Experimental Investigation of the Starshade Prototype Petal Creep Behavior

Starshade Science and Industry Partnership (SIP) Telecon

May 20, 2021

Tendeg, LLC

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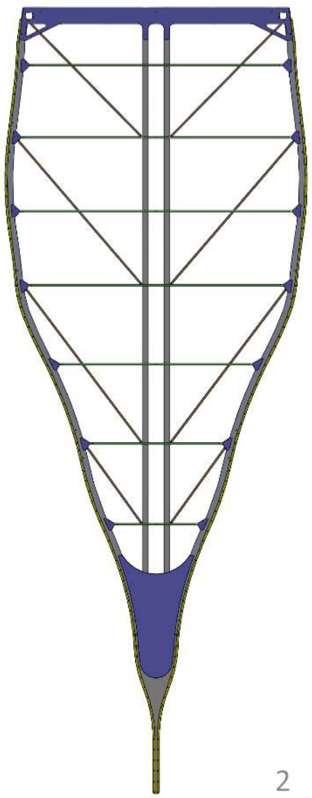
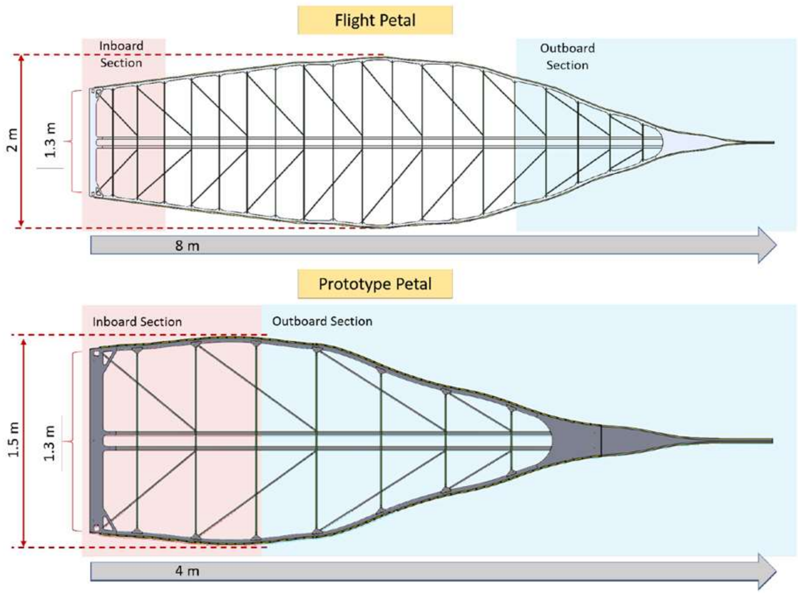
Program Objectives

- Pathfinder program to empirically assess creep behavior in a Starshade prototype petal assembly
  - Shape changes due to long term storage of a furled petal can impact optical contrast
    - KPP5 (pre-launch shape accuracy) Budget: ± 70 microns (manufacturing, AI&T, storage)
      - Suballocation for creep is ± 20 ppm (ground storage)
- Testing does not fulfill an S5 milestone, but informs design for Milestone 5B
- Program outline
  - Define furling stiffness in the Protopetal
    - Correlate the FEM model with a bending test experiment
  - Detect shape change at the system level, in the Protopetal
    - Furl the petal to representative strain levels and with proper interfaces
    - Correlate furl interface load conditions with FEM
    - Measure the in plane and out of plane shape of the petal
    - Compare measurement sets to detect changes
  - Determine if the joints in the Petal are contributing to creep
    - Isolate joint components by building joint coupon sub-assemblies
    - Load the coupons to simulate furling loads
    - Correlate the test conditions with FEM
    - Measure the shape of the coupons to detect changes



Protopetal Test Article

- Existing petal test article manufactured at Tendeg in Dec 2018
  - ¾ scale width, ½ scale length
  - Developed to satisfy Milestones 6A and 5A
  - Completed 54 thermal cycles and 11 furls before this test campaign



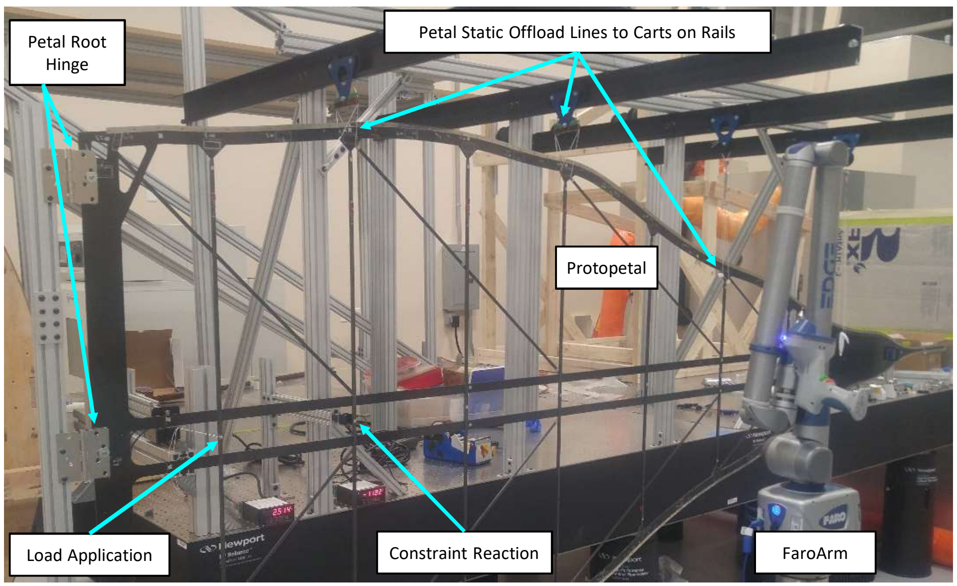
Prototype petal juxtaposed with the fight petal.

The manufactured Protopetal test article.

PROTOPETAL BENDING TEST AND ANALYSIS

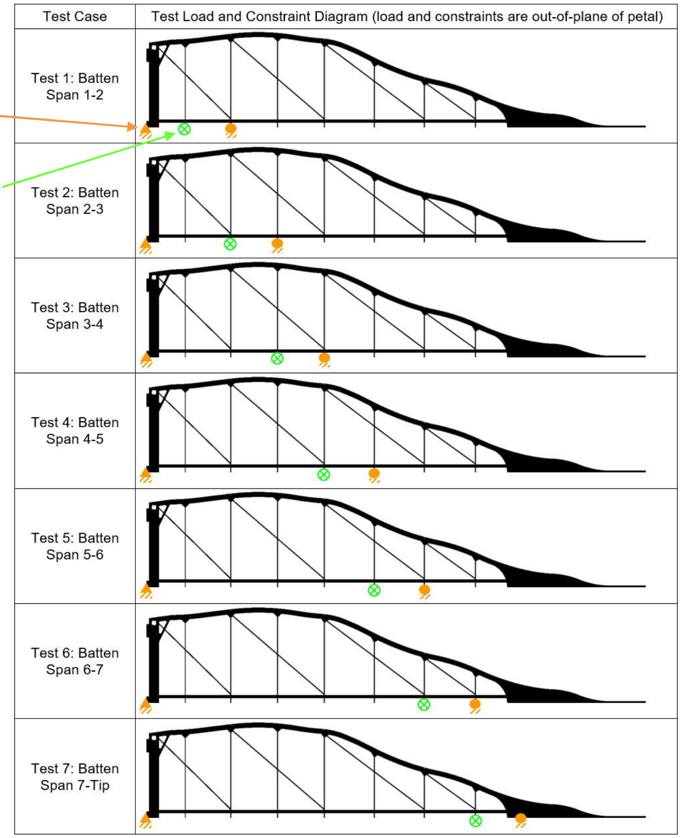
Protopetal 3-Point Bending Test

- **Test objective:** To correlate Protopetal FEM loads and deflection to out-of-plane 3-point bending test.
- **Load applied:** Out-of-plane to one batten at a time. Tested all battens along Protopetal length.
- **Out-of-plane Constraints:** Petal root hinges and batten adjacent to applied load.
- **Vertical Offload:** static lines to carts on rails in direction of loading.
- **Data collection:** Load cells at applied and reaction locations. Laser scan petal displacement.



Protopetal Bending Test Setup

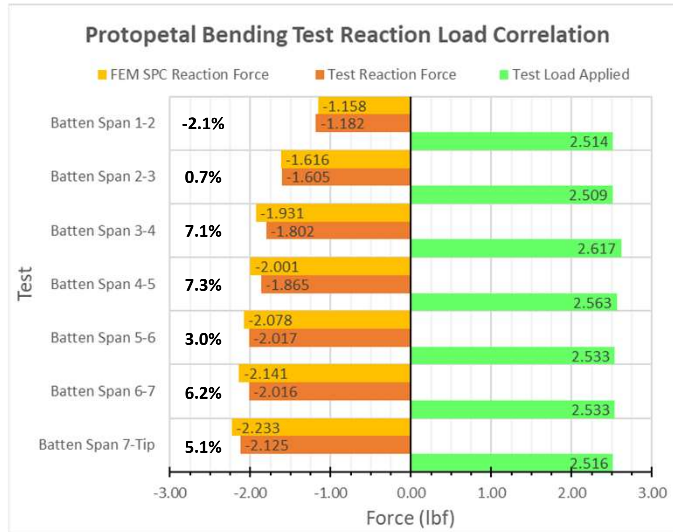
Bending Tests Performed



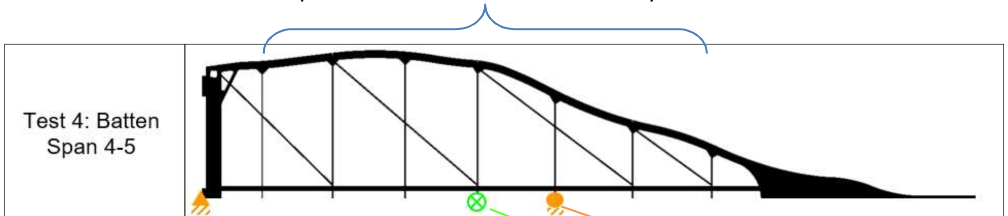
Bending Test Force Correlation

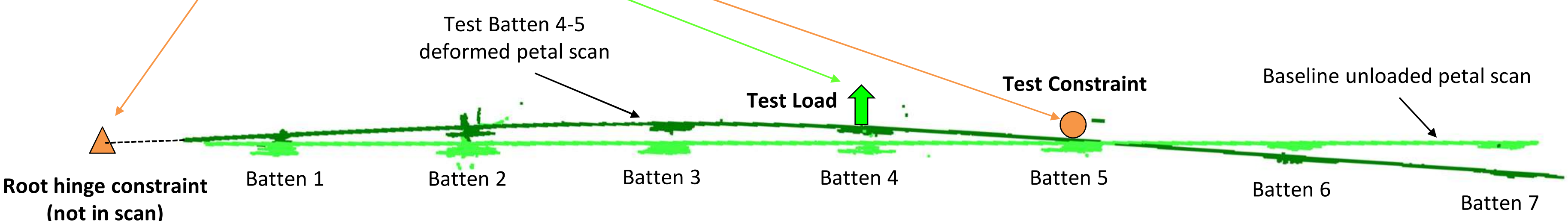
TENDEG

- Test load correlation focused on the reaction load at the constrained batten
- Batten reaction load correlates to within 10%
  - Large displacement nonlinear Nastran FEM



