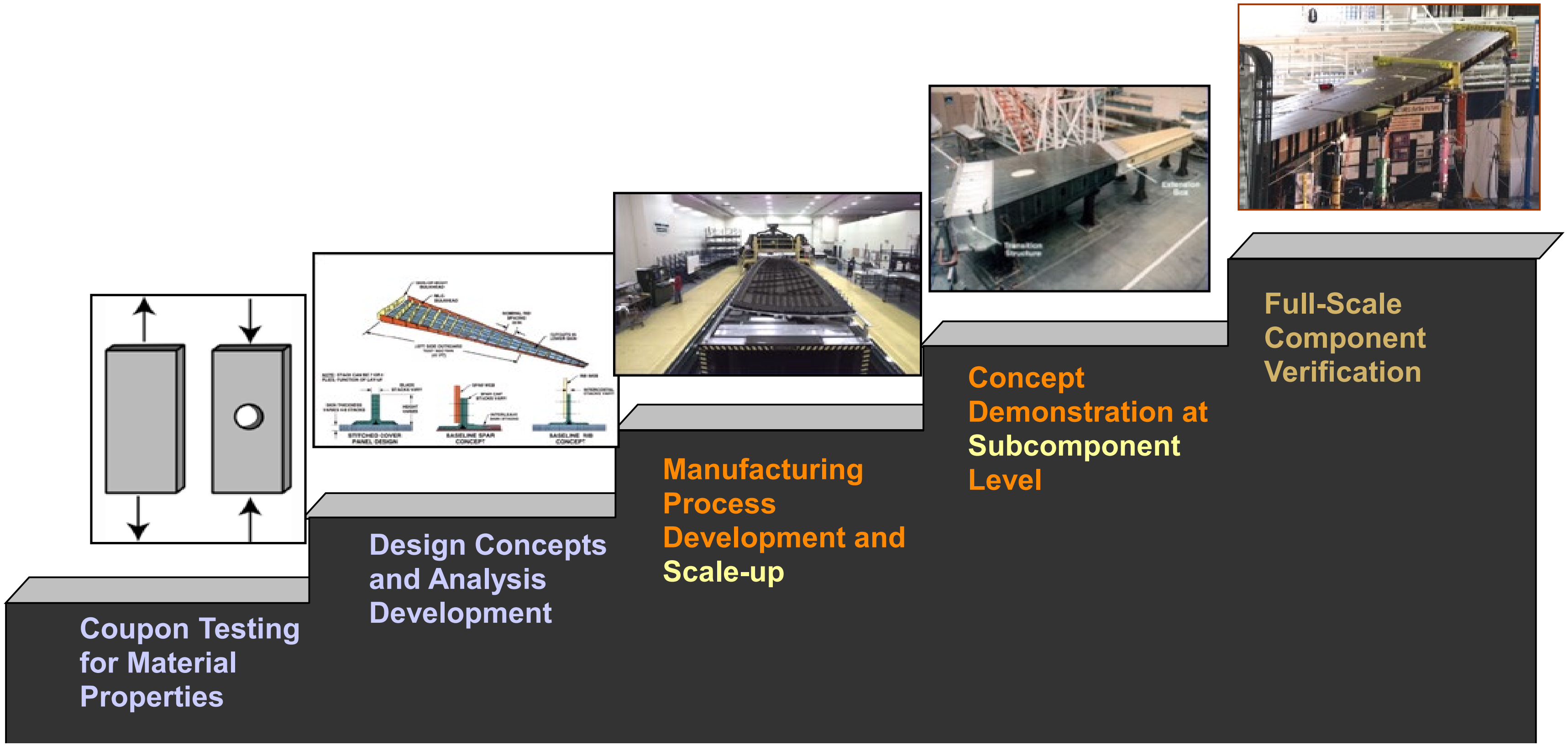
CTE took the highest line loads, applied it to the whole joint, and demonstrated joints to these line loads

CPD Joint Line Loads with 2.0 FS, (lb/in)	
Axial Compressive Nx	-3,998
Hoop Compressive Ny	-980
Hoop Tension Ny	906
Shear, Nxy	1640

Composite Technology for Exploration (CTE)
Approach

CMH-17 and Airframe Industry Standard Practice

- ***Technical Maturity: consistent, predictable response***



CTE Joint design development is based on the building block approach. Scale up verification is related to subcomponent work.

Composite Technology for Exploration (CTE)

Approach

Damage Tolerance

NASA-STD-5019-A, *Fracture Control Requirements for Spaceflight Hardware* (incorporates MSFC-RQMT-3479 non-metallic fracture control requirements)

- **Key CTE Fracture Control Requirements**
  - (FCR5) Classification of parts-
    - All bonded joints are considered fracture critical
  - (FCR13) General approach for Fracture Critical Composites Hardware
    - Perform damage tolerance testing on coupons and elements

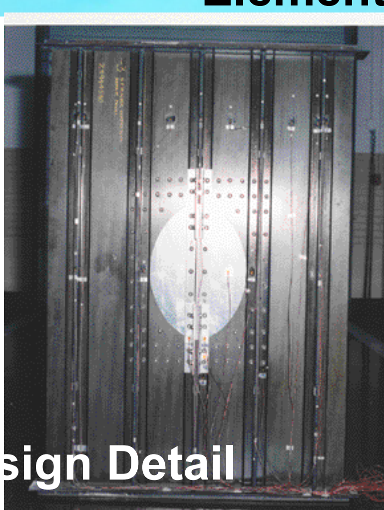
CTE Joint design development includes damage tolerance testing at the joint element and component levels

Definitions

Coupon

Element

Subcomponent



sign Detail

For CTE purposes a jointed sandwich panel is considered a conic or cylindrical section subcomponent.

Composite Technology for Exploration (CTE)
Highlights

Longitudinal Joint (L-Joint)

1. Designed, built, and tested L-Joint and sub-elements. Showing 87% mass reduction and 98% part count reduction over state of the art joint designs.
2. Designed and tested L-joint element and buckling panels for sub-component / scale up testing.
3. Validated pre-test predictions are within 9% based on non-linear analyses approaches

Circumferential Joint or End Ring (C-Joint)

1. Updated Circumferential joint interface to SLS defined interfaces. Expecting 50% mass and 50% part count reduction.
2. C-Joint 3D woven design based on evolving design process methodology using analytical approaches using commercially available and custom software
3. Contract in place with Bally Ribbon Mills (BRM) for weave design development and manufacturing.
4. Contract in place with Cornerstone Research Group (CRG) for Resin Transfer Molding (RTM) of C-Joint parts.

Focus on L-Joint Work, Can discuss 3D Woven C-Joint work in progress and advancing in FY19.

Materials Update

Material Testing

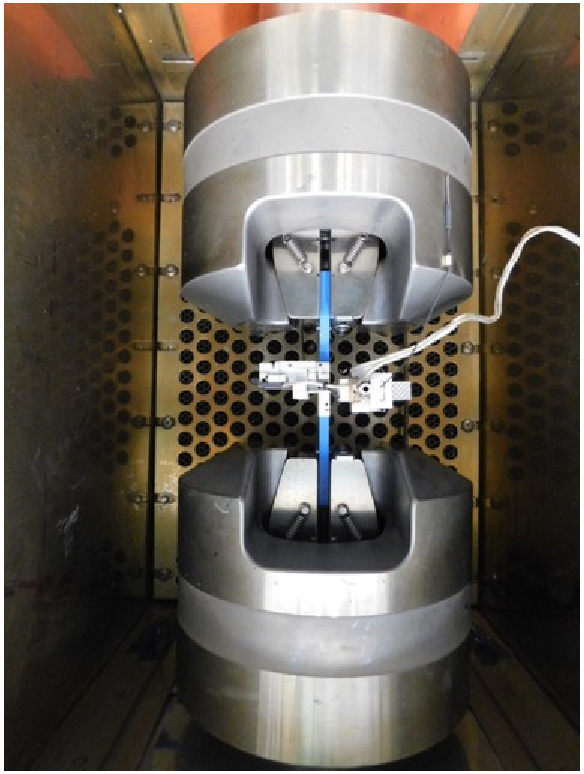
Material Tests Supporting Longitudinal Joint Analysis

Completed testing of Hysol 9396.6MD potting adhesive

- Tensile test of core splice material (NIAR).

Completed testing of FM209-1M film adhesive

- Thick adherend shear tests (Element Labs).
- Tensile test of cured film adhesive (NIAR).



Completed Strain Energy Release rate testing of jointed interface

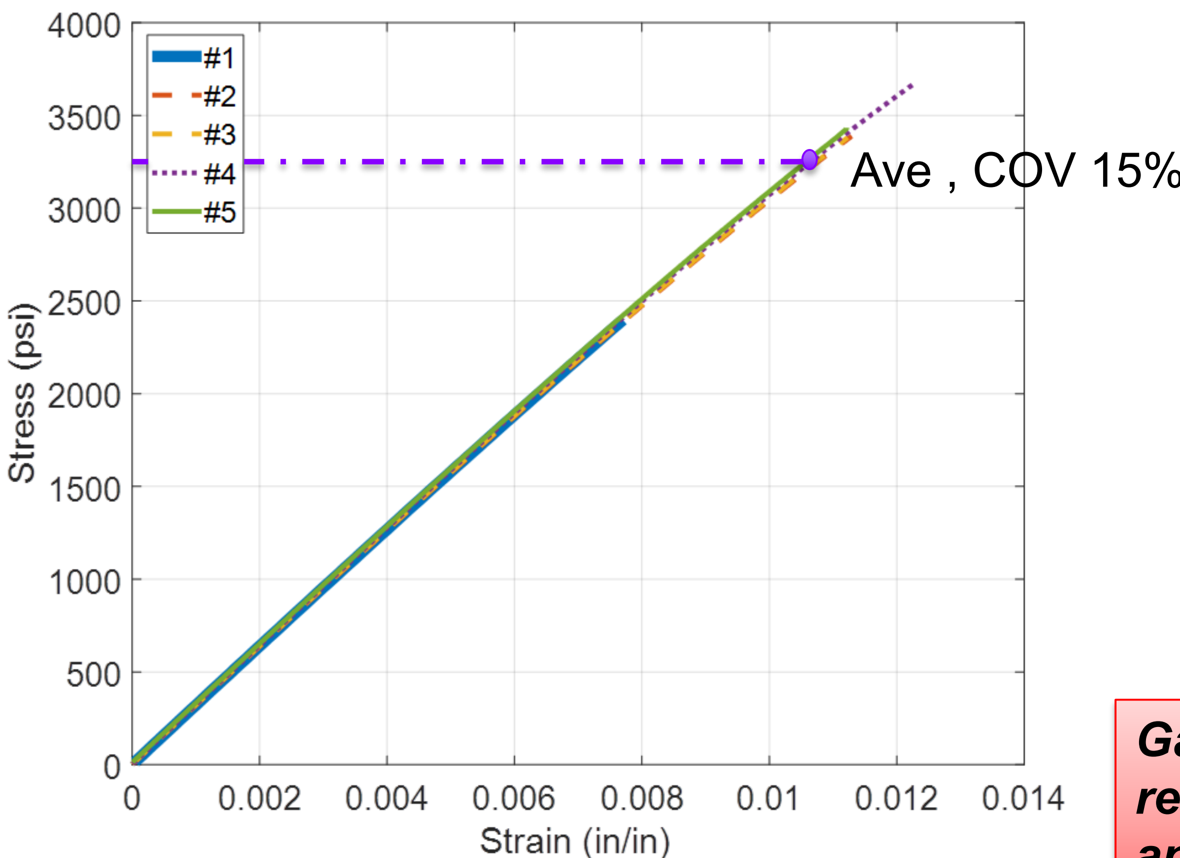
- Mode I, Mode II and Mixed Mode (NIAR)

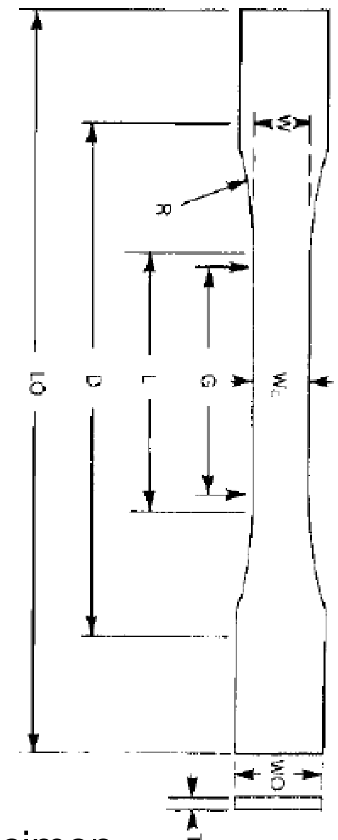
Property testing was necessitated to attain good joint predictions.

Material Updates

Analyses Inputs Required Adhesive Testing

- Joint Gap Fill Material – EA 9396.6NA
  - ASTM 638
  - Confirms manufacturer's data





Specimen
.25" thick x .50 Wide (Gage)

Gap fill data became relevant in hoop tension analyses and testing

Composite Technology for Exploration (CTE)

Material Updates

- Film Adhesive – FM 209-1M
  - ASTM D638 tensile
  - ASTM D5656 thick adherend shear testing

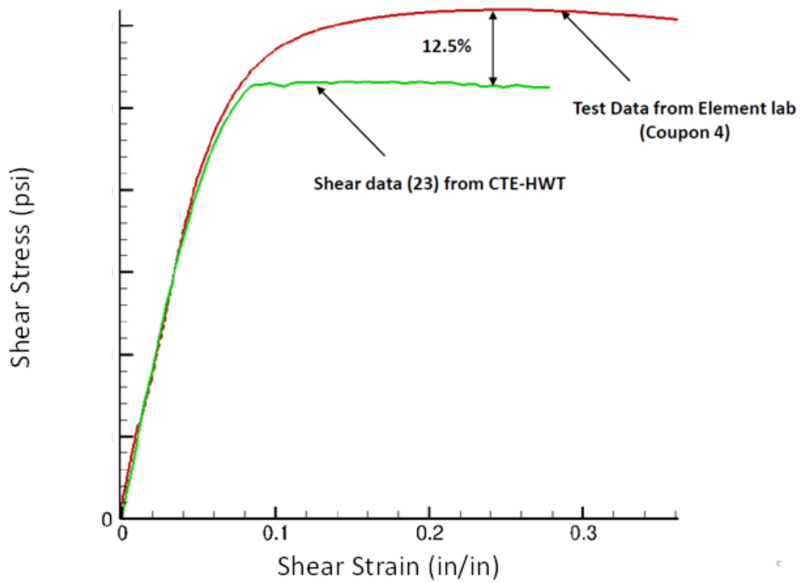
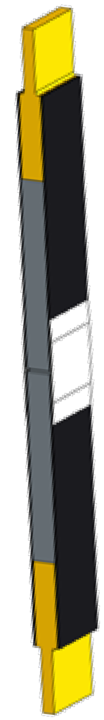


Figure 2. Comparison of analytical shear stress/strain curve to Element Labs shear stress/strain test results.



Hoopwise Tension

Tested and analytically verified FM-209-1M shear behavior.

Shear Stress Strain data resolved into property data used in Abaqus.

Composite Technology for Exploration (CTE)
Material Updates

Joint - Sandwich Interface Fracture Toughness Characterization

Objective

- Obtain strain energy release rate data facesheet to joint interface for joint failure predictions

Approach

- Take ASTM Composite Fracture Toughness Standards (D5528 D7905 and 6671) and establish a test design that can characterize a joint interface

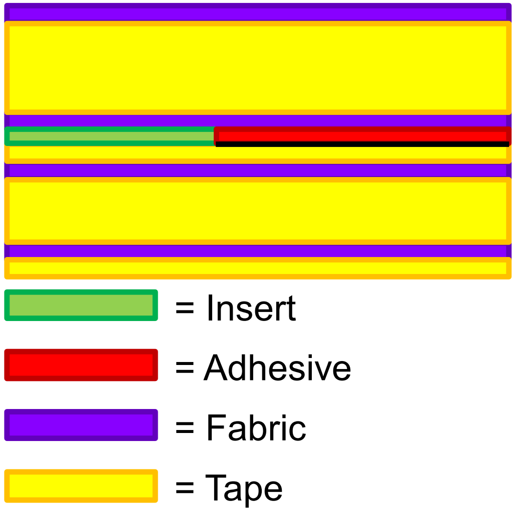
Challenge

- Get correct bending stiffnesses for Double Cantilever Beam coupon, and get correct interface
- CTE mismatch between fabric and tape materials and/or co-bond process had caused panel warping

Design

- Got a flat panel with equivalent DCB arm stiffnesses using a hybrid fabric / uni tape design

CTE Point Design Joint

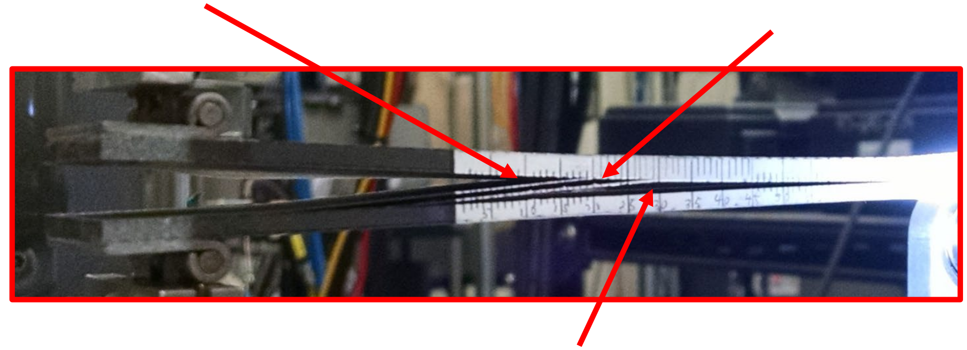


DCB hybrid design

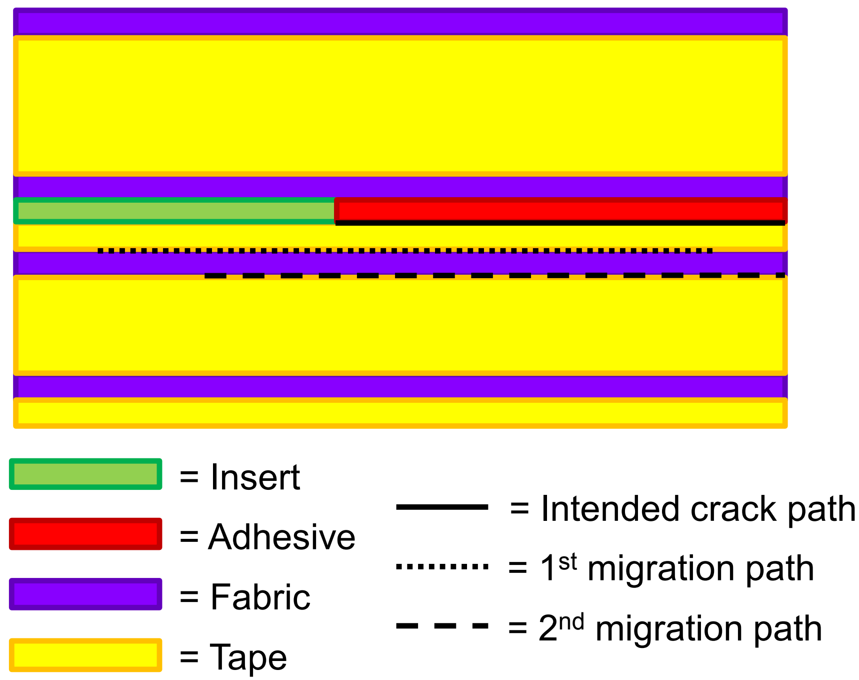
Composite Technology for Exploration (CTE) Material Updates

Mode I Fracture Toughness

- Little (or zero) crack growth was observed at the intended tape/fabric interface with adhesive in tests
- 5 of 6 tests had 2 delamination migrations
  - 1st migration was one interface below intended interface
  - 2nd migration was two interfaces below intended interface
  - Resulted in the fabric layer almost completely separating from coupon



Cross section of CTE-068 hybrid coupons, not to scale. Non-Standard Fracture Toughness Coupon



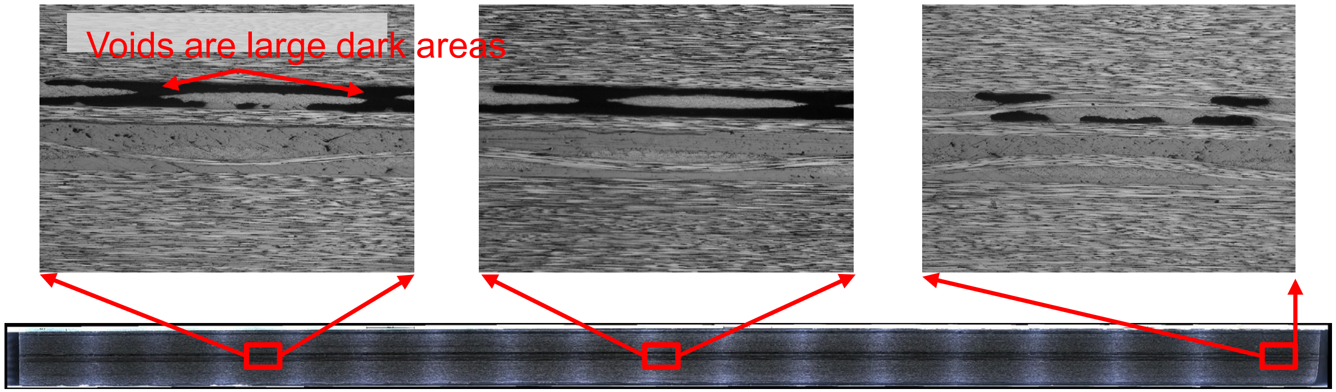
Mode II Fracture Toughness

- Little (or zero) crack growth was observed at the intended tape/fabric interface with adhesive
- 6 of 6 tests had at least one delamination migration
  - Sometimes difficult to determine whether observed crack was one or two interfaces below intended adhesive interface

Composite Technology for Exploration (CTE)
Material Updates

CTE-068-D-MSFC-2 Microscopy

- Untested section of panel cut and polished for microscopy: CTE068-D-MSFC-2-CrossSection-1
- Extensive voids observed in **one** of the fabric lamina near the adhesive/Teflon insert layer
- *This is not representative of what we get in CTE joints, it is a function of the test coupon manufacturing*



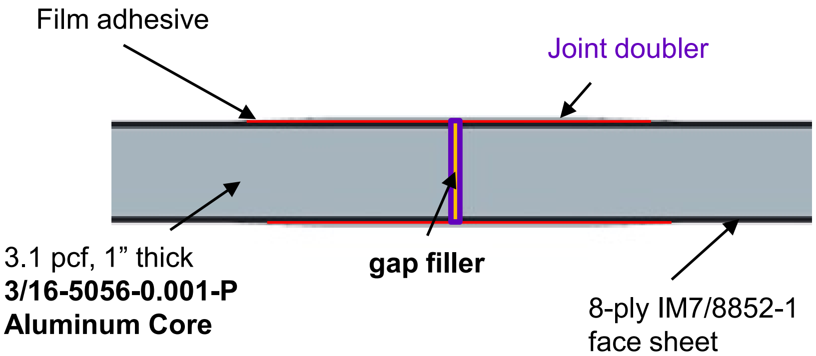
Conclusions

- Warpage in the test coupons was reduced by using the hybrid layup design
- Significant porosity was observed in one of the interior fabric lamina near the adhesive/Teflon insert layer
- Little to no delamination was observed in tests coupon adhesive layer where failure was intended
- NIAR tested coupons all exhibited at least one delamination migration event during testing

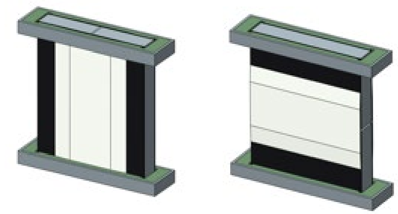
Fracture toughness values calculated are not representative of interlaminar failure properties for the adhesively bonded fabric-to-tape material interface, they are considered conservative. More work is needed to get better properties.

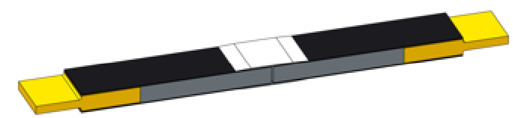
Design Update

Composite Technology for Exploration (CTE)
Design Updates



Designed L-joints and tests, verified design to 2.0 FoS





CTE Longitudinal Joint Mass and Part Count	Total Mass (lb-f)	# Fasteners	Part Count
Metallic Splice / Bolted with 1 Row of Bolts – Core Densification	**330**	2100	**2116**
Metallic Splice / Bolted with 1 Row of Bolts – Bushings	207	2100	4216
Composite Bolted with 1 Row of Bolts- Core Densified	290	2100	2116
Composite Bolted with 1 Row of Bolts- Bushings	167	2100	4216
Composite Bolted FailSafe – Core Densified	234	530	546
Composite Bolted FailSafe – Bushings	144	530	1076
All Bonded	**42**	N/A	**40**
CTE Final Design, As Built Data	**27**	0	**40**

Proven: 2.0 FoS Bonded longitudinal joint
87 - 92% mass reduction and 98% part reduction.

MASS: As analyzed bonded joint mass **0.38 lb-f / ft**
As built mass 0.25 lb-f / ft
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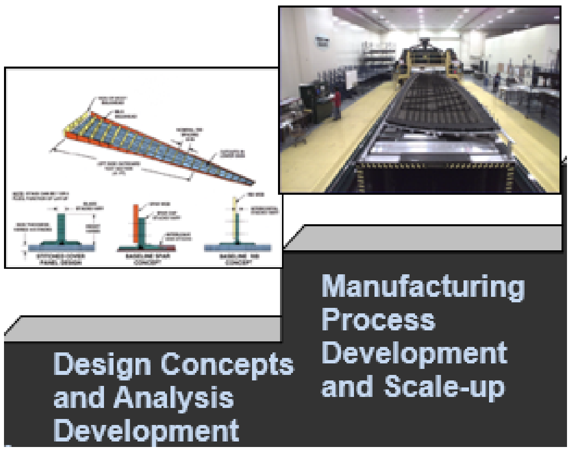
Composite Technology for Exploration (CTE)

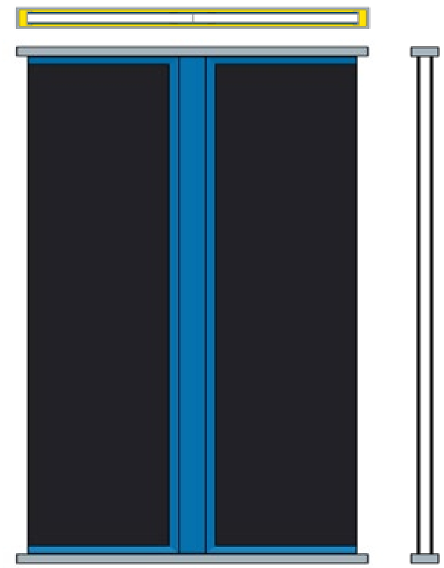
Design Updates

Addressing processing size and loads scale up issues with buckling tests and combined loads test designs.



Completed Buckling Panel Test Article Design. 30” x 62”

Pristine and Damaged Tests Completed

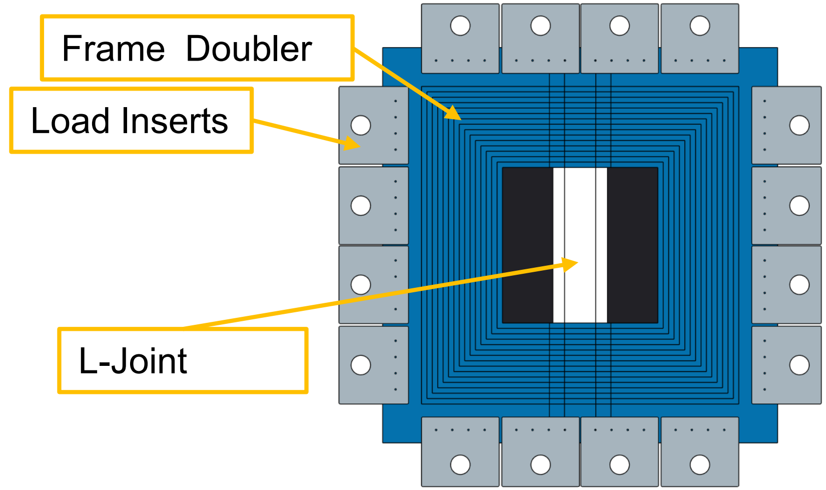


Bucking test designs developed to demonstrate critical L-joint loading, joint manufacturing scale up, and damage tolerance at the sub-component level.

Composite Technology for Exploration (CTE)

Design Updates

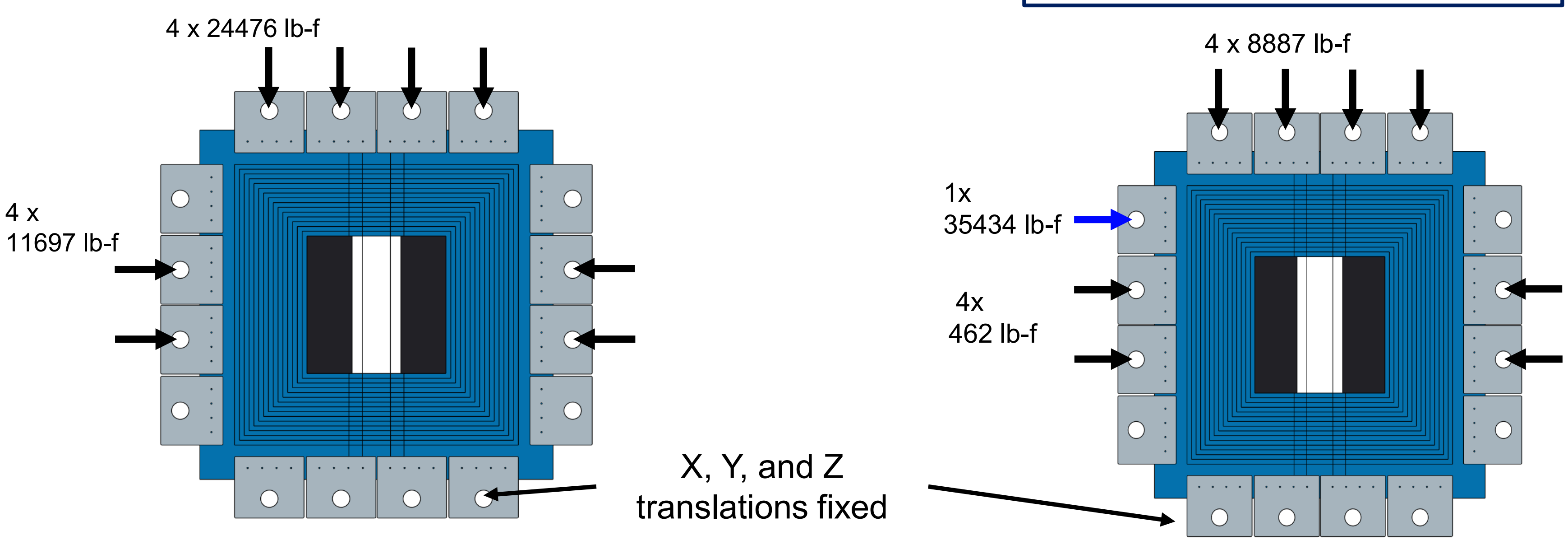
Combined load tests designs developed to demonstrate critical L-joint loading, joint manufacturing scale up, and damage tolerance at the sub-component level, and further validate analyses.