Extent of petal deflection measurement by laser scan





Protopetal Bending Test Laser Scan Point Clouds Comparing Test Span 4-5 with Baseline (looking petal edge-on)

Bending Test Deflection Correlation

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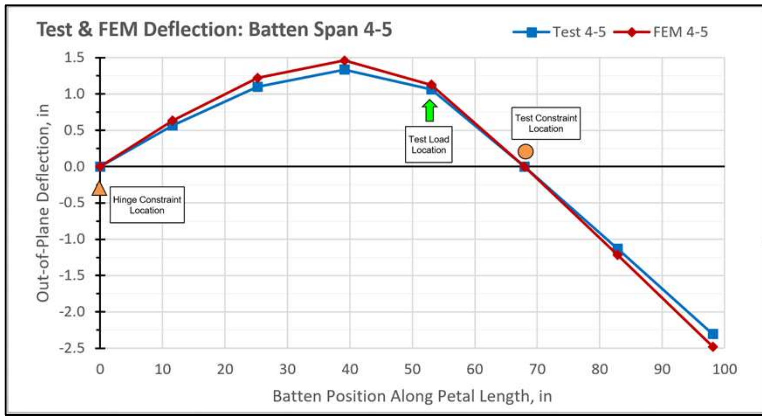
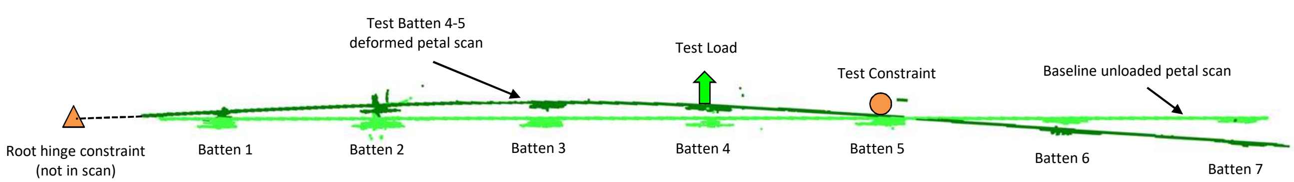
- Test displacement correlation focused on the deflection at the loaded batten
- Displacement of loaded batten correlates within 10%
  - Large displacement nonlinear Nastran FEM
  - Battens between the test constraints correlate to within 20%. Battens beyond constraints are not correlated.



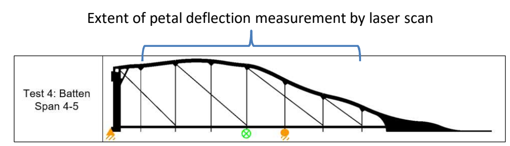
Protopetal Bending Test Deflection Correlation

Test Span	Compare Test to FEM Deflection (%)							
	Batten 1	Batten 2	Batten 3	Batten 4	Batten 5	Batten 6	Batten 7	
Batten Span 1-2	-3.5%	0%*	Deflection of battens beyond the constrained batten are not correlated.					
Batten Span 2-3	6.3%	6.1%	0%*					
Batten Span 3-4	11.4%	9.9%	7.7%	0%*				
Batten Span 4-5	12.3%	11.2%	9.3%	6.2%	0%*			
Batten Span 5-6	7.5%	7.6%	6.7%	5.1%	3.5%	0%*		
Batten Span 6-7	17.6%	16.8%	15.0%	12.7%	10.3%	8.4%	0%*	Orange = constraint
Batten Span 7-Tip	19.3%	18.0%	15.9%	13.1%	10.4%	7.0%	0%*	Green = load

*Note: Test displacement at the constraint points are set to zero and deflection of the petal between them is measured, therefore resulting in perfect correlation at the constraint battens.



Protopetal Bending Test Laser Scan Point Clouds Comparing Test Span 4-5 with Baseline (looking petal edge-on)



PROTOPETAL FURLING TESTS AND ANALYSIS

Furling Test Campaign Overview

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Test	Name	Boundary Condition	Test Temperature	Test Duration	Recovery Duration
Furl Test #1	DrumRT	On drum	Room Temp.	2 weeks	1 week
Furl Test #2	Drum40C	On drum	40 °C	2 weeks	2 weeks
Furl Test #3	InterfacesRT	On cart/snubbers interfaces	Room Temp.	2 weeks	5 weeks
Furl Test #4	Interfaces40C	On cart/snubbers interfaces	40 °C	2 weeks	9 days

Furl Test 1 - DrumRT

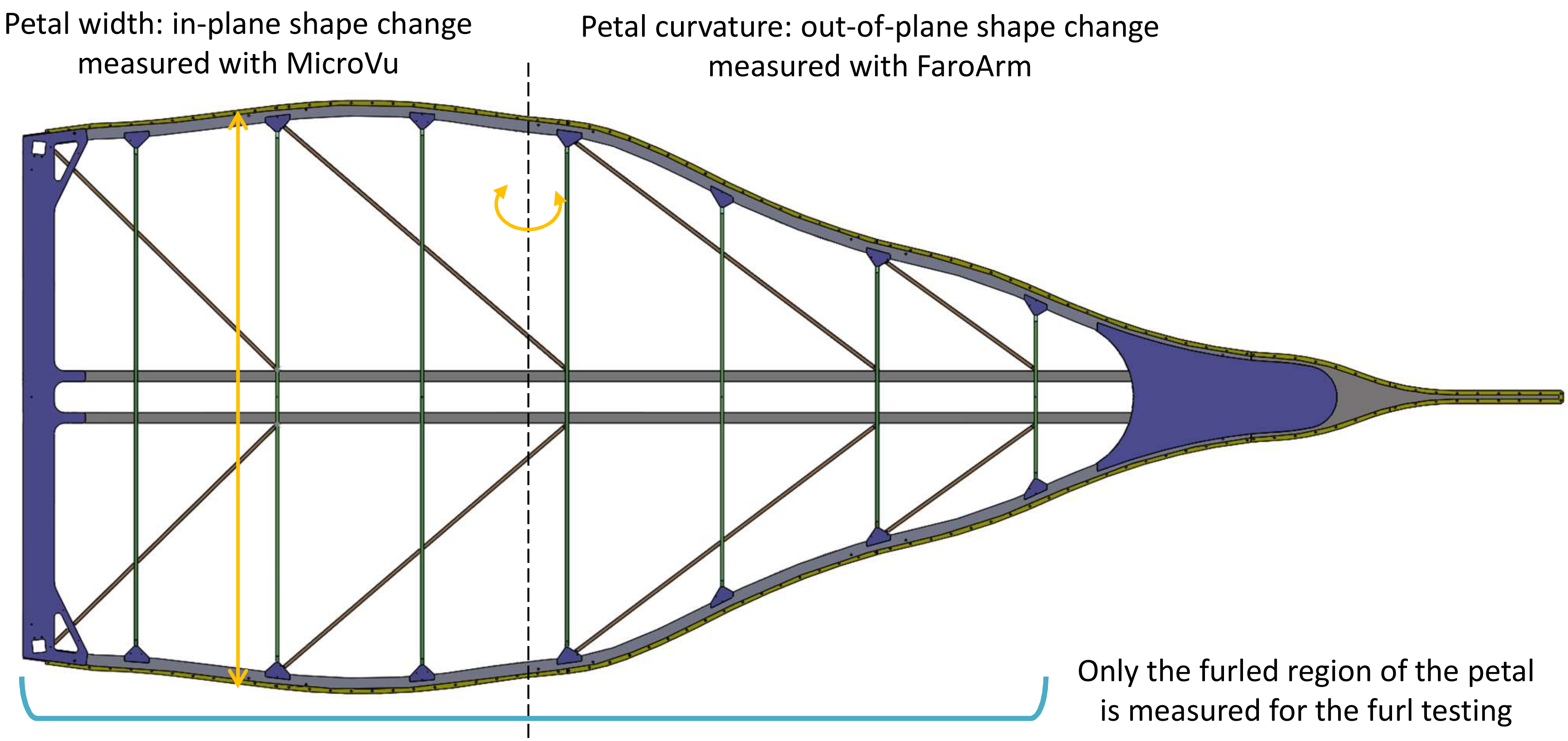
Furl Test 2 – Drum40C

Furl Test 3 - InterfacesRT

Furl Test 4 – Interfaces40C

Pathfinding test campaign – each test builds in complexity

Furl Test Objective: Measure Petal Shape Change



Test/Metrology Order of Operations

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Pre-test FaroArm Scan (out of plane)

Petal curvature: out of plane shape change

Same or next day

Furl Test

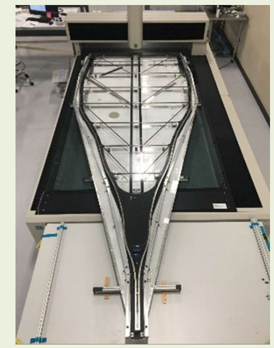
2 weeks

Immediately after unfurl

Post-test FaroArm Scan (out of plane)

Same day

Post-test MicroVu Scan (in plane)



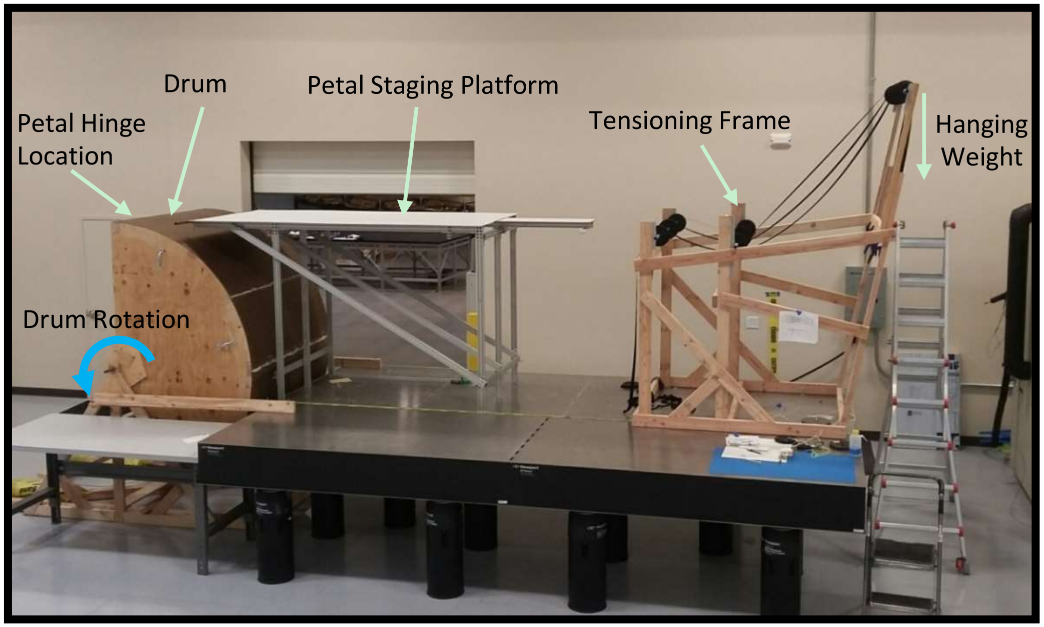
1-5 weeks

Recovery Period

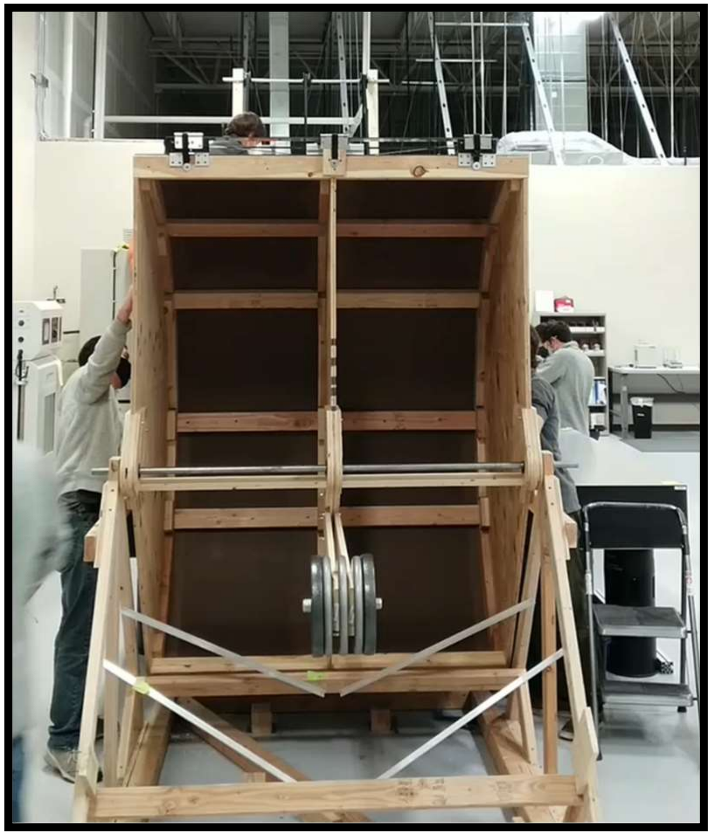
Post-recovery FaroArm Scan (out of plane)

Test Setup: Protopetal Furling Rig

Drum diameter (Ø) is 2.25 m, equal to stowed truss Ø.
The smallest potential furl Ø that the petal, smallest Ø of stow spiral.



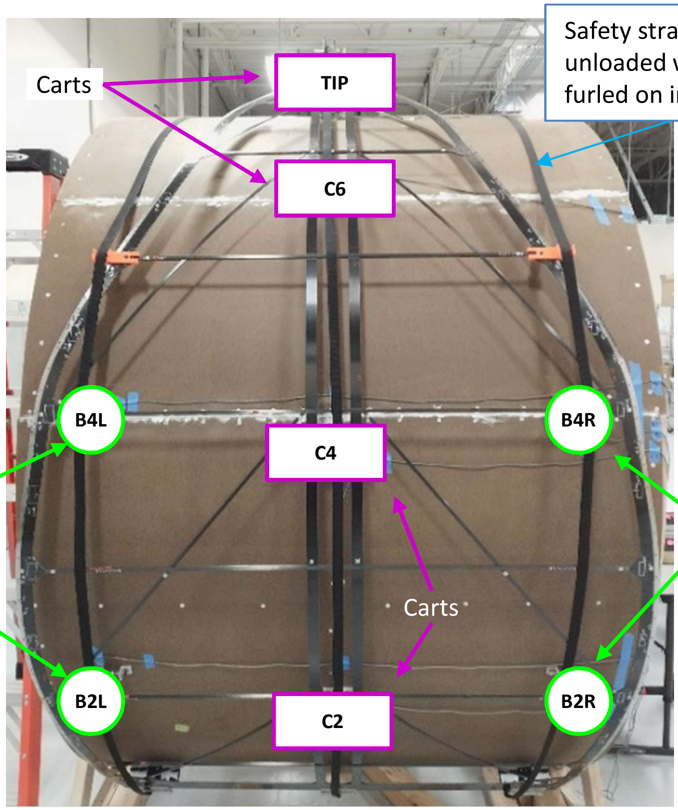
Full petal furling rig system



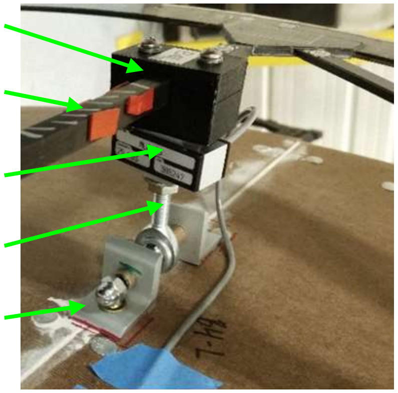
Example video of petal furling operation for Test 3

Test Setup: Petal Interface Loads

TENDEG



Petal cart and batten snubber interface and loadcell locations



Snubber on Petal Batten with Loadcell

Cart on Petal Spine with Loadcell

Test Analysis: Nastran FEM Model

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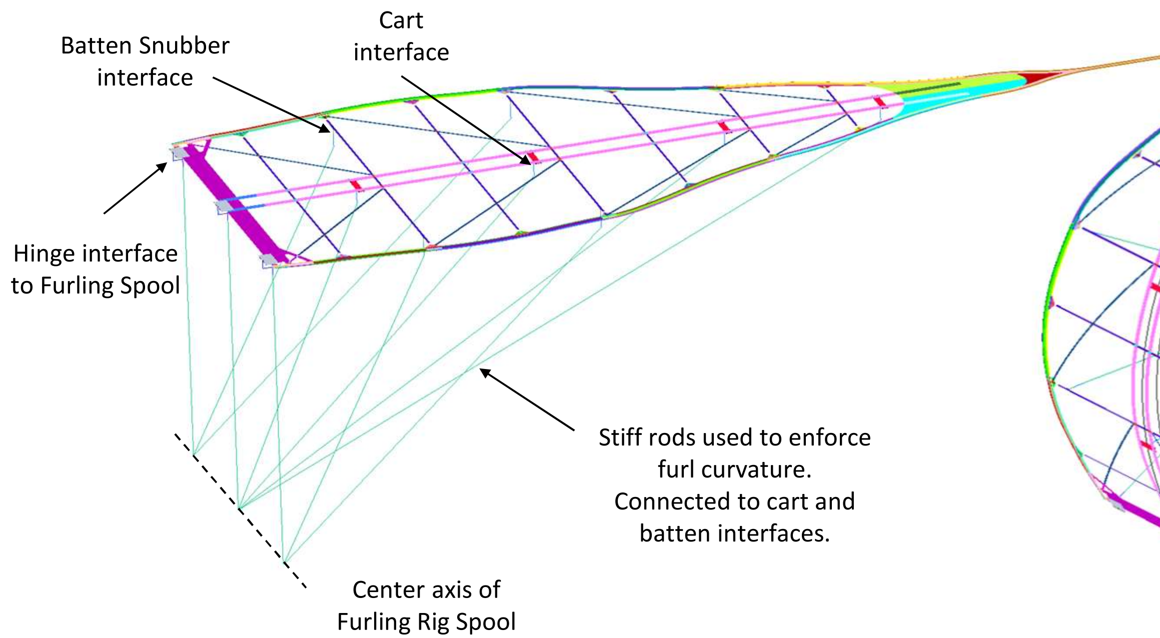
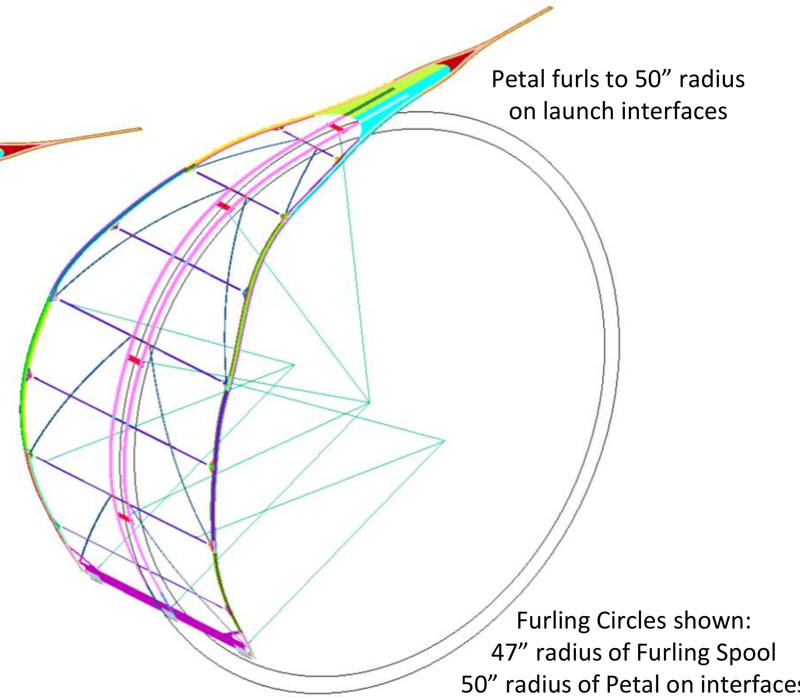
- Furl FEM builds on the correlated FEM from 3-point bending test
- Cart and snubber interfaces are added
- Rods are used to enforce the curvature to the flat petal