Panel is 32” x 28”

Max Axial Combined Load

Max Shear Combined Load



NDE Update

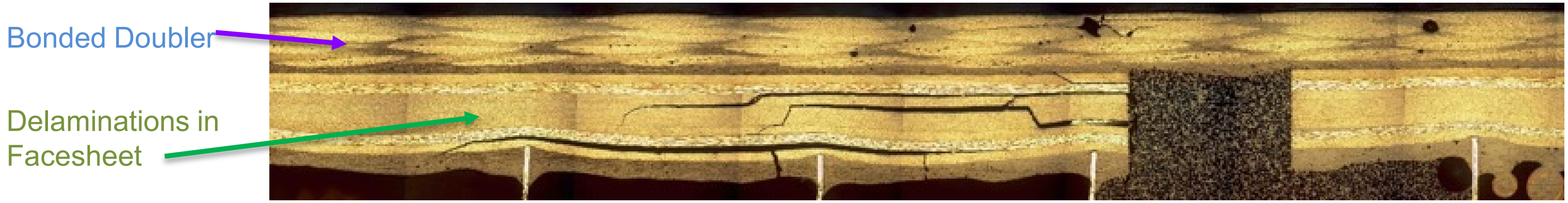
Damage Tolerance Testing

Damage Testing

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

Accomplishments:

- Performed Impact Survey to determine BVID Impact Energy Level
- Determined 6 ft-lb Impact offset from the joint splice for the test panels
- Damage on the order of 0.8" Diameter



X-Ray CT Cross Section View of Impacted Region (6 ft-lb)

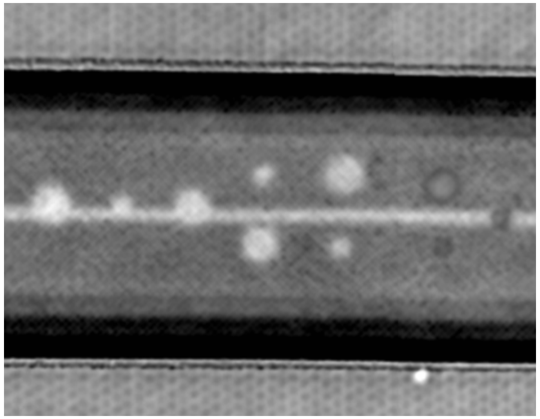
Established BVID for CTE L-Joint for use in damage tolerance testing.

Non-Destructive Evaluation (NDE)

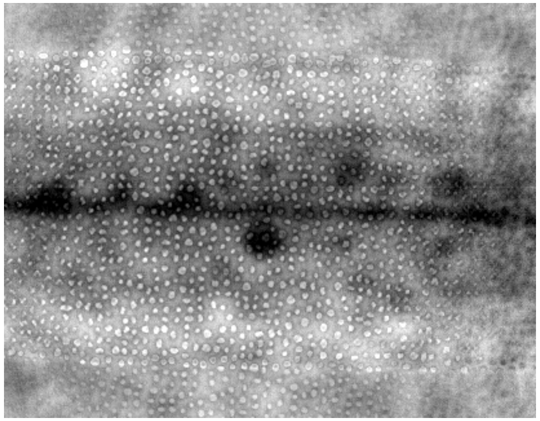
Nondestructive Evaluation:

Required to measure if damage grows for damage tolerance life testing . Thermography was preformed in the presence of Visual Image Correlation paint.

CTE-101 Joint Standard Panel Comparison



Nominal thermography image of joint standard, demonstrating detectability to below 0.25”



Thermography image through VIC speckle pattern: 0.25” defect barely visible and on par with fogging; 0.5” defects still detectable, with reduced contrast.

Imaging through VIC speckle pattern reduces sensitivity somewhat, but relevantly-sized indications may still be visible. Damage expected is on the order of 0.8” diameter, decided to go with Themography.

Technical – Analyses and Testing

Pre-test analysis and post-test analyses were performed on the longitudinal bonded joint sub-element test coupons (pristine only) to correlate with testing performed at Southern Research

- *Axial Edge-Wise Compression (AEWC) coupons*
- *Hoop Edge-Wise Compression (HEWC) coupons*
- *Hoop Tension (HT) coupons*

Analysis included linear analyses used in the design of sub-element test coupons and nonlinear progressive damage models for joint failure prediction

- *Linear analysis used in pre-test design and initial pre-test predictions*
- *Nonlinear analysis included nonlinear material properties and modeling of potential failure modes including delamination between plies of doubler or face sheet laminates, fiber and matrix failure of face sheet and doubler laminates, and debonds between face sheet and doubler due to adhesive failure*
  - *Cohesive zone model adopted to simulate delamination and debonds*
  - *Continuum damage model used to simulate in-plane failure modes*

Composite Technology for Exploration (CTE)
Longitudinal Bonded Joint Failure Prediction Model

Performed assessment of NASA available analysis tools for prediction of composite joint failure

- Damage Models Considered in Longitudinal Bonded Joint Failure Prediction:
  - COmplete STress Reduction (COSTR*) Damage Model
  - Cohesive Zone Modeling (CZM)
  - NASA CompDam Analyses
  - LSM Samcef Analyses

COSTR was deemed the best from a predictive capability and efficiency points of view

- Cohesive Zone Modeling (CZM)
  - VCCT and CZM indicated failure initiation not failure propagation
- NASA CompDam Analyses
  - CompDam took a long time and was deemed not efficient
- LSM Samcef Analyses
  - Samcef did not predict failure progression well

Description & capability of COSTR Damage model

- In-Plane Progressive Damage Analysis tool for predicting residual strength and failure modes of laminated composite structures.
  - Utilized **Hashin-Rotem Failure Criteria** to identify fiber and matrix damage, simple damage evolution laws to simulate damage by reducing stresses to zero instantaneously or gradually & incorporates quadratic matrix strain criterion to create virtual cracks
  - Captures fiber & matrix failures in a lamina. Delamination and debonding between plies and adherend captured using cohesive zone model
  - Efficient model - Uses simple modeling techniques and fairly large size elements

- Damage model developed to run with Explicit solver using Abaqus VUMAT subroutine

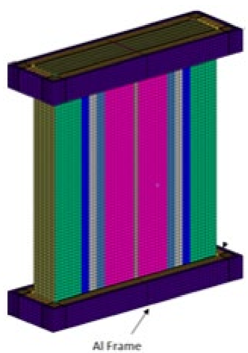
- Limitation of COSTR Damage Model
  - Not validated for fabric or metal matrix composites
    - Testing currently being performed to validate fabric damage model

Composite Technology for Exploration (CTE)

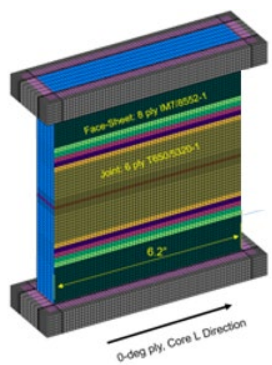
Longitudinal Bonded Joint Sub-Element Test Coupon Design

- Longitudinal bonded joint sub-element test coupon models were developed and analyzed to test joint capability and validate structural models for joint failure prediction for critical joint loading conditions
  - Axial Edge-Wise Compression (AEWC)
  - Hoop Edge-Wise Compression (HEWC)
  - Hoop Tension (HT)
  - Shear *

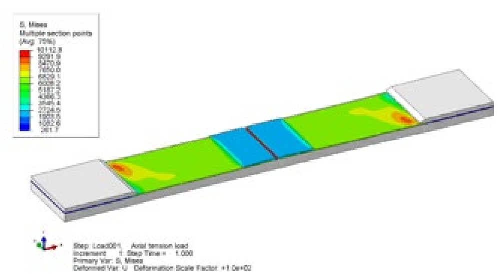
CPD Joint Line Loads with 2.0 FS, (lb/in)	
Axial Compressive Nx	-3,998
Hoop Compressive Ny	-980
Hoop Tension Ny	906
Shear, Nxy	1640

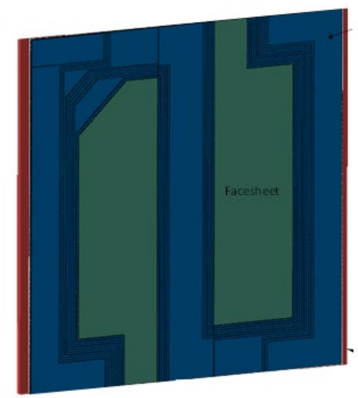


AEWC test specimen



HEWC test specimen


HT specimen

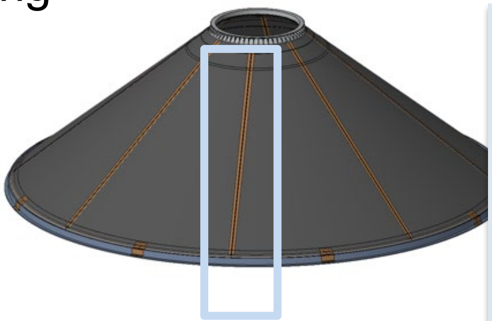


Shear test specimen

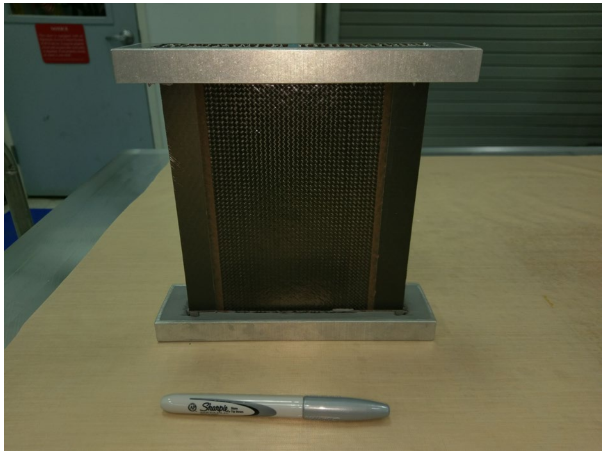
*Team determined (by Margins) that pure shear test was not a design driver. In addition, it is the most complicated and costly joint sub-element test.

Composite Technology for Exploration (CTE)
Longitudinal Joint Testing

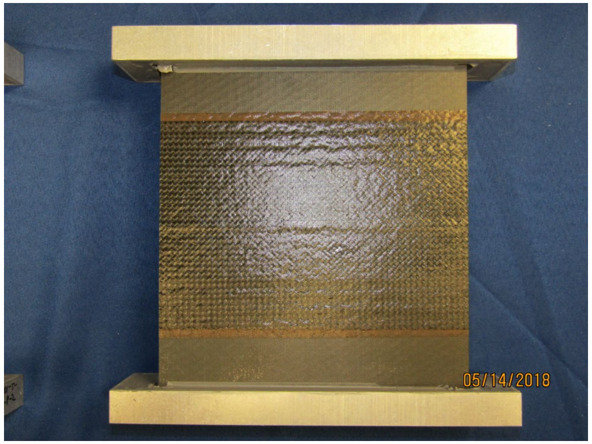
- Longitudinal Bonded Joint Sub-Element Testing
  - 58 specimens have been tested.
    - Axial Edgewise Compression
    - Hoop Edgewise Compression
    - Hoop Tension
    - Pristine and Damaged
  - Testing performed by Southern Research (SR)
- 3 Bonded L-Joint Sub-Element Tests are in progress Remaining.
  - Includes 2” diameter flawed, to evaluate analyses tools and this test vs actual damage.



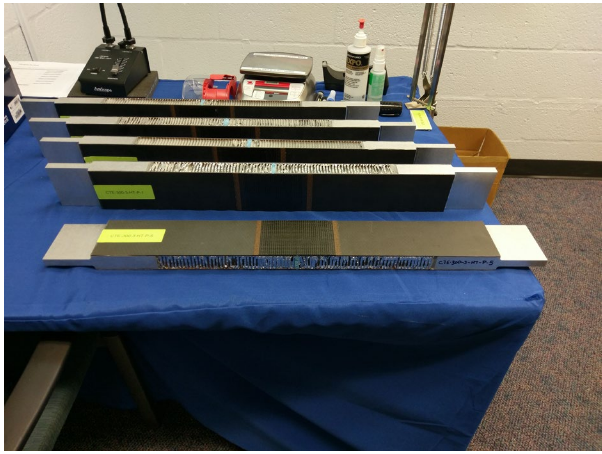
Bonded panels prior to sub-element manufacturing



- Axial Edgewise Compression



- Hoop Edgewise Compression

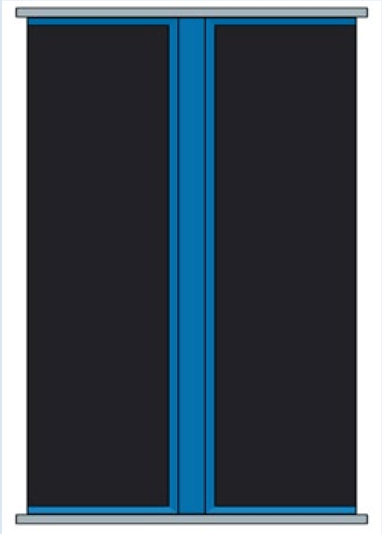


- Hoop Tension

CTE Test Status

Large-Scale, L-Joint Buckling Testing

- 2 Buckling Panel tests Completed by MSFC / ET30.
  - Pristine to buckling, and failure
  - Damaged to buckling 4 times, damaged inspected, then taken to failure



Buckling test panels are approximately 30” x 62”.

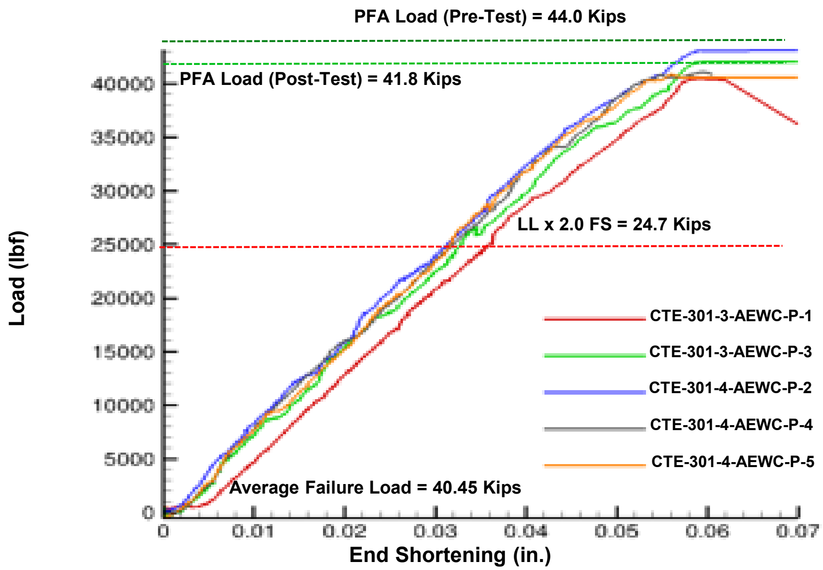
Panel Type	Panel Configuration	Purpose	Test Plan
Panel 1	CTE Acreage Panel - Bonded Joint	Evaluate Jointed Configuration Peformance - No Damage	Step #1- Test to Buckling Initiation - Step #2 - Inspect Step #3 -Test Panel to Failure with Edge Braces
Panel 2	CTE Acreage Panel - Bonded Joint with Impact Damage	Evaluate Damaged Jointed Configuration Peformance - Impact Damage	Step #1- Test to Buckling Initiation - No Damage Step #2 - Inspect, Impact Damage, then Inspect Damage Step #3 -Test Damaged to Buckling Initiation 4 times Step #4 - Inspect Damage Progression Step #5 -Test Damaged Panel to Failure with Edge Braces

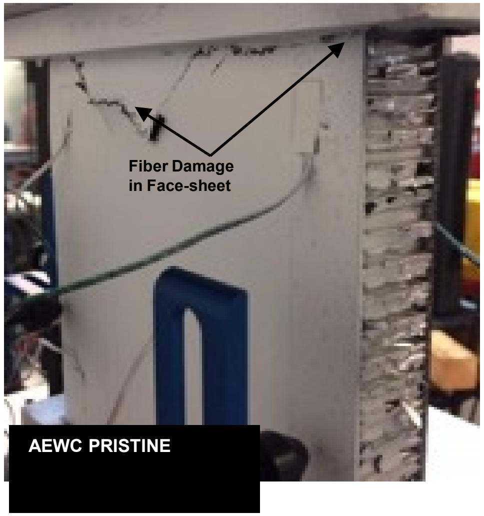
CTE Longitudinal Bonded Joint Buckling Sub-Element Testing Summary of Results

Sub-Element Testing and Analyses

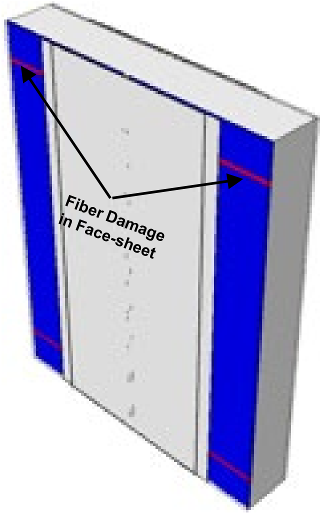
- **All Pristine AEWC coupons failed above CTE Point Design Limit Load (LL or DLL) with 2.0 FS**
- Progressive damage analysis (PDA) using cohesive zone and COSTR damage model used to predict joint failure
- ***Pre-test and post-test correlation achieved within 5% and 3%, respectively, of average test data for all tests***

AEWC – PRISTINE COUPONS





Failed AEWC Coupon

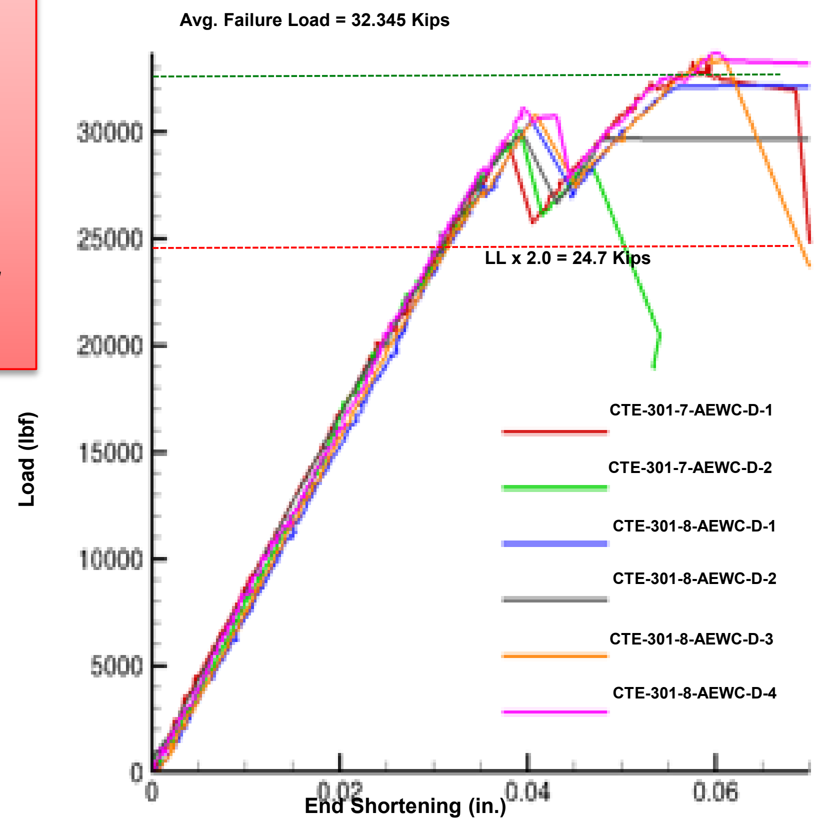


PFA of AEWC Coupon

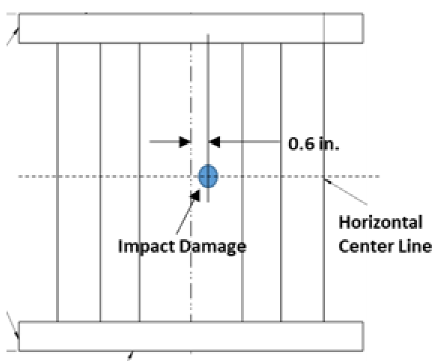
Composite Technology for Exploration (CTE)
Sub-Element Testing and Analyses

- **AEWC Impact damage coupon strength dropped by 24%**
- **All impact damaged AEWC coupons failed above CTE Point 2x DLL**
- **Joint is damage tolerant in this load direction**
- ***Analysis on impact damaged specimens not performed, modeling 'actual' damage is a challenge area***

AEWC – IMPACT DAMAGED COUPONS



Test Setup of AEWC & HEWC Coupons



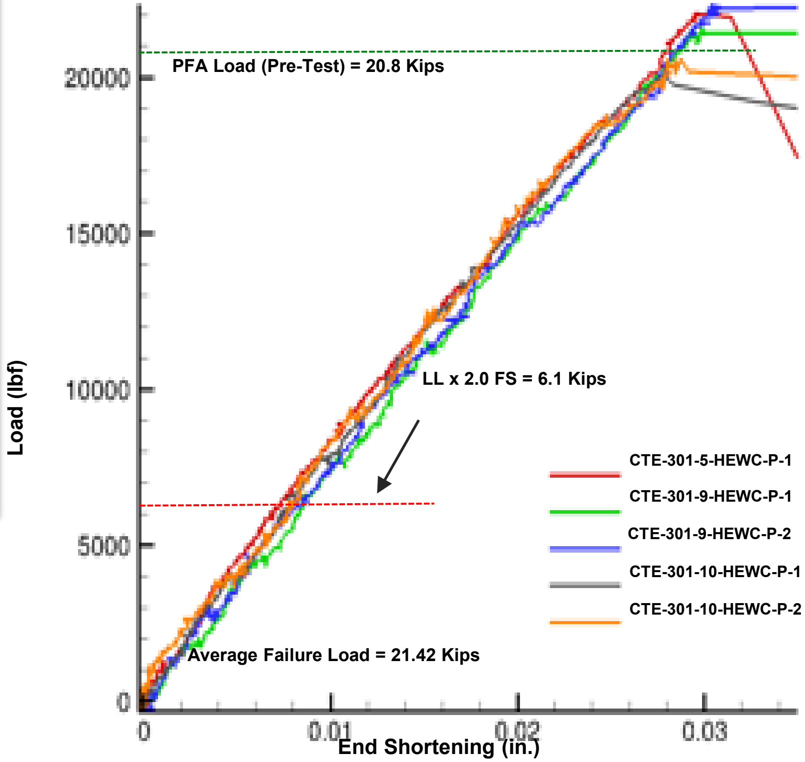
Impact Damage Location

Composite Technology for Exploration (CTE)

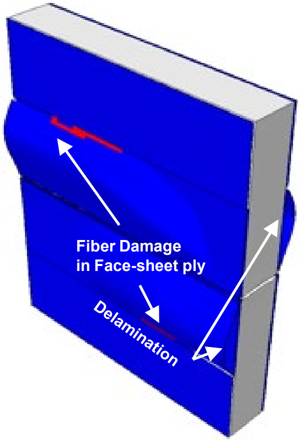
Sub-Element Testing and Analyses

- **All pristine HEWC coupons failed above CTE Point Design Limit Load with 2.0 FS**
- Progressive damage analysis (PDA) using cohesive zone and COSTR damage model used to predict joint failure
- Failure mode captured in analyses
- Pre-test and post-test correlation achieved within 3% of average test data for all tests

HEWC – PRISTINE COUPONS



Failed HEWC Coupon



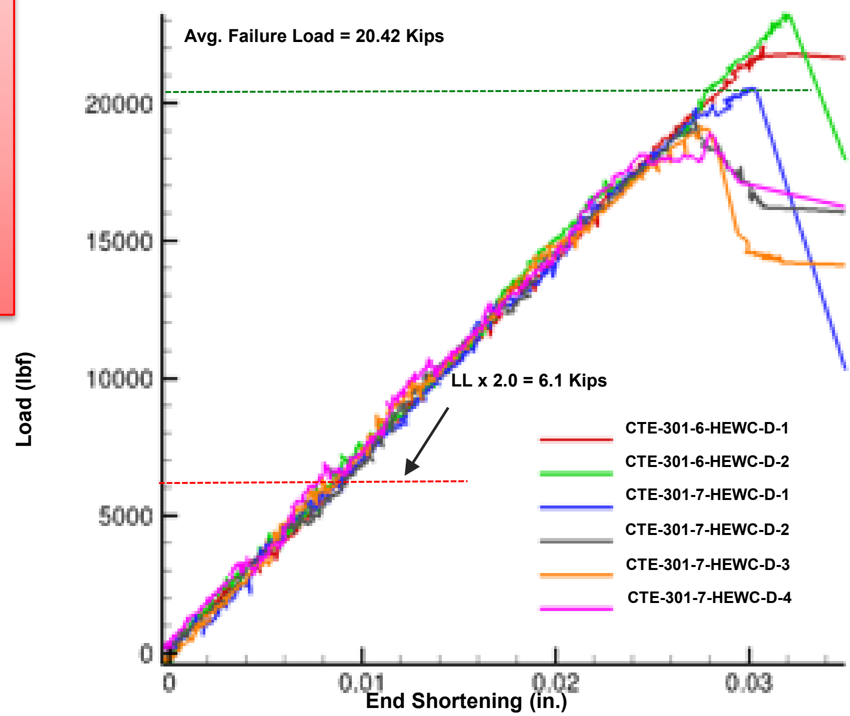
PFA of HEWC Coupon

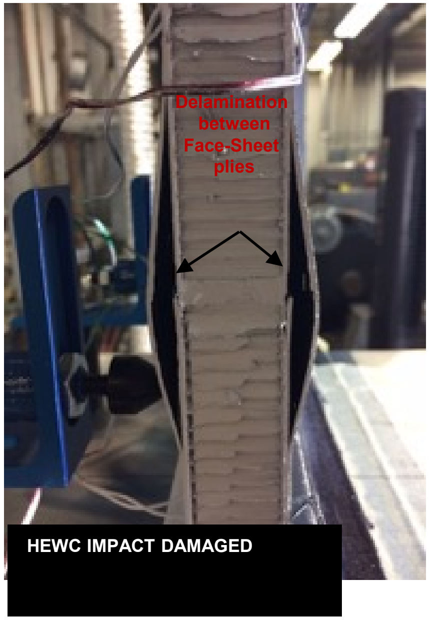
Composite Technology for Exploration (CTE)

Sub-Element Testing and Analyses

- **No apparent HEWC strength reduction with impact damage**
- **All impact damaged HEWC coupons failed above CTE DLL with 2.0 FS**
- **Joint is damage tolerant in this load direction**
- Impact Damage analysis not performed

HEWC – IMPACT DAMAGED COUPONS

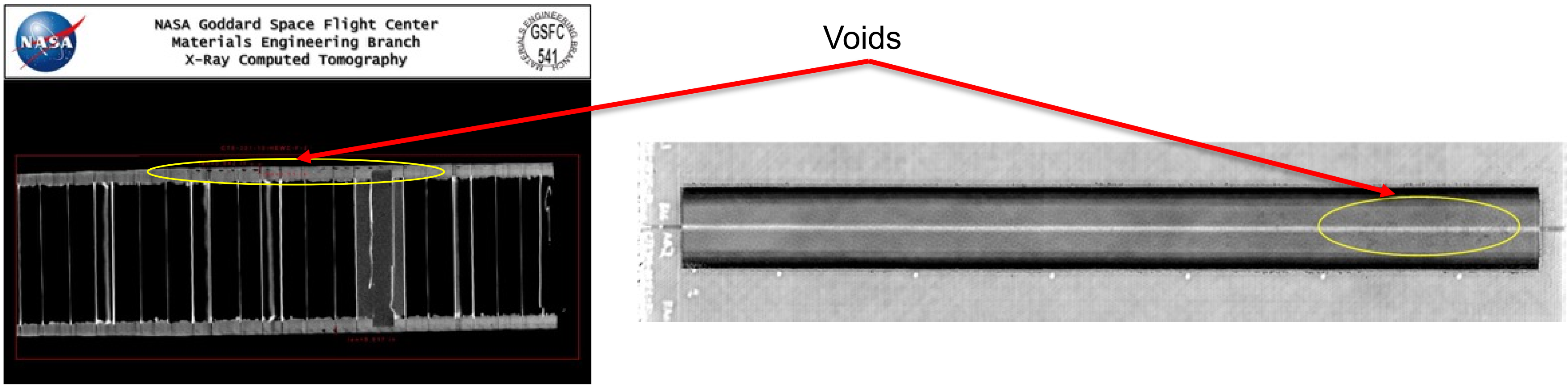




Failed HEWC with impact damage

Sub-Element Testing and Analyses

Two longitudinal joint panels for HEWC tests had NDE-detected flaws due to manufacturing. These were inspected at high resolution and tested.



- **HEWC pristine average test failure load (All Panels): *21.4 kips***
  - **Same parent joint panel: 21.2 kips**

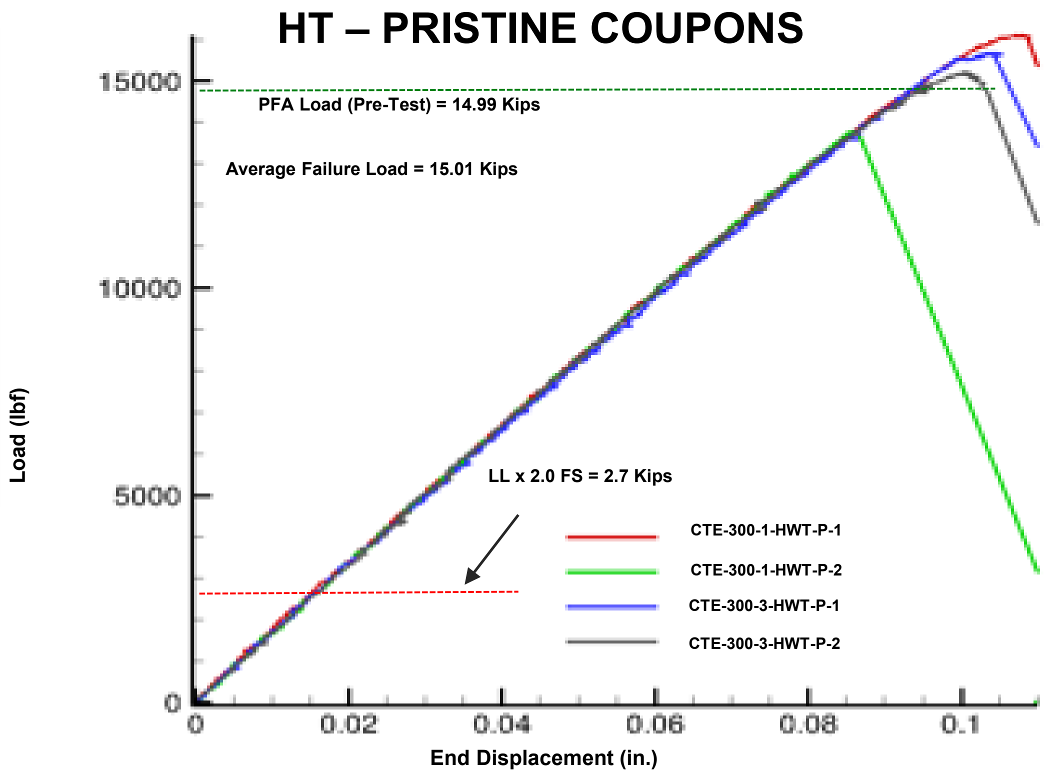
- **HEWC NDE-detected flawed average test failure load: *21.9 kips***
  - **Within 1-standard deviation to pristine test results**

NDE-detected flaws in joint material, measured at 0.004” and clustered, had no apparent effect on joint performance.