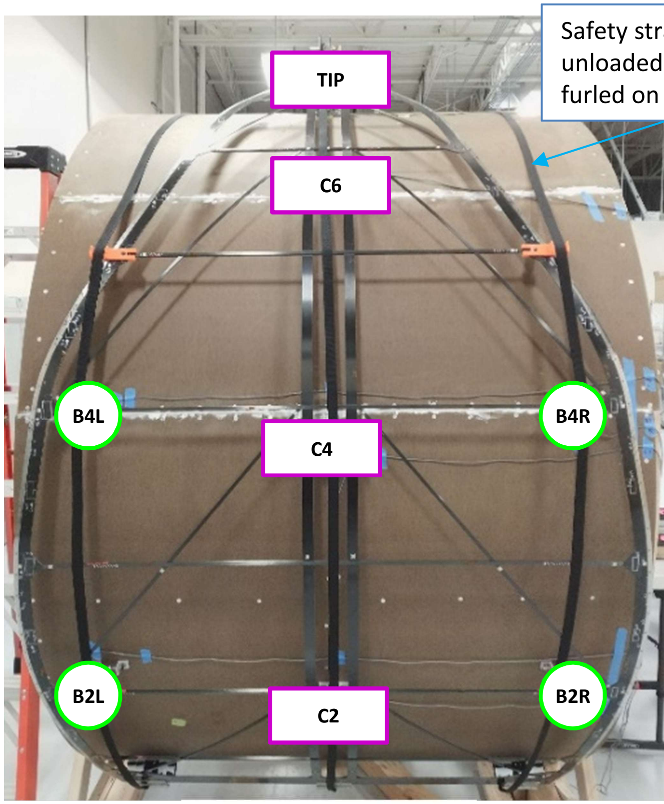


Protopetal Nastran Furl FEM Prior to Furling



Protopetal FEM Furled on Launch Restraints

Test Analysis: Interface Loads Correlation

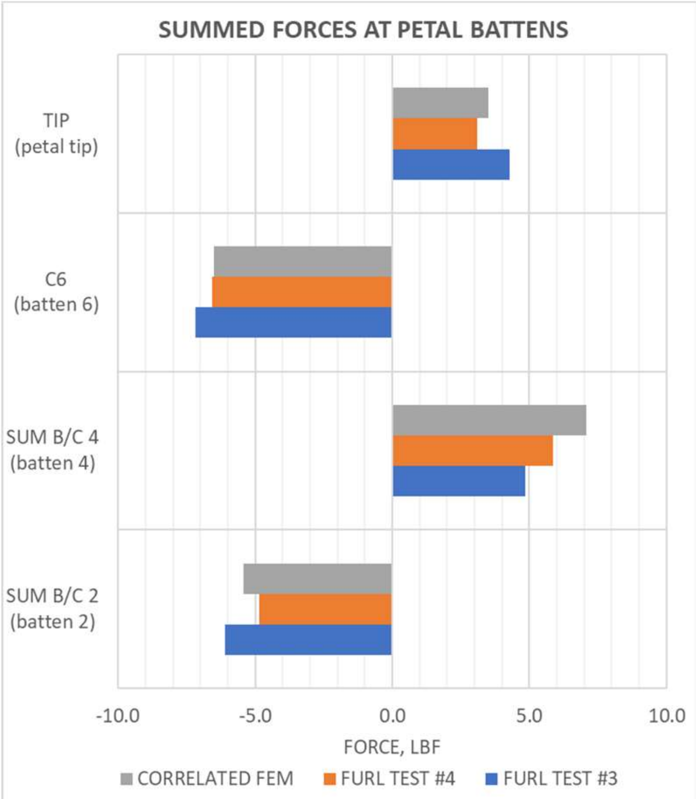


Safety straps unloaded when furled on interfaces

Sum forces at batten load cells B4L + C4 + B4R

Sum forces at batten load cells B2L + C2 + B2R

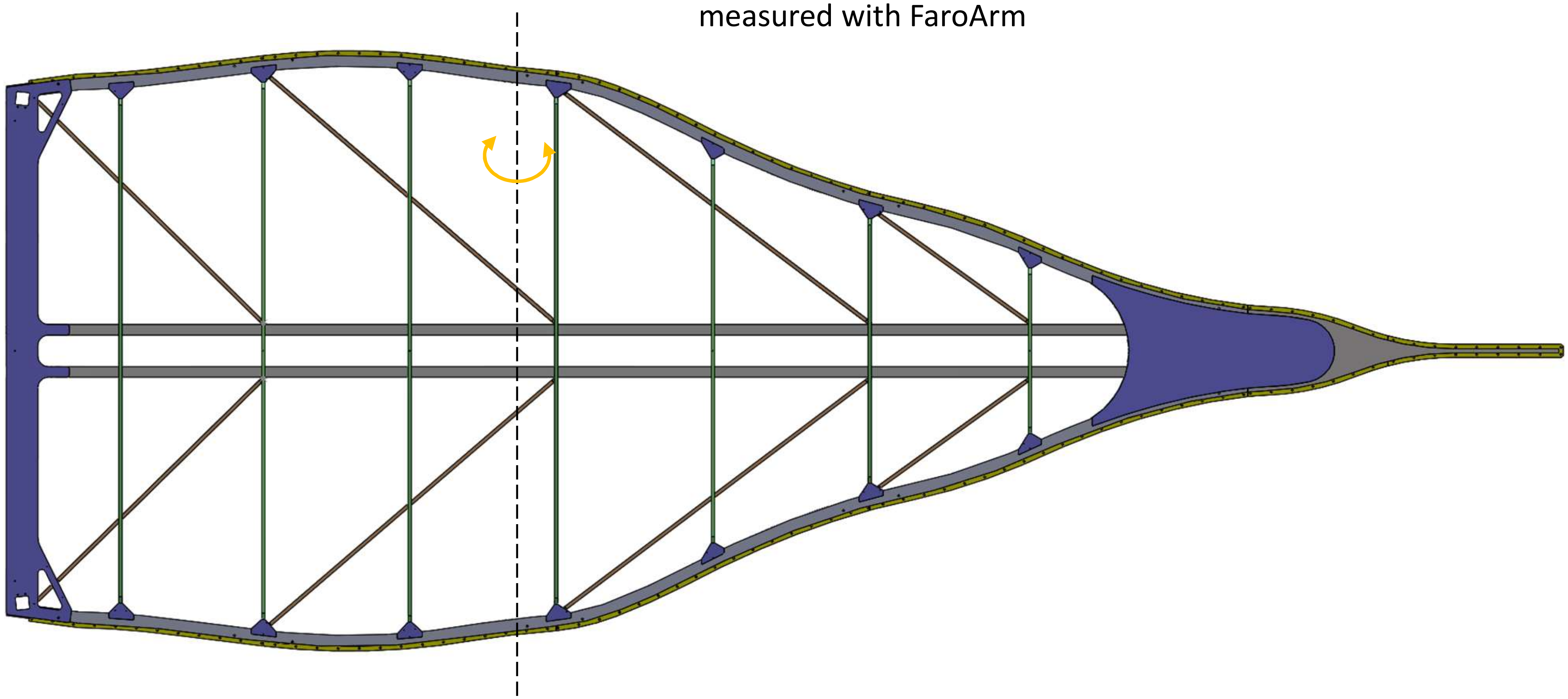
Loadcell Locations



Furl Test Summed Forces Compared to FEM

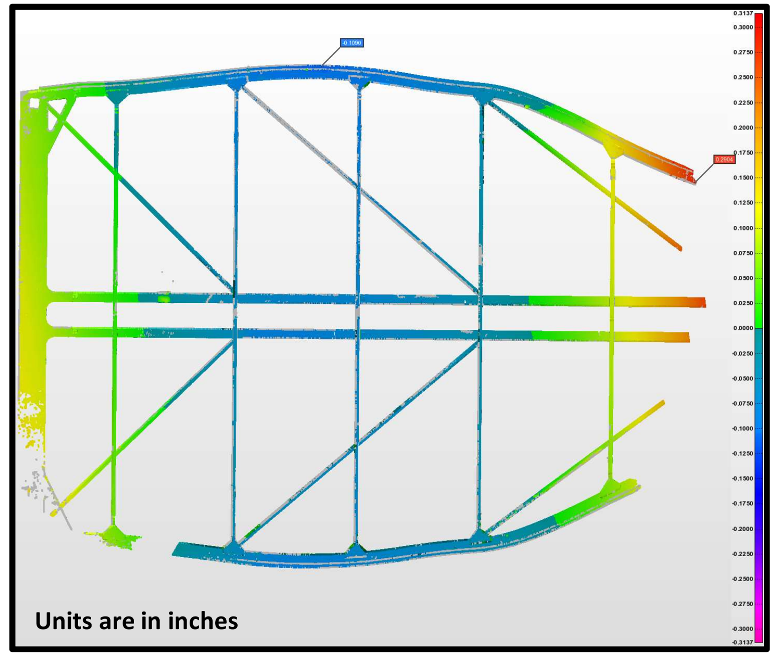
Petal Curvature: Out-of-Plane Shape Change