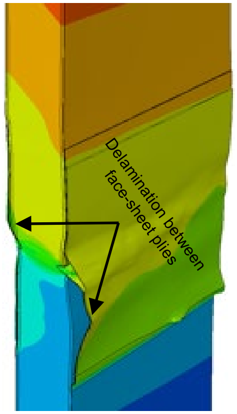
Composite Technology for Exploration (CTE)

Sub-Element Testing and Analyses

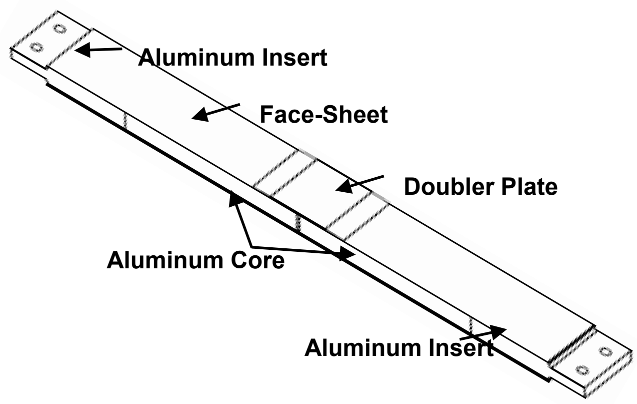
- **Pristine HT coupons failed above CTE Point Design Limit Load (LL) with 2.0 FS**
- Progressive damage analysis using cohesive zone and COSTR damage model used to predict joint failure
- Pre-test analyses achieved within 1% of average test data



Failed HT Coupon



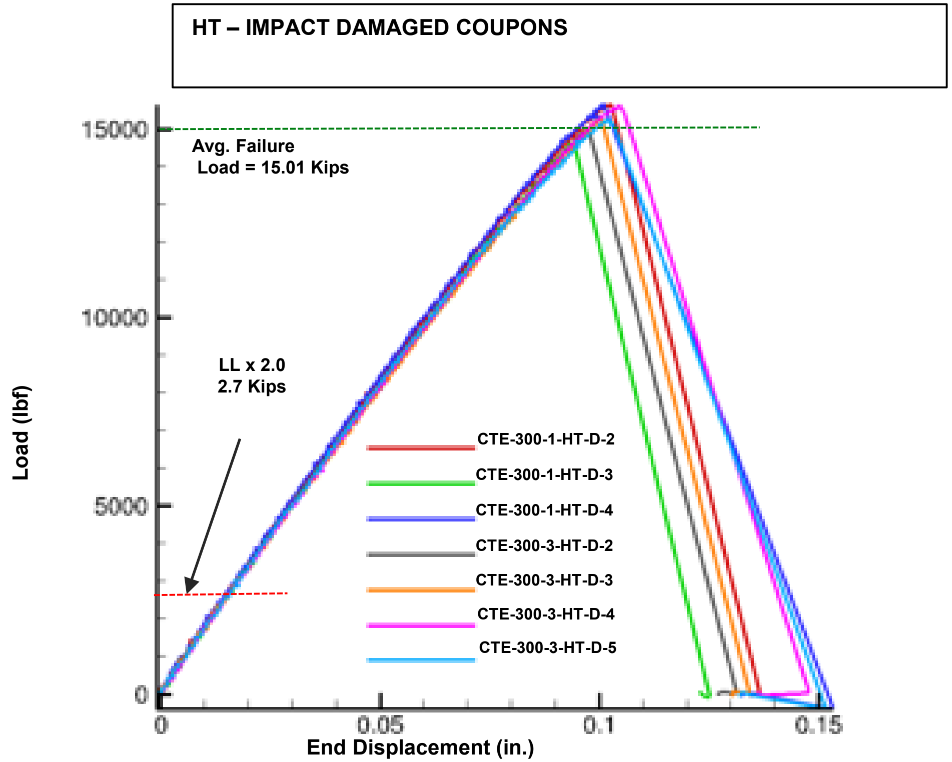
PFA of HEWT Coupon

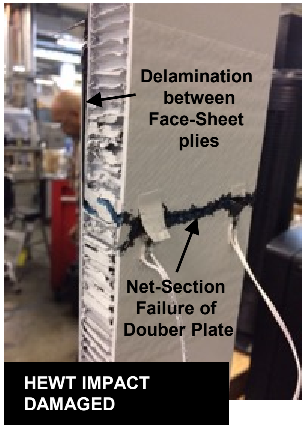


Composite Technology for Exploration (CTE)

Sub-Element Testing and Analyses

- **No HT strength reduction with impact damage**
- **All impact damaged HEWC coupons failed above CTE DLL with 2.0 FS**
- **Joint is damage tolerant in this load direction**
- Impact damage analysis not performed





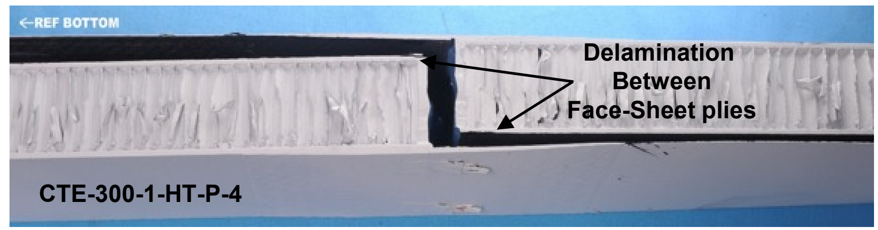
Failed HT Coupon

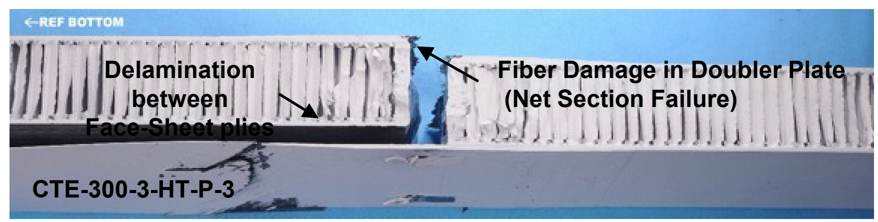
Composite Technology for Exploration (CTE)

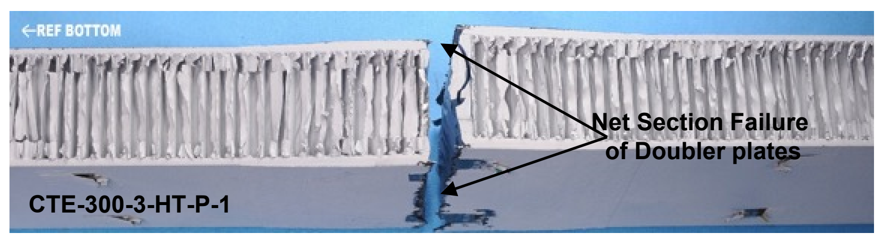
Sub-Element Testing and Analyses

- Hoop Tension: Dominant failure load during testing was either delamination between face sheet plies and/or net section failure of doublers.

Coupon ID	Test Failure Load (kips)	Strain at failure (SG-1), Micron	Failure Mode
CTE-300-1-HT-P-1	16.117	0.02	Delam/NSF
CTE-300-1-HT-P-2	13.767	0.014	Delam/NSF
CTE-300-1-HT-P-3	15.584	0.0197	Delam/NSF
CTE-300-1-HT-P-4	13.003	0.0138	Delam
CTE-300-1-HT-P-5	13.897	0.015	Delam
CTE-300-3-HT-P-1	15.666	0.026	NSF
CTE-300-3-HT-P-2*	15.196	0.027	NSF
CTE-300-3-HT-P-3	15.018	0.022	Delam/NSF
CTE-300-3-HT-P-4	15.891	0.035	NSF
CTE-300-3-HT-P-5	16.000	0.029	NSF
Average	**15.014**		



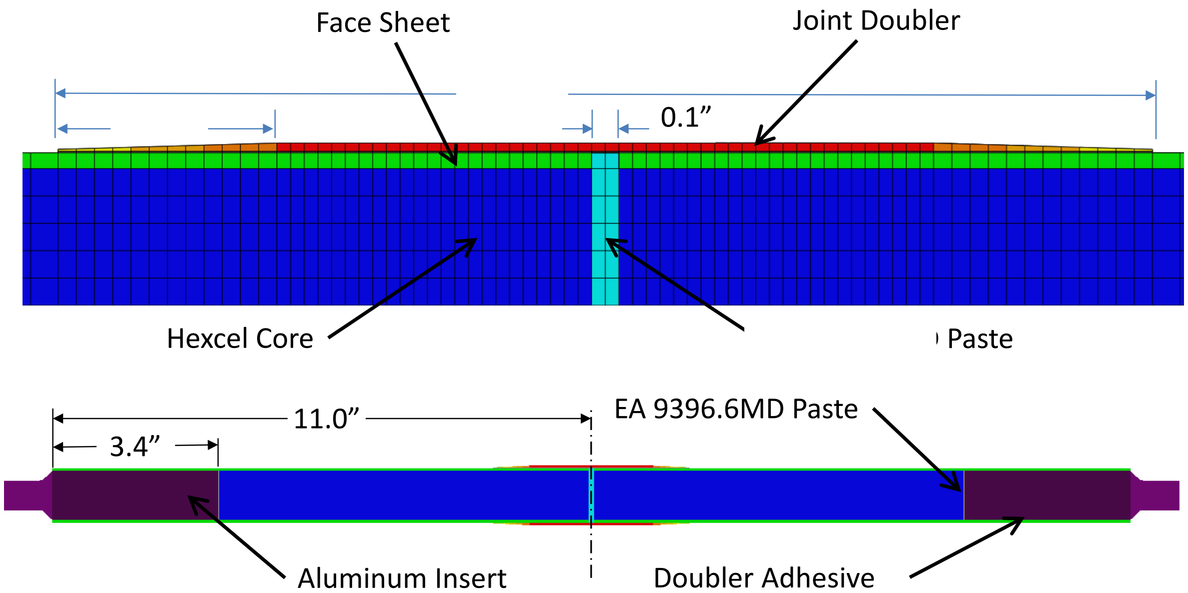




Sub-Element Testing and Analyses

- Abaqus Linear Analysis

Linear Model/Analysis Details – Hoop Tension Joint Coupon

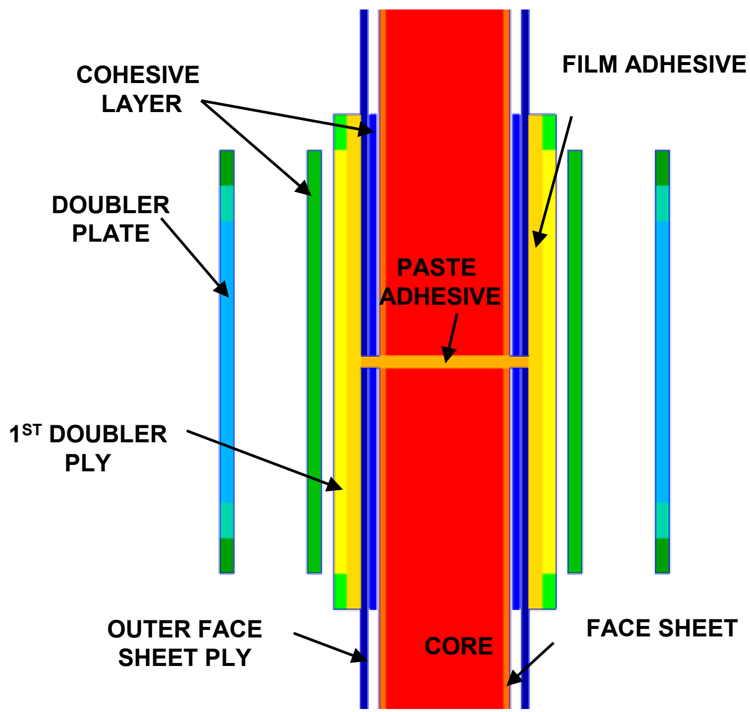


Element Type:
SC8R – Face-sheet, Doubler, adhesive
C3D8 – Core, Gap Filler, and aluminum insert

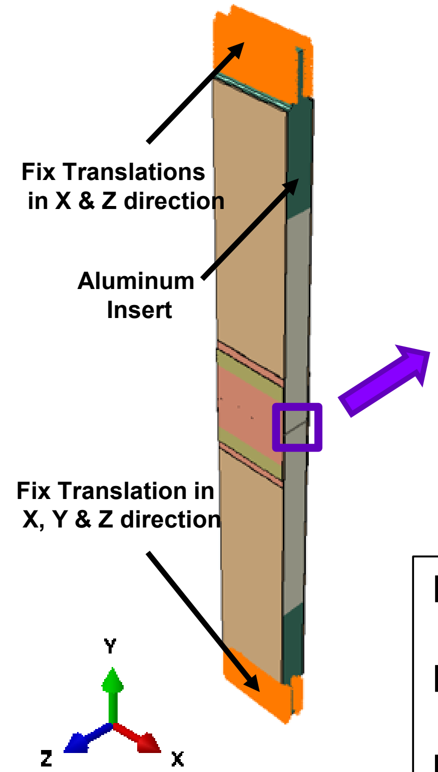
Sub-Element Testing and Analyses

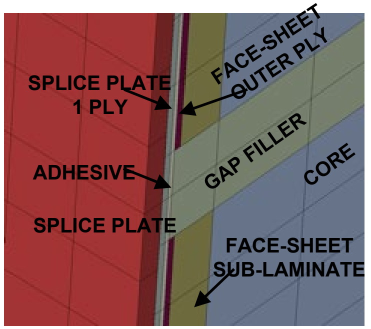
- Abaqus Nonlinear Explicit Analysis

PFA Model/Analysis Details – Hoop Tension Joint Coupon



Modeling Details of HT Coupon





Element Type:
SC8R – Face-sheet, Doubler
C3D8 – Core, Adhesive Layer, Gap Filler
COH3D8 – Cohesive Layer between Doubler & face-sheet plies

COSTR Damage Model used

Sub-Element Testing and Analyses

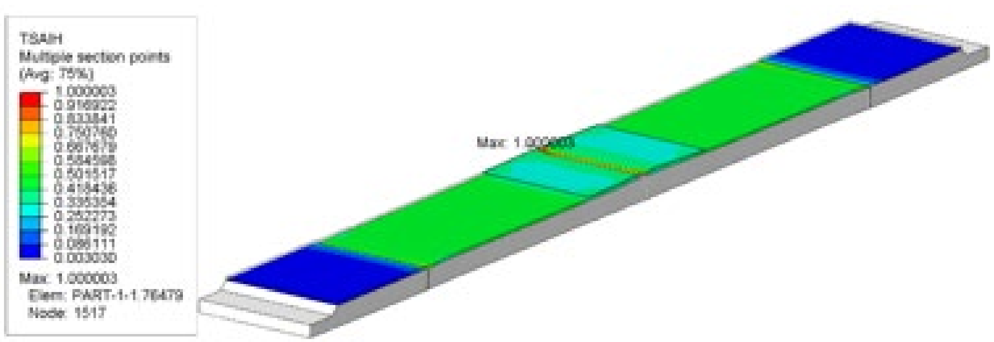
Longitudinal Joint Hoop Tension Sub-Element Pristine Coupon Test/Analysis Correlation

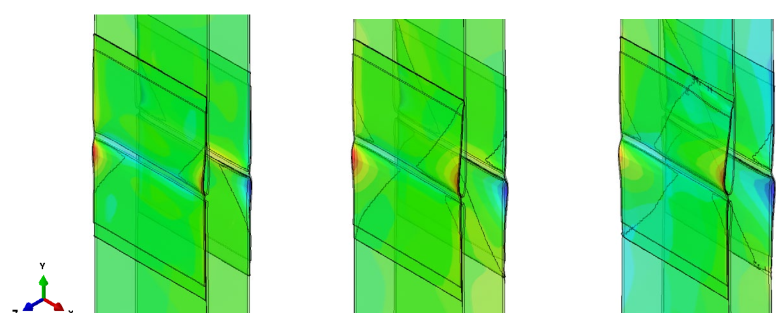
- **Linear analysis**
  - Predicted pre-test failure load was 13.92 Kips
  - Predicted failure mode was joint doubler failure

Nonlinear PFA analysis

- **Predicted pre-test failure load was 14.99 Kips**
- **Predicted failure mode was face sheet delamination**
- **Post-test analysis not performed due to pre-test prediction correlation**

Failure Index





Uz Displacement Contour (At 13.8 Kips) | **Uz Displacement Cont (At 14.66 Kips)** | **Uz Displacement Contours (At 15.00 Kips)**

Sub-Element Testing and Analyses

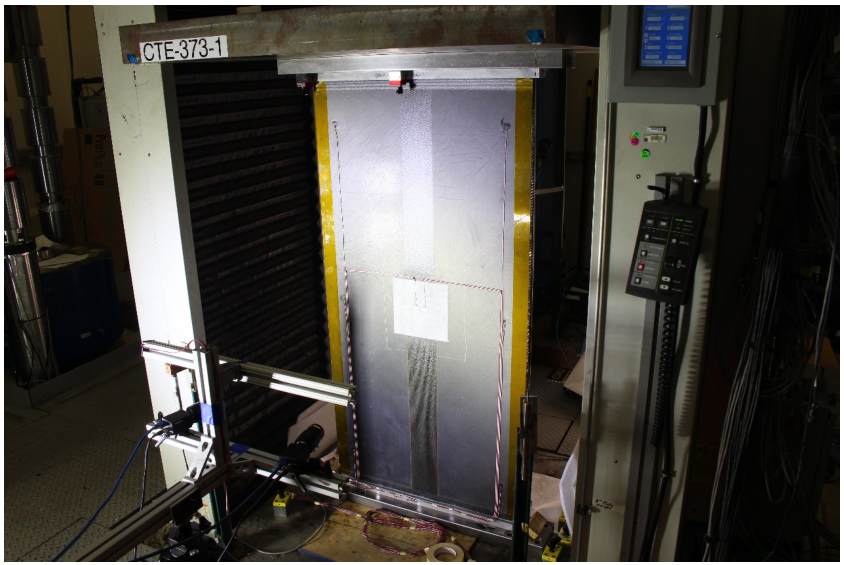
Longitudinal Joint Sub-Element Coupon Testing/Analysis Conclusions

- All joint sub-element coupons (pristine, impact-damaged, and flawed) failed above CTE Point Design limit loads with 2.0 FS
  - All joint tests showed repeatable failure loads and failure modes leading to joint sub-element coupon failure
  - AEWC sub-element coupon tests all failed at potted ends as predicted due to fiber failure at potted ends (difficult to design to fail at joint)
  - HEWC and HT sub-element coupon tests all failed at joint as predicted due to face sheet delamination
- Comments on analysis correlation
  - Pre-test PFA correlation was within 9% of average test data (AEWC: +8.8%, HEWC: -2.9%, HT: -0.2%)
  - Post-test PFA correlation was within 5% of average test data (Adjusted AEWC model, Final +3.3%)
- Comments on important features to consider in joint failure analysis prediction
  - Important to know failure properties and allowables for all joint materials
  - Important to consider all expected damage modes in analysis
  - Important to include non-linear material behavior in adhesive and gap filler

CTE Large-Scale Longitudinal Bonded Joint Buckling Panel Testing Summary of Results

Large-Scale Longitudinal 62”x 30” Bonded Joint Buckling Panel Test Set-Up

Testing performed on 250 KIP Instron – MSFC Building 4619/Room 153



Panel Buckling Test Set-up

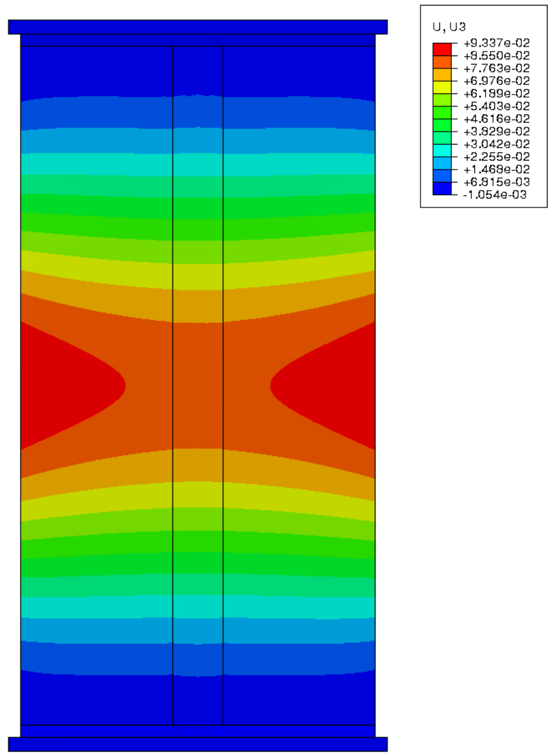
Panel Failure Test Set-up

Side rails added to prevent buckling

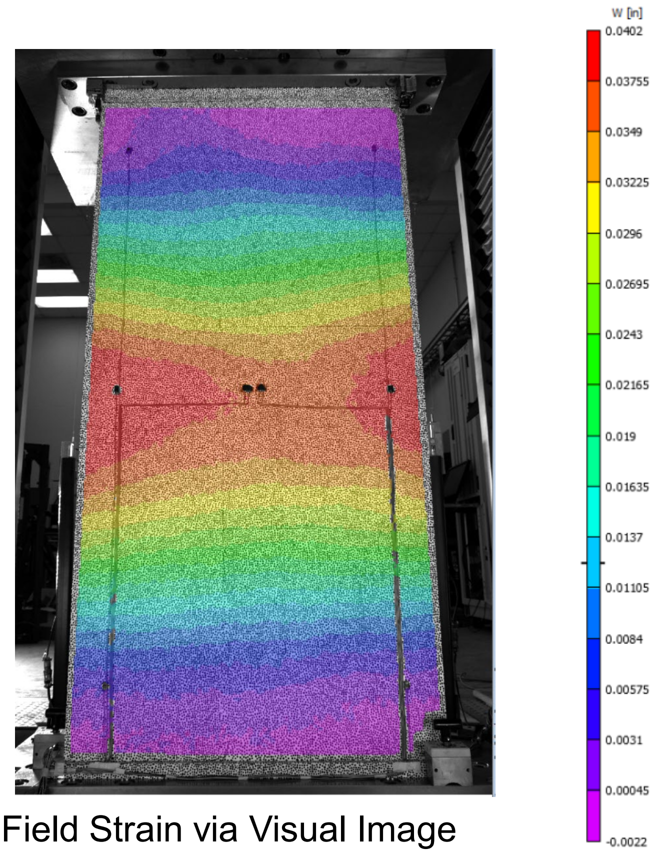
Sub-Component Testing and Analyses

CTE 373-1 Panel Test: Pristine Panel Buckling Test Buckling Initiation Shown

- Pre-test analysis predictions included 1% geometric imperfections based on first buckling mode shape
  - Buckling load is within 3%
  - Mode shape is in good agreement with prediction
- Post-test NDE showed no damage to panel or joint



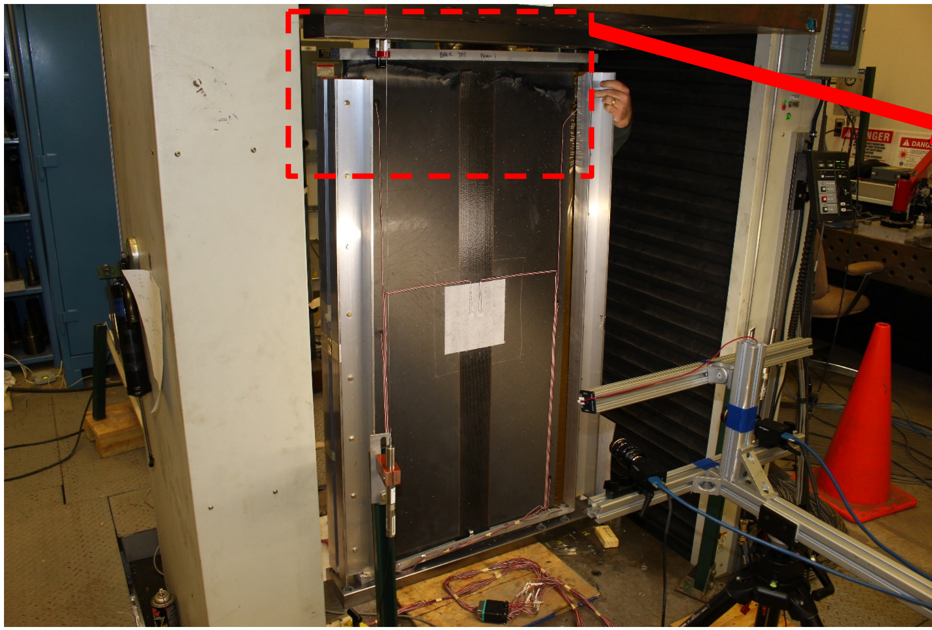
Out-of-Plane Displacement at Pre-Test Analysis Prediction of Buckling Load = 76.1 Kips



Full Field Strain via Visual Image Corrulation

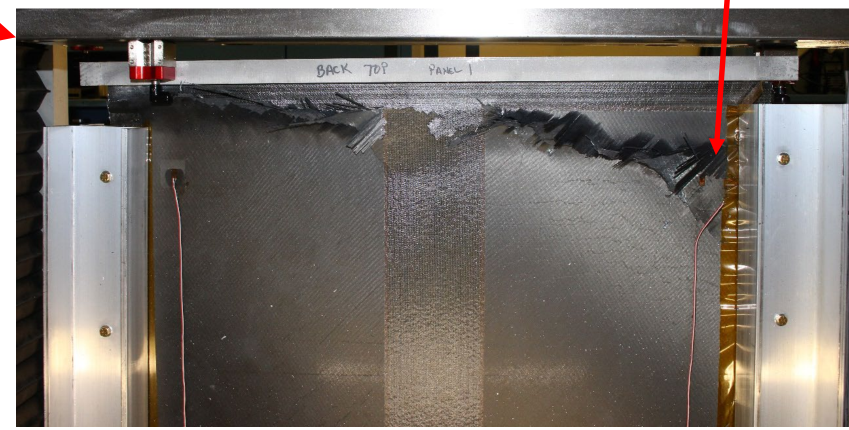
- Out-of-Plane Displacement
- Test Buckling Initiation Load = 73.8 Kips

CTE 373-1 , Pristine Panel at Failure



CTE 373-1 Panel at Failure

Failure location along top upper end



Local Region Showing Facesheet Failure

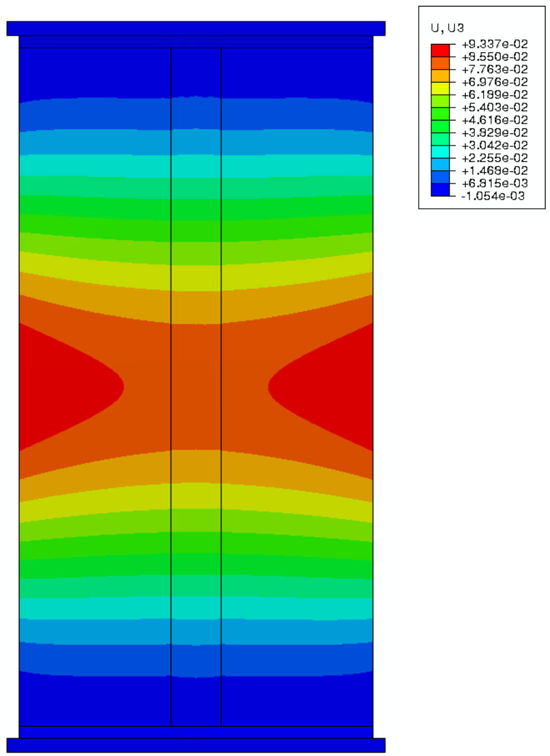
Pristine panel failed at 176.8 Kips (5893 lb-f/in)
DLL with 2.0 FS Is 120 Kips design load

Failure in the end indicates joint strength was ‘at least’ 5893 lb-f/in
(For reference AEWC coupon achieved 6966 lb-f/in)
indicates a MS of 0.47 demonstrated in the scale-up joint

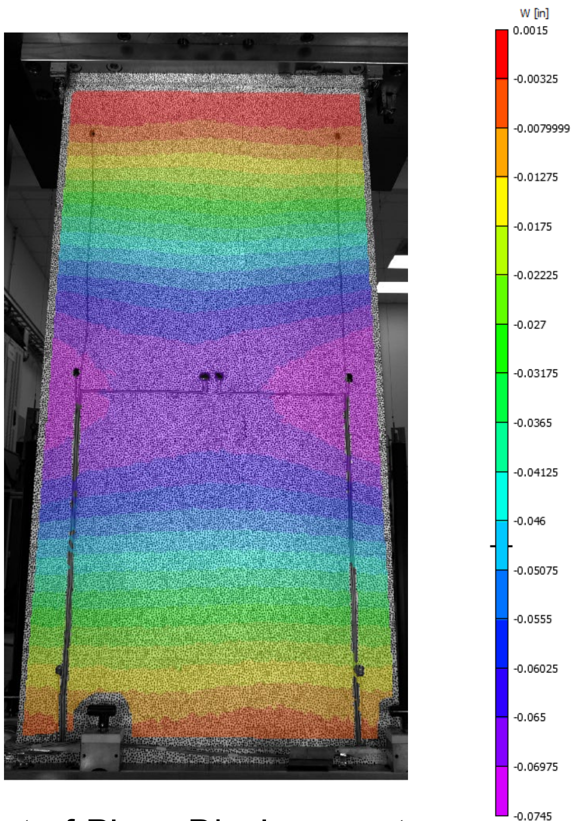
Sub-Component Testing and Analyses

CTE 373-2 Panel Damaged Panel Testing: Buckling Initiation Shown without damage

- Buckling mode shape is in good agreement
  - CTE 373-2 panel is suspected of having more imperfections which lowered buckling initiation load
  - No post-test NDE performed, no test anomalies



Out-of-Plane Displacement, w
Pre-Test Analysis Prediction Buckling Load = 76.1 Kips



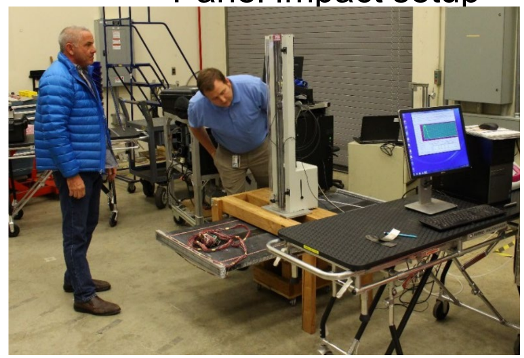
Out-of-Plane Displacement, w
Test Buckling Initiation Load = 60.0 Kips

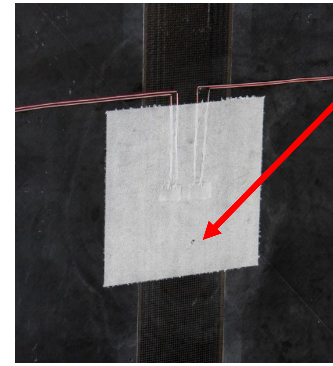
Sub-Element Testing and Analyses

CTE 373-2 Panel Damage Tolerance Tests

- CTE 373-2 panel was impacted with 6 ft-lbs of energy to cause BVID damage
- Post impact NDE showed damage in an area 1.03” x 0.84”
- Panel was cycled 4 times to 60 Kips load (buckling initiation)
  - The load equals the axial compression design limit load of 2000 lb-f /in
- Pre and Post test NDE performed
  - No damage growth
- CTE bonded joint design demonstrated to be damage tolerant at critical buckling and Nx DLL for RTA conditions.