Petal curvature: out-of-plane shape change
measured with FaroArm



Test Metrology: FaroArm Scans

Protopetal hanging vertically on static offload for FaroArm scans and Recovery periods



PolyWorks point cloud example: Pre-Test 4 to Post-Test 4. Blue indicates where petal is closer out of plane in Post-Test 4, red is where the petal is further away

Furl Test Results: Petal Curvature Change

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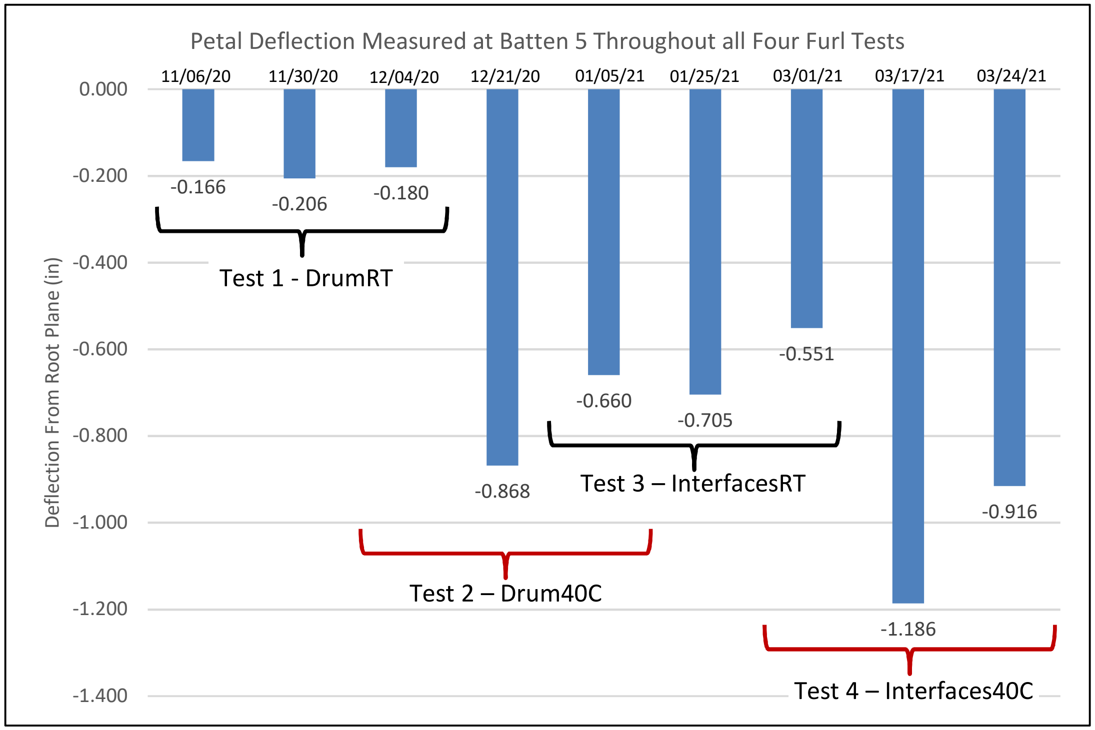
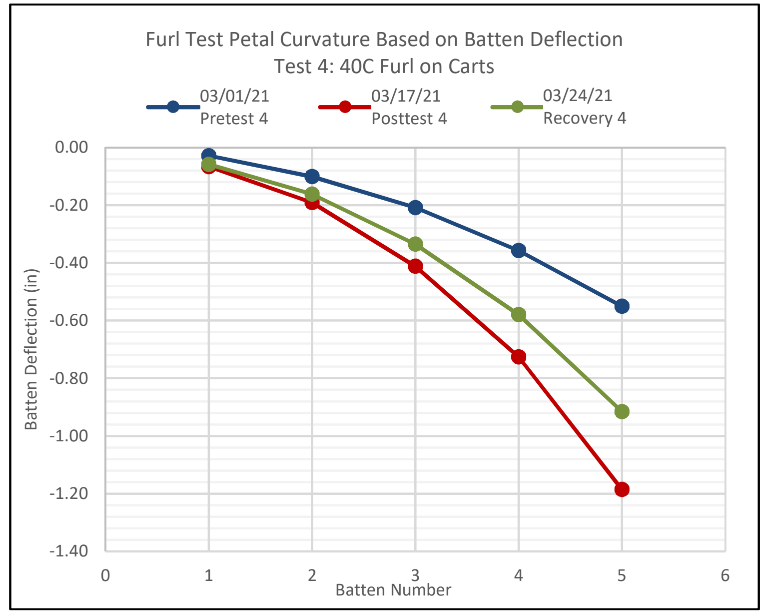
- Petal deflection is reported at each batten throughout the test campaign
  - Deflection measured at Batten 5 shown as example

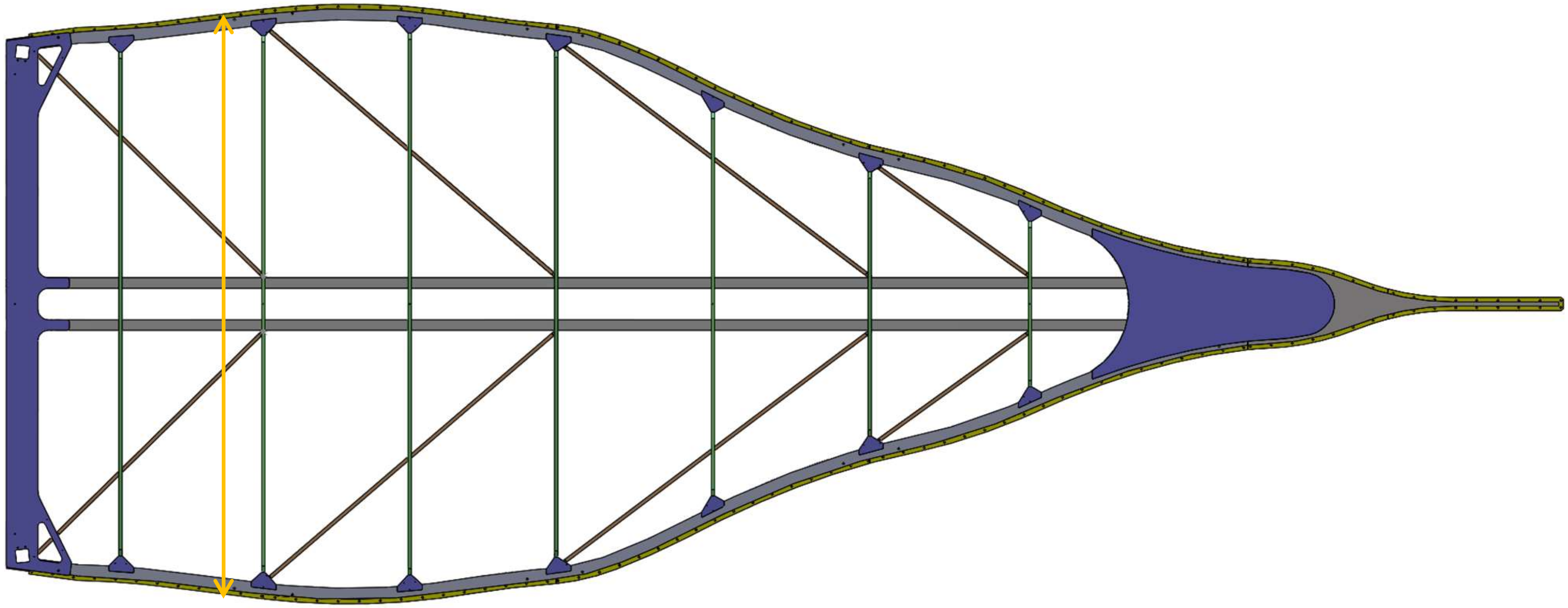




Extrapolating out to an 8 meter petal would be significant deflection (10-28 inches). Note that is without Pop-Up Ribs which provide significant out of plane stiffness that flattens the petal.