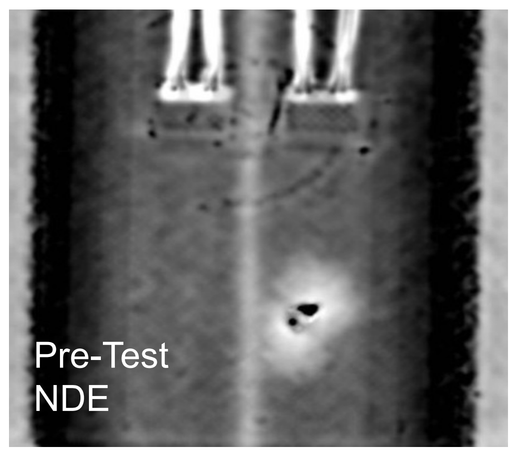
Panel Impact setup

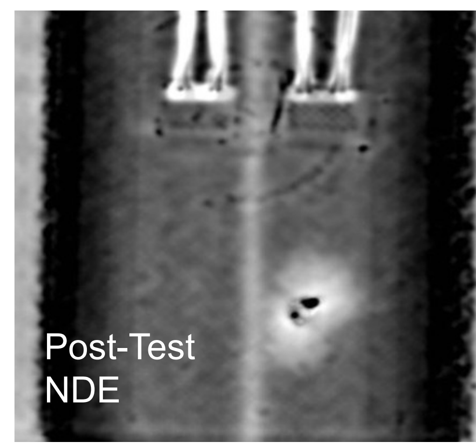




Impact damage site (black dot)

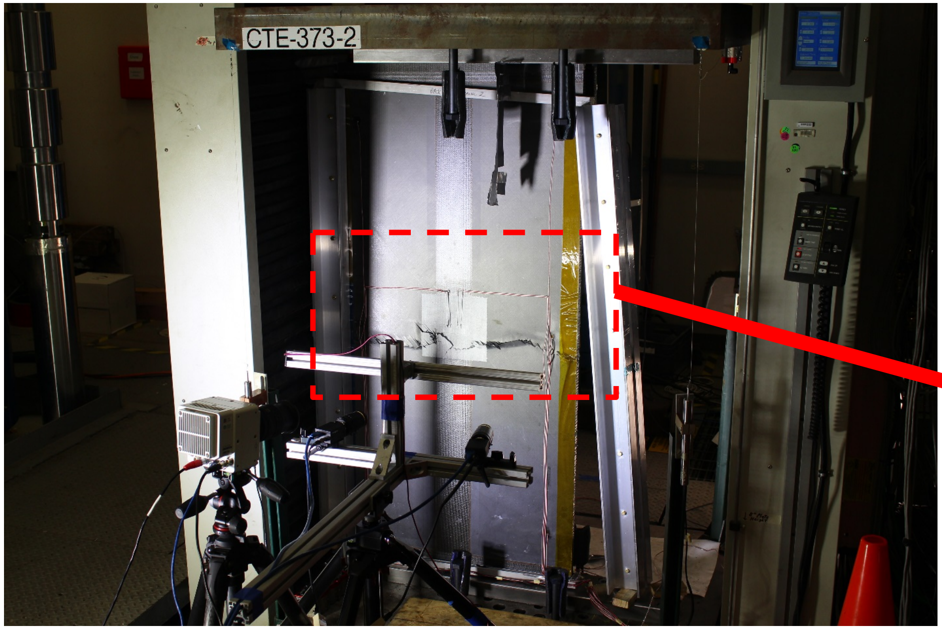
Pre and Post Test NDE shows damage with the same size and features





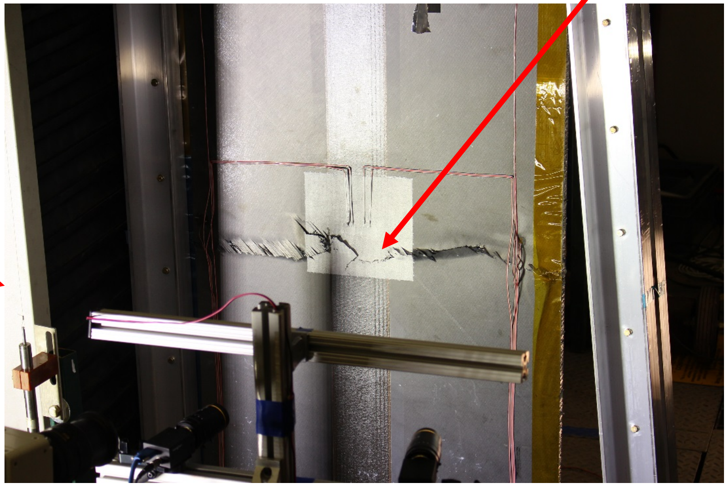
Sub-Component Testing and Analyses

CTE 373-2 Panel at Failure with Damage



Damaged Panel at Failure

Damage goes through impact location



Local Region Showing Facesheet Failure

Impact damaged panel failed at 143.4 (4780 lb-f/in)
That is a 19% reduction from pristine panel strength

Failure in joint is a true joint strength
indicates a MS of 0.22 with damage on a scale-up joint

Sub-Element Testing and Analyses

Summary

- Successful testing of CTE longitudinal bonded joint panels
- CTE 373-1 panel buckling initiation occurred at 73.8 Kips which was very close to analysis prediction of 76.1 Kips
- CTE 373-1 panel failed at 176.8 Kips which was higher than 120.0 Kips based on design load of 4000 lb/in (Includes 2.0 FS)
  - Panel failure at upper region of panel
- CTE 373-2 panel buckling initiation occurred at 60.0 Kips
- CTE 373-2 panel was impact damaged with 6 ft-lbs of energy and then successfully tested to 60.0 Kips (buckling initiation) for 4 cycles with no damage growth
  - **This meets the 2000 lb-f/in line load**
- CTE 373-2 panel with impact damage failed at 143.4 Kips which was higher than 120.0 Kips based on design load of 4000 lb/in (Includes 2.0 FS)
  - Panel failure at middle of panel
- In all panel failure tests, failure did not initiate in joint doubler

Technical – Analysis Tool Development

Sub-Element Testing and Analyses

Technical Progress: Joint Analysis Strategy

Preliminary Joint Sizing

A4EI
HyperSizer
Joint Designer

Uses Line Loads
Closed-form solutions to determine margins

Rapid analysis times
(~10 min)

→

Detailed Joint Analysis
State-of-the-Art

Detailed FEM

Uses FEM stresses and strains to determine margins based on assumed failure criteria (Max. Strain, Hashin, SIFT, Line Loads, etc.)

Long analysis time
(~ 1-4 hours)

→

Joint Progressive Damage Analysis

Highly Detailed FEM

Use advanced FEM capabilities such as VCCT and cohesive zone modeling along with damage models to predict damage initiation, damage propagation, and joint catastrophic failure.

Very long analysis time
(~ several days)

Sub-Element Testing and Analyses

Rapid Bonded Joint Design Tools

These rapid bonded joint preliminary design tools are readily available by the NASA CTE team and are being assessed for their capabilities and limitations

- A4EI
  - Computer code for bonded joint design/analysis from USAF developed by John Hart-Smith in 1982
- HyperSizer
  - Computer software for bonded joint design/analysis (Bondjo) from Collier Research
- Joint Element Designer
  - Specialized finite element solution for bonded joint design/analysis developed for NASA ACT project by U. of Michigan and U. of Massachusetts Lowell
- Rapid Low Fidelity and 3D FEA
  - Rapid FEA models generated by scripts for bonded joint design/analysis to compare with above tools

Preliminary Joint Sizing

A4EI
HyperSizer
Joint Designer

Uses Line Loads
Closed-form solutions to determine margins

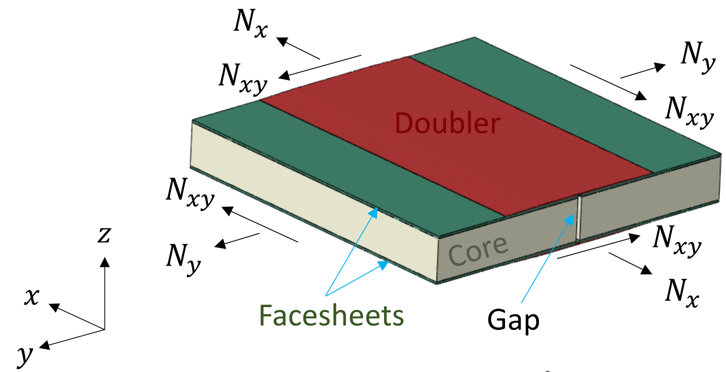
Rapid analysis times
(~10 min)

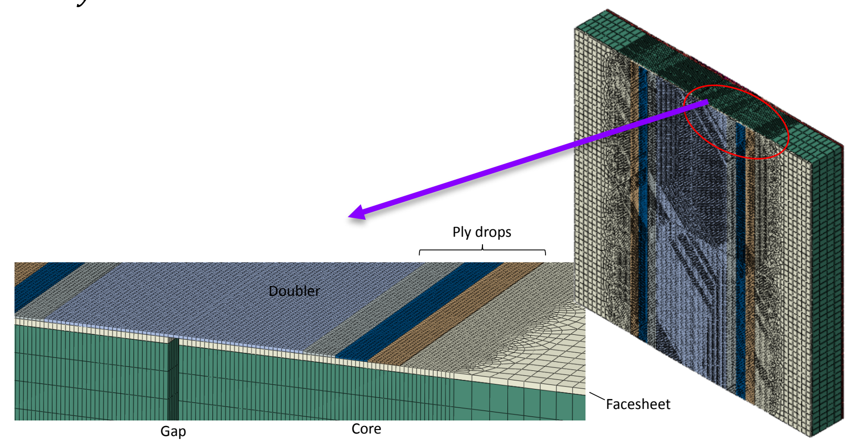
Joint Design Tools

Developing Parametric FE-based Joint Design Tool

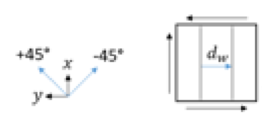
- **Objective**: Design tool to size longitudinal joints that considers:
  - Combined line loads (N_x, N_y, N_{xy})
  - 3-D stress state in core, facesheets, and doublers
  - Relevant design features: adhesive layer, ply drop off sequence, panel gap, and defects
- **Benefits**
  - Capture conditions that drive design: 3-D model with combined loads
  - Flexibility in the model to include geometric details (ply drops) and adhesive (with or w/o nonlinearity)
  - Compatible with any ply-level failure criteria

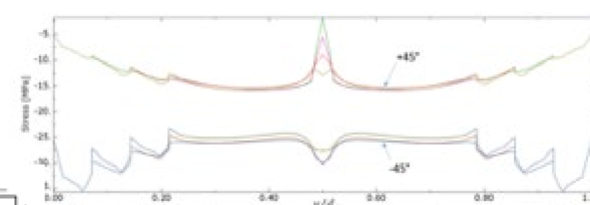
– **Compared results with A4EI, HyperSizer, and Joint Element Designer Tools**





Joint Parametric FE Model



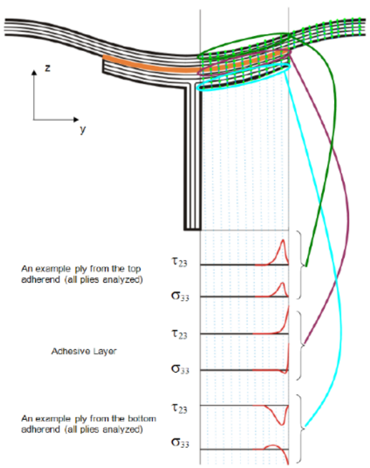


Joint Stresses along Joint Length

Composite Technology for Exploration (CTE)

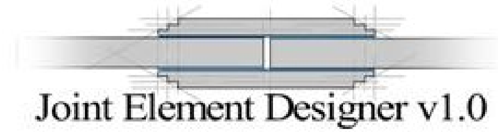
L-Joint Design Tools

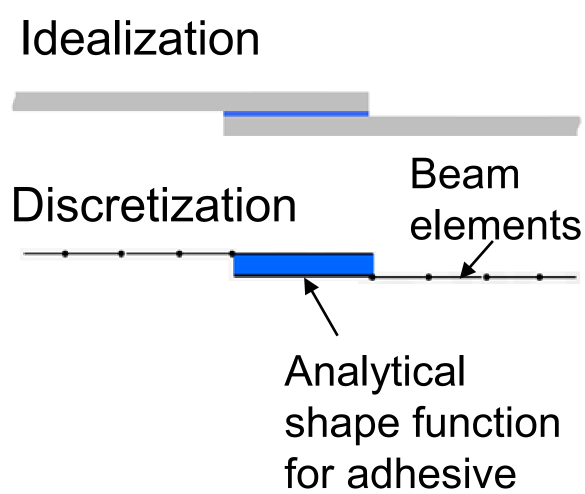
Hypersizer



Features:

- Full field stresses
- Many options for loading
- Linear displacement variation through thickness of core
- Analytical ODE solution
- Integrated with HyperSizer software suite

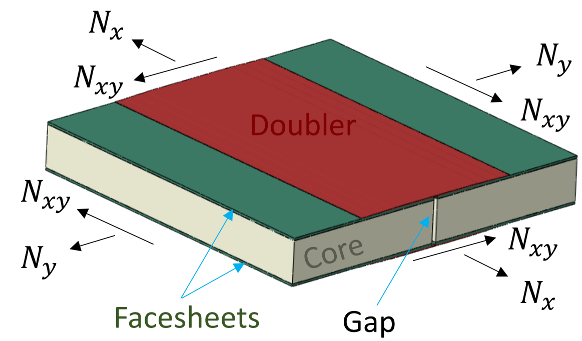


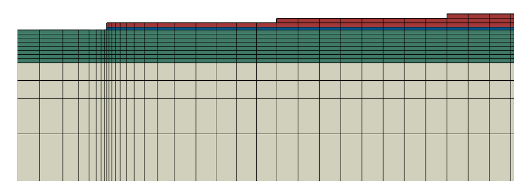


Features:

- Special quadratic 'adhesive' elements for adhesive and sandwich
- FEA-like model builder accommodates wide variety of joints

Parametric Continuum Solid Shell (CSS) FEA





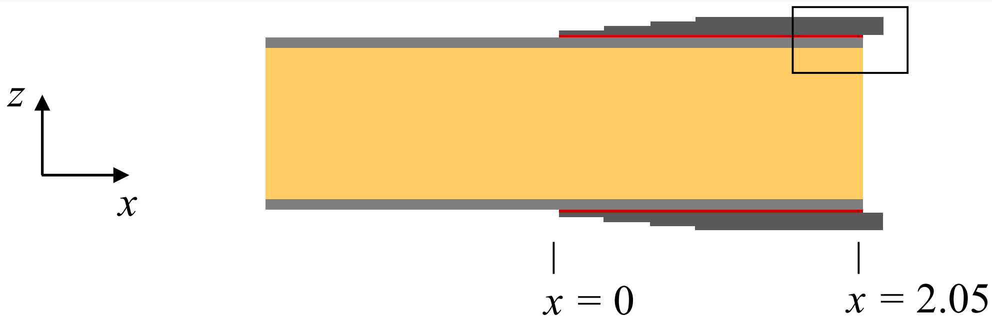
Features:

- Closer to true continuum solution than analytical tools
- Flexibility to account for many design features

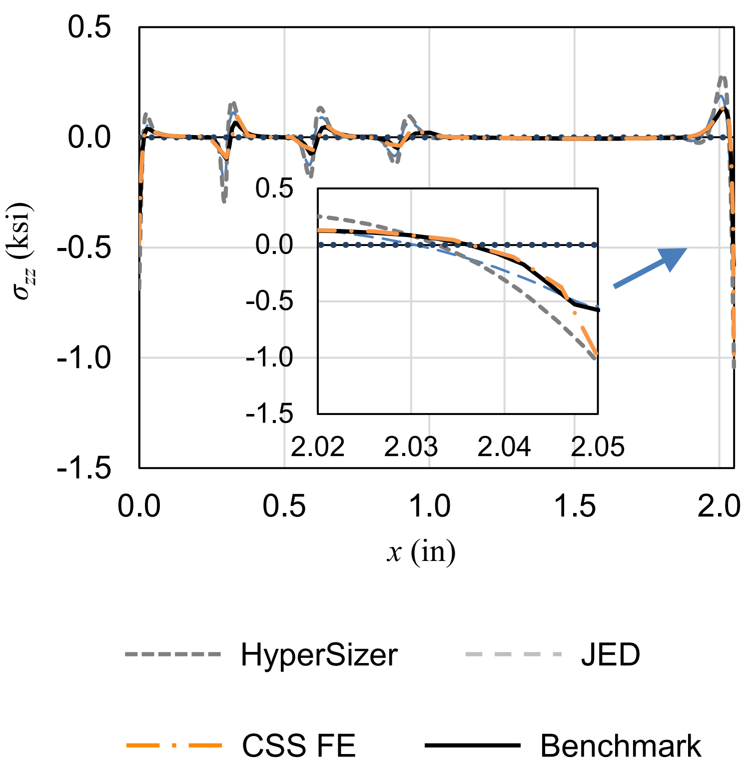
These tools are available to SLS-USA Teams