Petal Width: In-Plane Shape Change

Petal width: in-plane shape change
measured with MicroVu

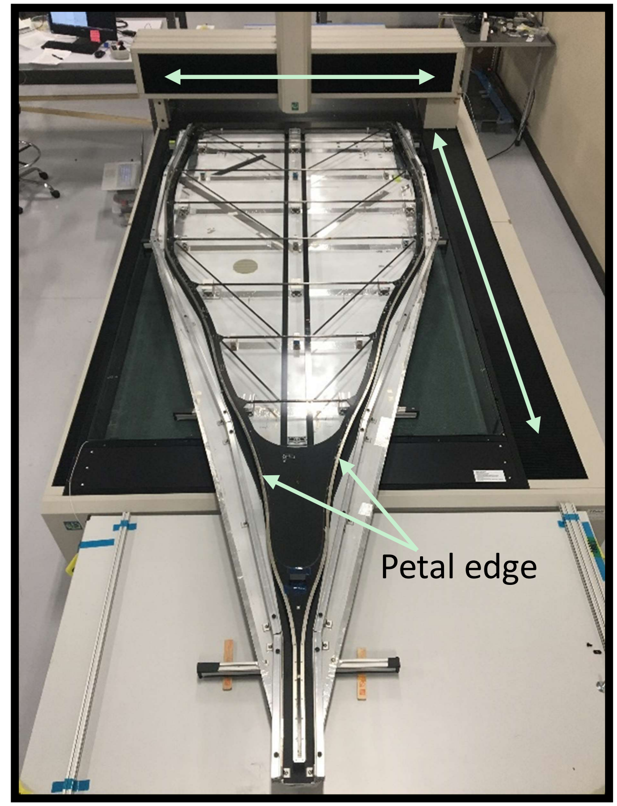


Test Metrology: MicroVu Scans

- MicroVu Excel 250ULC machine
  - Microscope mounted on (x, y) translation stages
  - InSpec software detects 2D location of part edges

- Stated raw measurement accuracy is $\epsilon = 5.5 + \frac{L}{300} = 14\ \mu m$ for the petal base (where L is in mm)
  - Error expression accounts for error due to thermal strain of the linear encoders
  - Additional post-processing was developed for Milestone 5A to compensate for this using temperature data from 6 MicroVu-mounted RTDs

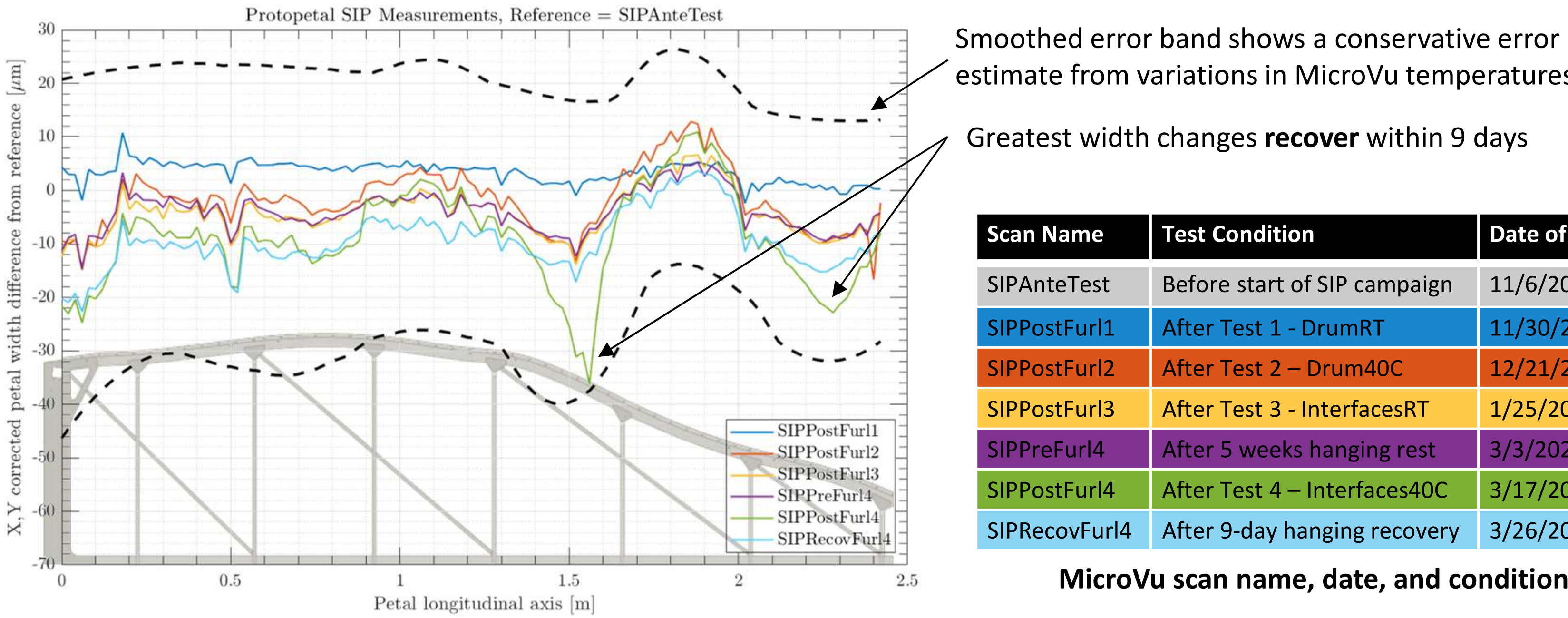
- The same post-processing from Milestone 5A is applied to this test campaign



The Protopetal during base scans on the MicroVu

Protopetal Petal Width Change

TENDEG



Total petal width change, differenced from the first MicroVu scan, SIPAnteTest

Scan Name	Test Condition	Date of Scan
SIPAnteTest	Before start of SIP campaign	11/6/2020
SIPPostFurl1	After Test 1 - DrumRT	11/30/2020
SIPPostFurl2	After Test 2 – Drum40C	12/21/2020
SIPPostFurl3	After Test 3 - InterfacesRT	1/25/2021
SIPPreFurl4	After 5 weeks hanging rest	3/3/2021
SIPPostFurl4	After Test 4 – Interfaces40C	3/17/2021
SIPRecovFurl4	After 9-day hanging recovery	3/26/2021

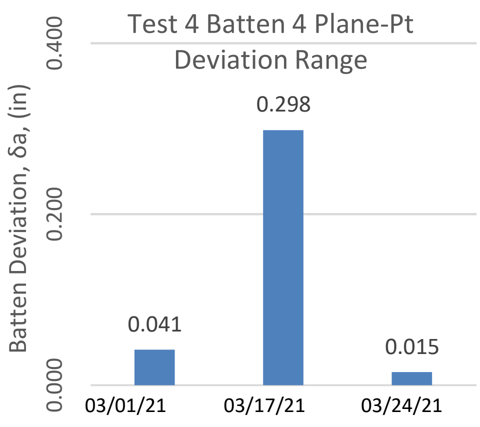
MicroVu scan name, date, and condition

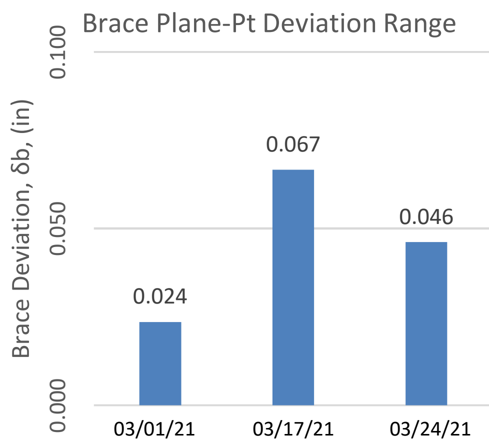
KPP5 suballocation for creep is ± 20 ppm (ground stowage)
Measured median petal width bias equals -8 ppm

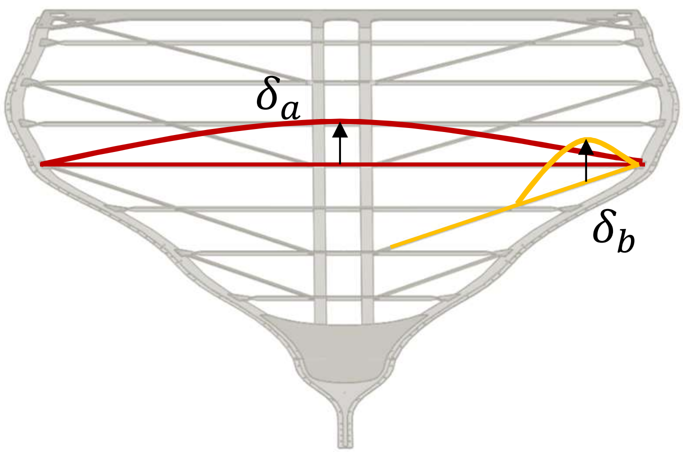
Petal Width Change Observations

- Out of plane batten and brace bowing was observed and measured in FaroArm scan data
- Petal curvature about the longitudinal axis would directly impact petal width
- Batten shape recovered after 1 week rest

For $\delta_a = 0.015$ in, the petal width change $\delta PW = -6.4$ µm



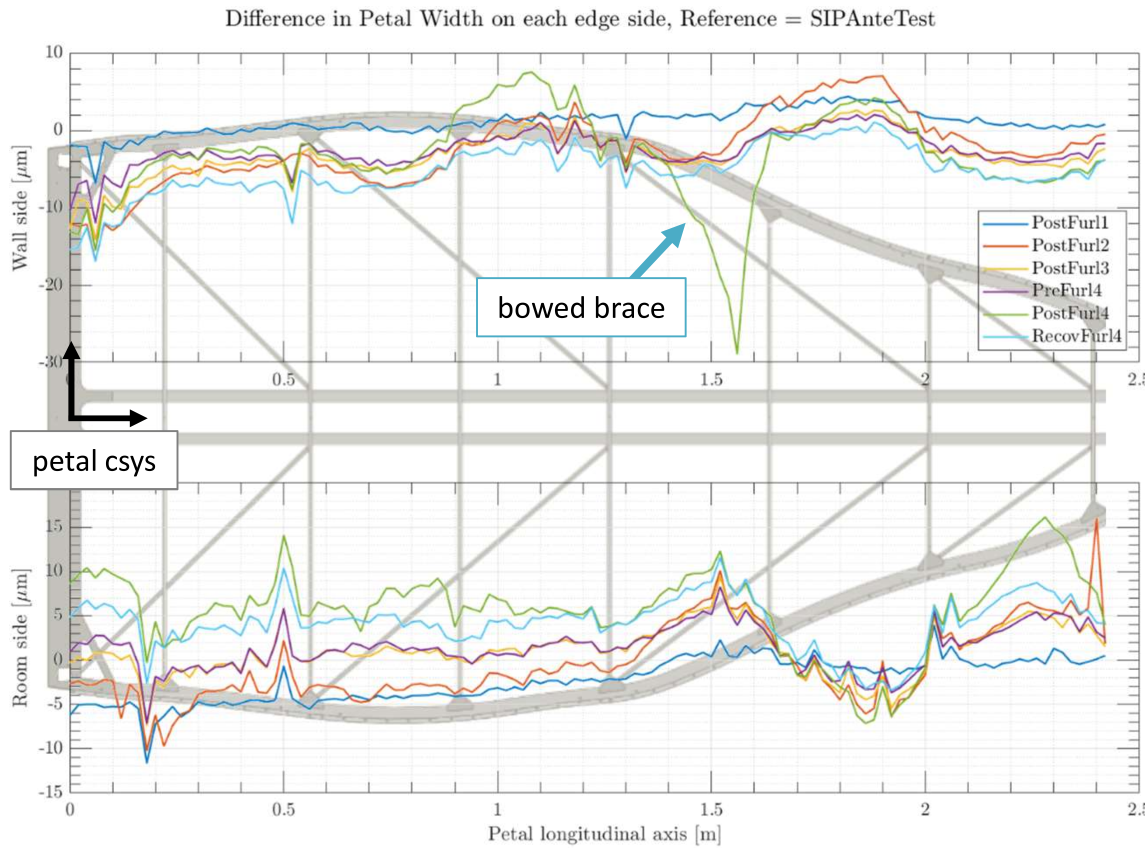




Unexpected batten and brace creep was measured but seen to recover after 1 week

Petal Width Change Relative to Each Edge

- Greatest petal width change **coincides** with location of a bowed brace
- Slight asymmetric alignment of the petal on the interfaces may have bowed this brace
- Pultruded battens and braces are off-the-shelf, non-flight, and have unknown matrix materials
  - Not representative of flight petal components



Petal width change on each edge side as expressed in petal coordinate system (csys), therefore petal is shrinking on both sides

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JOINT COUPON TESTING AND ANALYSIS

Joint Coupon Test Overview

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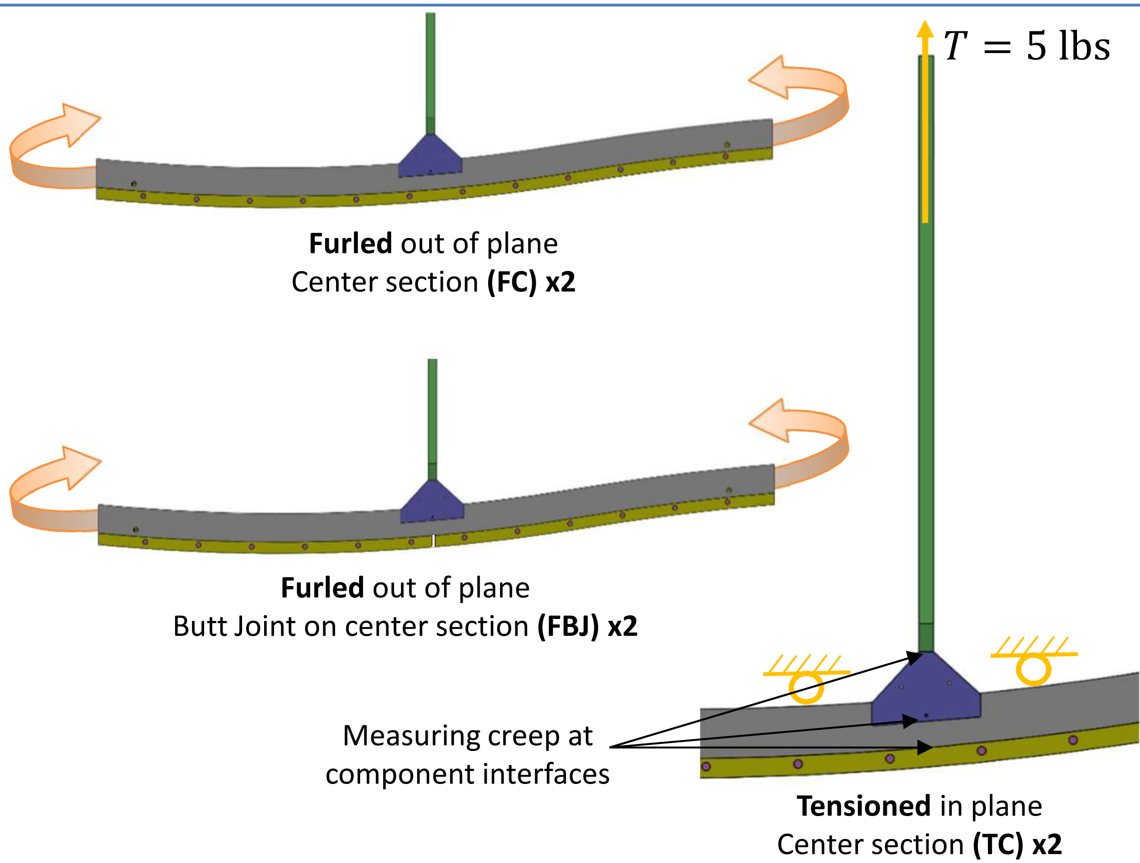
- **Joints may drive creep due to additional adhesive layers**
- Break out joint assemblies are made to study creep from the joint design
  1. Furled Center Section (FC) x2
  2. Furled Butt Joint (FBJ) x2
  3. Tensioned Center Section (TC) x2
- Two Tests
  - Held in loaded configurations
  - At constant 40C hot soak
  - For 1 and 2 weeks (Test 1 and 2)
- Measuring creep
  - In plane: **relative displacement** at the joint component interfaces
  - Out of plane: In the furled edges



Joint Coupon Test Articles

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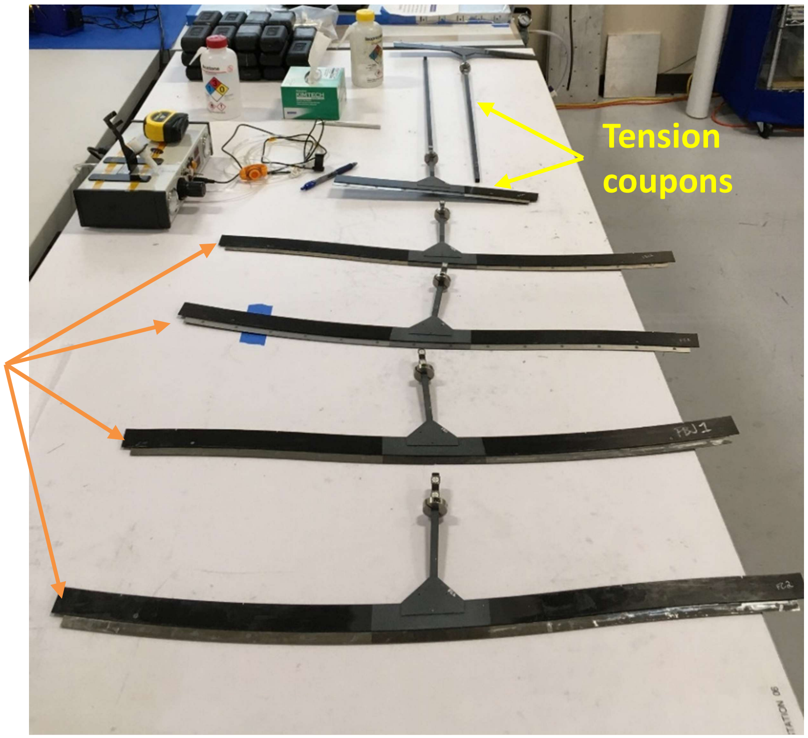
- Fabricated using the same procedures as the Protopetal
- Thermal cycled to match the Protopetal pre-conditioning
- Friction collar for DIC imaging positioning
- Speckled at joint region for DIC imaging

Coupon dry fit onto Protopetal fabrication fixtures

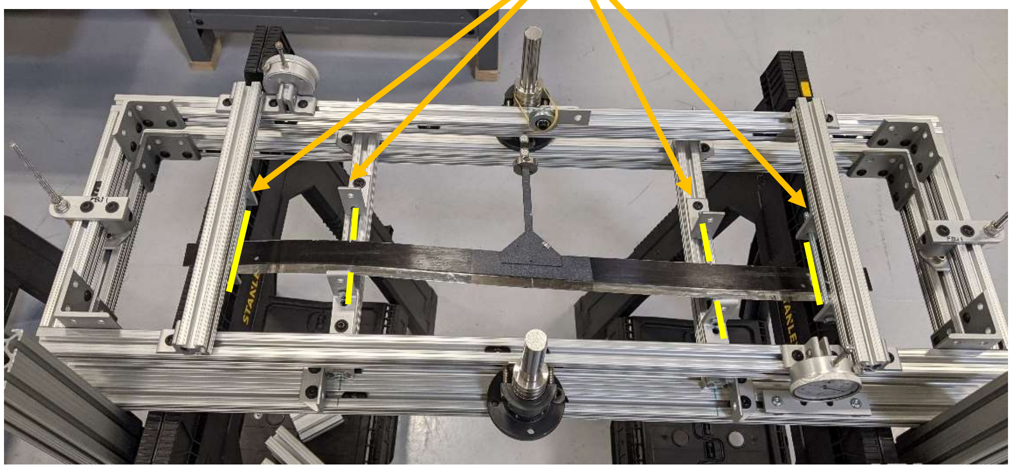


Completed joint coupon test articles

Joint Coupon Load Frames

TENDEG

4-point bending
test load frame



Example of a 4 point bending test load frame with joint coupon

Springs apply
tension load
to batten

Load reacted
at pins on
edge CFRP

Example of a tension test load frame with joint coupon

Joint Coupon Test Campaign Overview

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Test	Test Temperature	Test Duration	Recovery Duration
Coupon Test #1	40 °C	1 week	1 week
Coupon Test #2	40 °C	2 weeks	1 week