Composite Technology for Exploration (CTE)

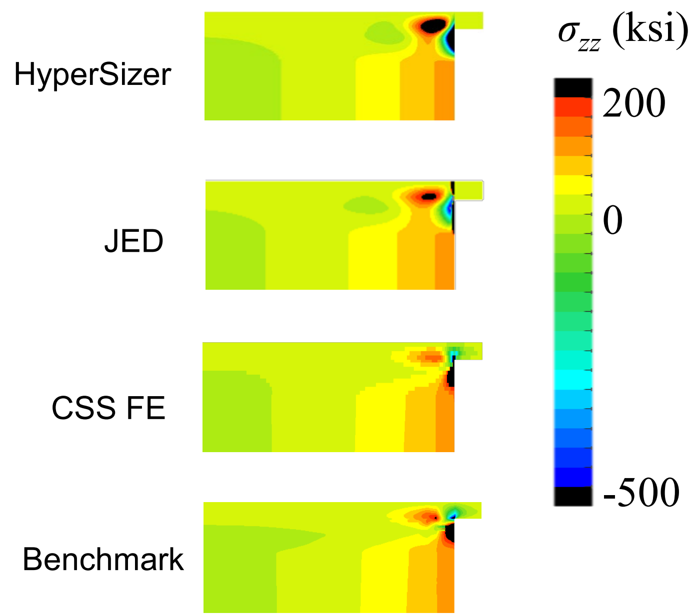
L-Joint Design Tool: Stress Field Verification



Adhesive stress comparisons



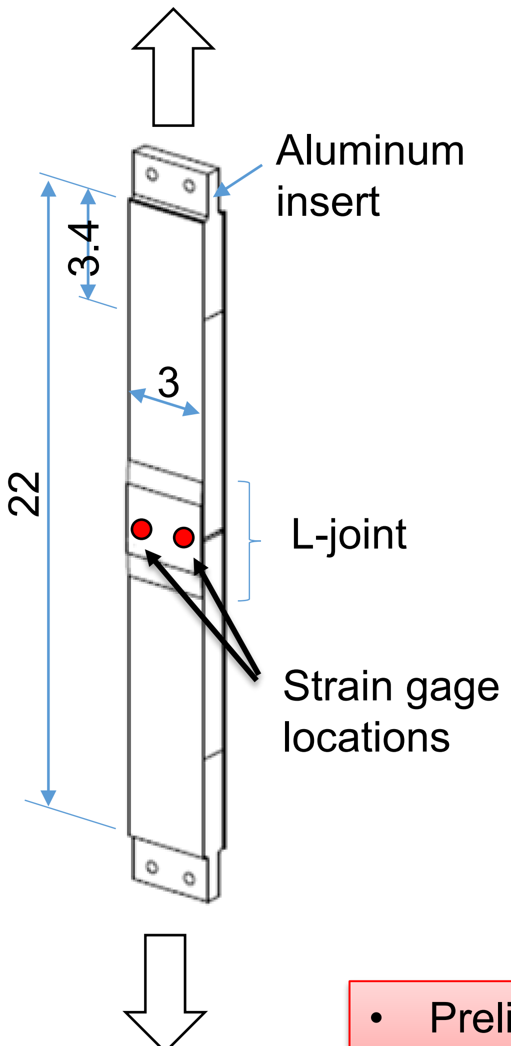
Full-field stress comparisons

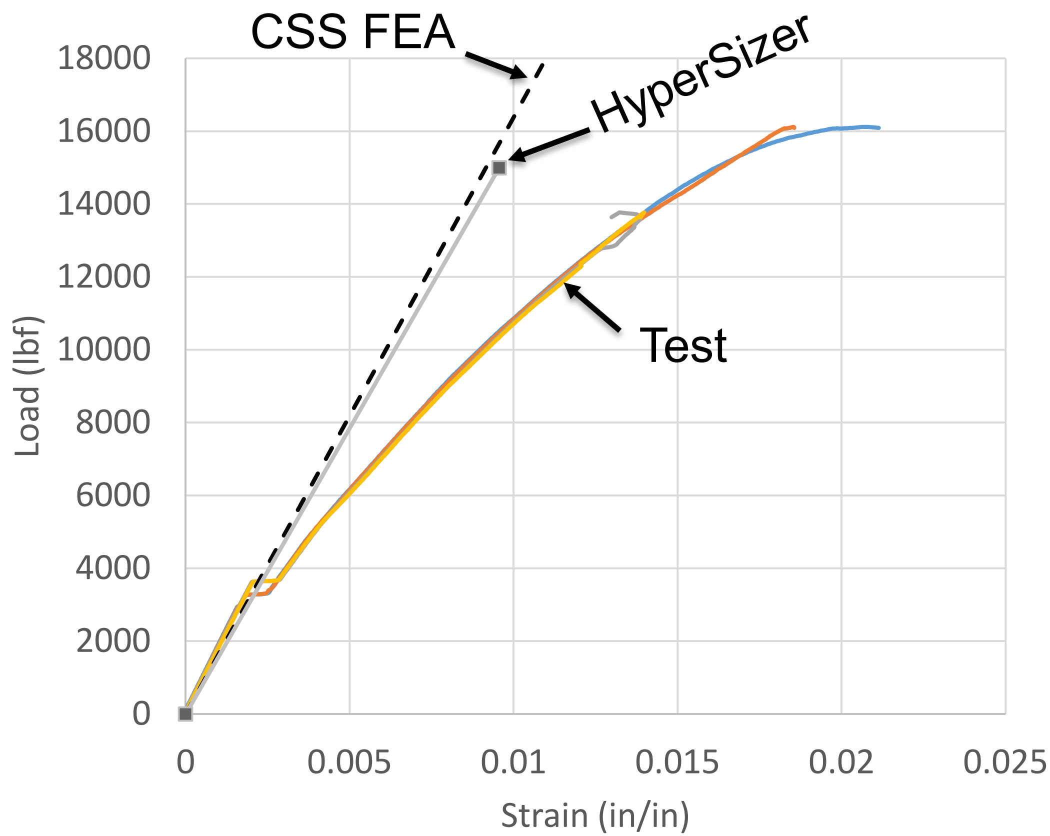


- Detailed comparisons of stress fields show capabilities of various tools
- Compared with highly refined FEA (Benchmark)
- Several improvements made to tools during study

Composite Technology for Exploration (CTE)

L-Joint Design Tool: Validation





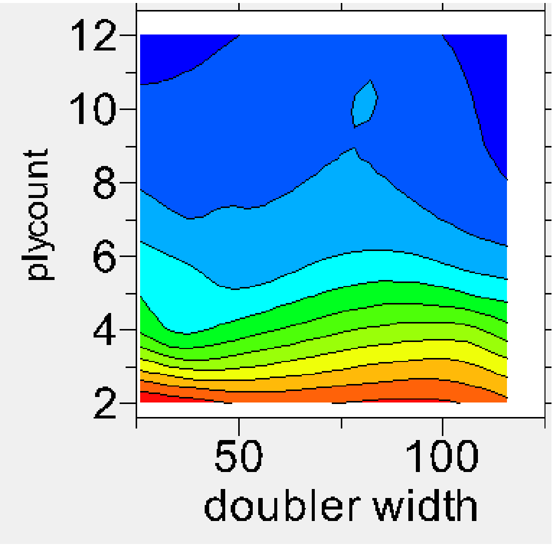
- Preliminary validation efforts show excellent agreement with test data
- Design tools do not capture nonlinearity since they are intended to be fast running

L-Joint Design Tool: Sizing/Optimization

Preprocessor **Python** → Solver **Abaqus** → Postprocessor **Python**

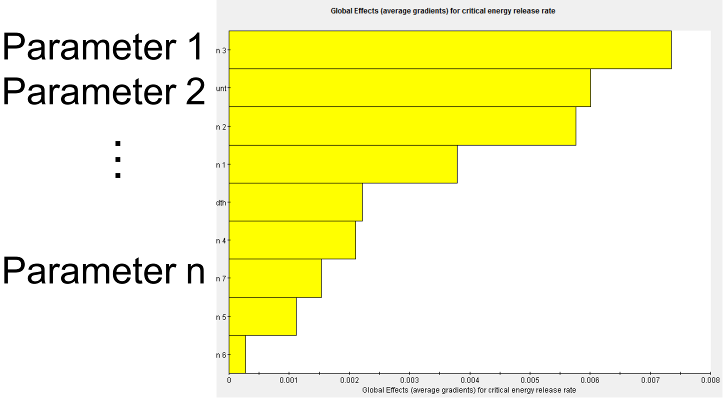
Abaqus: Simulia / Insight

Doubler net section failure margin



- Exploring using Simulia Isight for L-joint sizing and optimization
- Using parametric CSS FEA model
- Considering delamination and net section failure modes
- Design parameters:
  - Doubler width
  - Doubler ply count
  - Doubler ply orientations
  - Adhesive

Parameter sensitivity



COSTR Tool Advancement

Progressive Failure Model: Plain-Weave Fabric Laminates*

- Material model implemented in finite element for failure prediction

Abaqus ▪ Failure Criteria ▪ Stress Degradation ▪ Plane-Stress▪ Orthotropic Analysis for notched coupons using various failure criteria: Failure Criteria: Tsai-Wu, Hashin, Maximum Stress

- Post-damage added and assessed using response surface

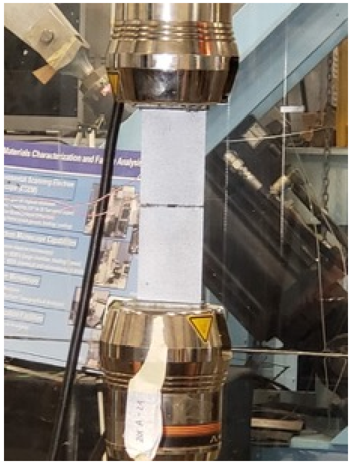
Ongoing test and modeling to enhance COSTR

Joint Progressive Damage Analysis

Highly Detailed FEM

Use advanced FEM capabilities such as VCCT and cohesive zone modeling along with damage models to predict damage initiation, damage propagation, and joint catastrophic failure.

Very long analysis time (~ several days)



LaRC Testing

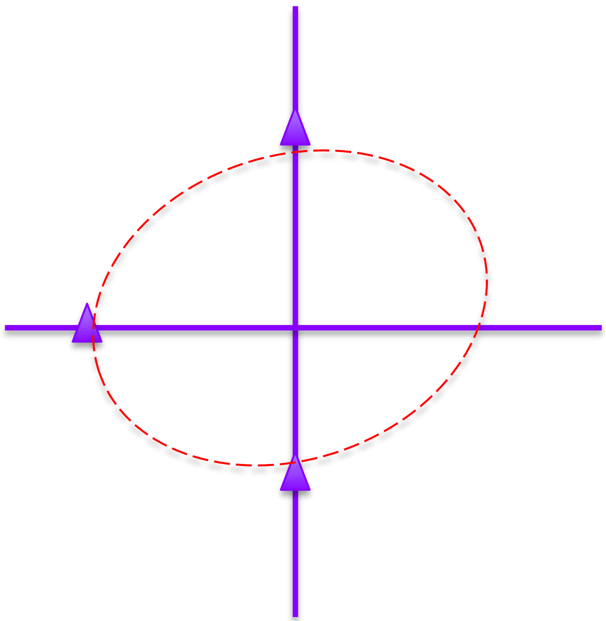
*Munden, D. C. "Development of a Progressive Failure Model for Notched Woven Composite Laminates, MS Thesis, Virginia Tech, 2018

Joint Failure Envelop Work

Working on approaches to establish bonded lap joint failure envelope

Looking at

- FEMs approach using material allowables (adhesive or adherend)
- Strain Invariant Failure Theory (SIFT)
- Empirical based on CTE test and ACT project test results



FY19 Effort to complete a failure envelope for L- Joints

Conclusions

- 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.**
  - Tested 2 scale up jointed panels in highest load direction. **Pristine and damaged joints met minimum CTE load requirements. Damaged joint withstood 4 life times with no damage growth**
  - Demonstrated manufacturing process parameters to produced repeatable, reliable and predictable longitudinal joint performance.

- **The CTE bonded joints with BVID are demonstrated damage tolerant in critical load conditions through element and sub-component tests.**

- Evaluated cohesive zone in-plane continuum damage model (COSTR) for longitudinal joint specimen failure predictions. **Established non-linear approach resulting in pretest predictions within 9% .**

Backup

CTE Test Status

Longitudinal Joint Sub-Element Testing

Joint Material/Panel Type	Test Type	CTE Milestone or Risk Reduction	Damage State	Number of Specimens	Testing Location	Status
Bonded Joint - Sub-element Coupon Testing	Axial Edgewise Compression	Milestone	Pristine	10	SR	**Complete**
		Milestone	Damaged/Impact	7	SR	**Complete**
		Milestone	1" Flawed	3	NIAR	In Work
		Milestone	2" Flawed	3	NIAR	In Work
	Hoop Tension	Milestone	Pristine	10	SR	**Complete**
		Milestone	Damaged/Impact	9	SR	**Complete**
	Hoop Edgewise Compression	Milestone	Pristine	7	SR	**Complete**
		Milestone	Damaged/Impact	6	SR	**Complete**
		Milestone	1" Flawed	3	NIAR	In Work
		Milestone	2" Flawed	3	NIAR	In Work
		Risk Reduction	NDE Flawed (Unplanned)	4	SR	**Complete**
Bonded/ Bolted Joint - Sub-element Coupon Testing	Axial Edgewise Compression	Risk Reduction	Pristine	5	NIAR	In Work
		Risk Reduction	Damaged/No Bondline	5	NIAR	In Work
	Hoop Tension	Risk Reduction	Pristine	5	NIAR	In Work
		Risk Reduction	Damaged/No Bondline	5	NIAR	In Work
	Hoop Edgewise Compression	Risk Reduction	Pristine	5	NIAR	In Work
		Risk Reduction	Damaged/No Bondline	5	NIAR	In Work
End-Potting Evaluation Testing	Axial Edgewise Compression	Evaluation Testing	Pristine	4	SR	**Complete**
NIAR Evaluation Testing to compare to SR Results	Hoop Edgewise Compression	Evaluation Testing	Damage/Impact	1	NIAR	**Complete**
			Total Specimens	**95**	**Total Complete**	**58**

- 58 of 95 L-joint sub-element have been tested.
- Testing occurred at Southern Research in Birmingham, AL
- One equivalency test occurred at National Institutes of Aviation Research (NIAR) at Wichita State University.
- The remaining sub-elements will be tested at NIAR.

CTE Test Status
Circumferential Joint Testing

Joint Type	Joint Material/Panel Type	Damage State	Priority	Test Type	Number of Specimens	Status
C-Joint Bottom End-ring	CTE Pnt Design Panel Bonded to 3D Woven Flange	Pristine	Milestone	Compression Strength (Nx)	5	In Work
		Damaged/Impact	Risk Reduction		3	In Work
		Flawed	Risk Reduction		3	In Work
		Pristine	Milestone	Moment +	5	In Work
		Damaged/Impact	Risk Reduction		3	In Work
		Flawed	Risk Reduction		3	In Work
		Pristine	Milestone	Moment -	5	In Work
		Damaged/Impact	Risk Reduction		3	In Work
		Flawed	Risk Reduction		3	In Work
				Total	33	

Joint Type	Joint Material/Panel Type	Damage State	Priority	Test Type	Number of Specimens	Status
8552-1 / IM7 Sandwich and 5320-1 /IM7 Pi Preform	Pi Preform Co-Bonded Joint Representation	Pristine	Milestone	Tension	8	In Work
		Pristine	Milestone	Compression	8	In Work
		Pristine	Milestone	Weak Axis Shear	8	In Work
				Total	24	

- Contracts with Bally Ribbon Mills (3D weave) and Cornerstone Research Group (resin infusion) are in place.
- Testing will occur at either NIAR or a NASA Center.

- 24 pi preform sub-elements will be tested.
  - Includes 3 different test types.
  - Data from the pi preform sub-element testing could affect the C-joint sub-element design.
- 33 C-joint sub-elements will be tested.
  - Includes 2 different test types and 3 different damage states (pristine, damaged, and flawed).