Order of Operations

Faro/DIC Pre-test Scan

Load Fixture

1-2 week Hot Soak

DIC within 5 minutes
Faro within 20 minutes

Faro/DIC Post-test Scan

Test 1:
2 Additional DIC image set

1 Week Recovery

Faro/DIC Post-recovery Scan

Joint Coupon Bend Test FEM Correlation

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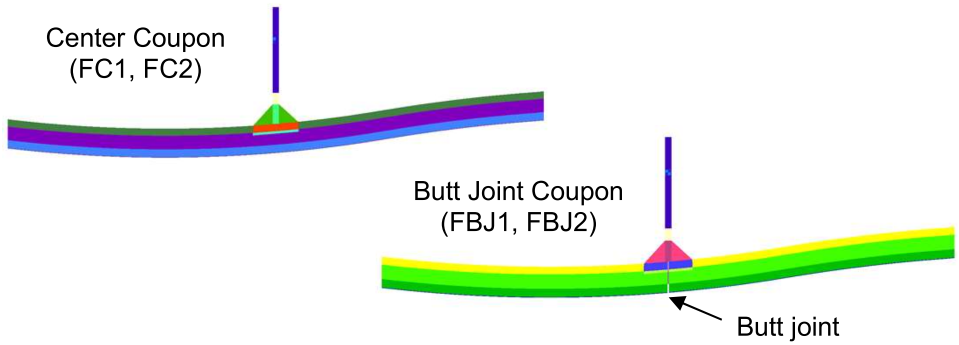
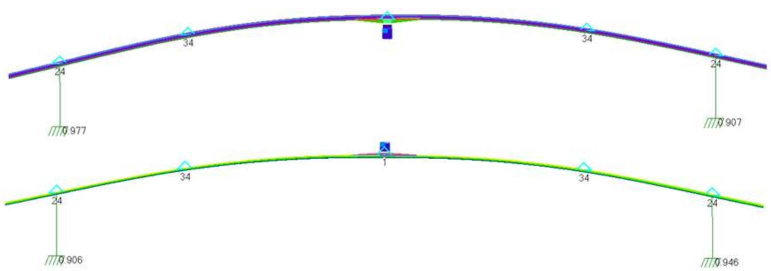
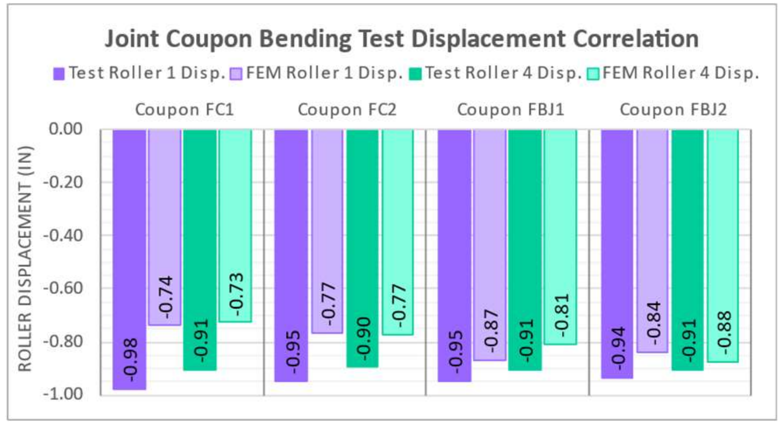
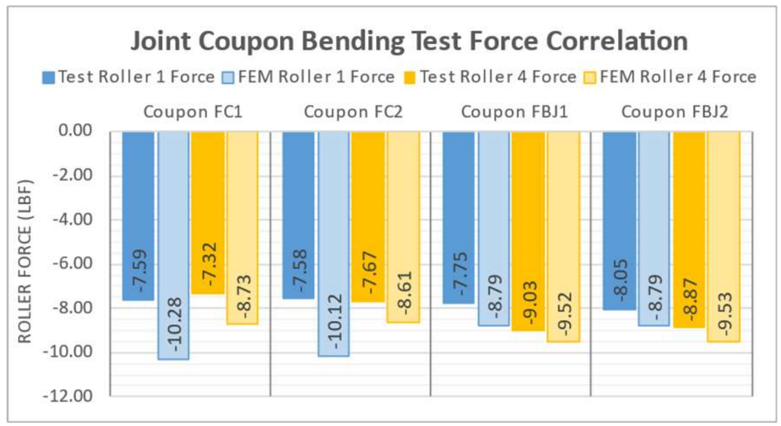


Creep Coupon Bend Test Models Extracted from Protopetal FEM



Coupon Bend Test FEM with Enforced Deflection and Constraints





Out of Plane Metrology: FaroArm Scans

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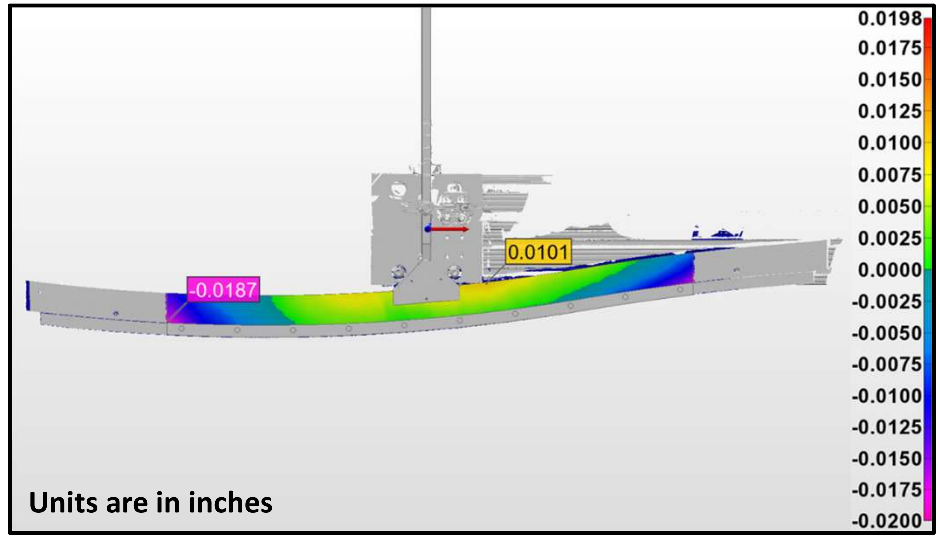
- FaroArm scan generates a point cloud
- Point cloud is reduced to just the Structural Edge section
- Point cloud is compared to CAD to determine out of plane deflection



PolyWorks example: FC1 coupon after Test 2 compared to CAD. The (+) indicates area is closer out of plane, (-) is further away out of plane. Units are in inches

Bending Coupon Curvature Results

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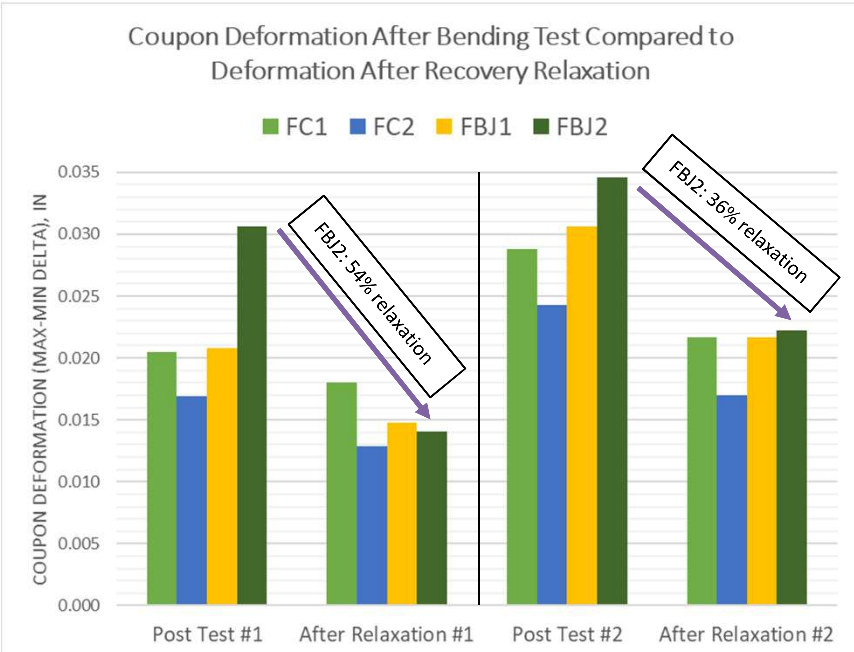
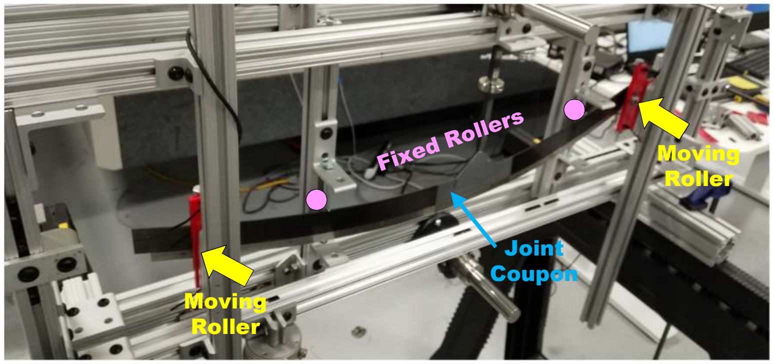


Coupon test 1: 40C for 1 week | Coupon test 2: 40C for 2 weeks

Joint coupons demonstrate a set out of plane deformation immediately after test that reduces after relaxation



Joint coupon in a bending test load frame

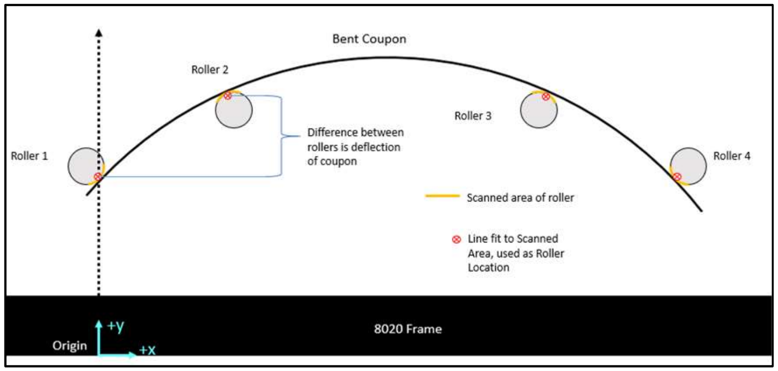


Diagram of a bending test joint coupon in a load frame with reference points used to measure applied deflection

Metrology: Digital Image Correlation (DIC)

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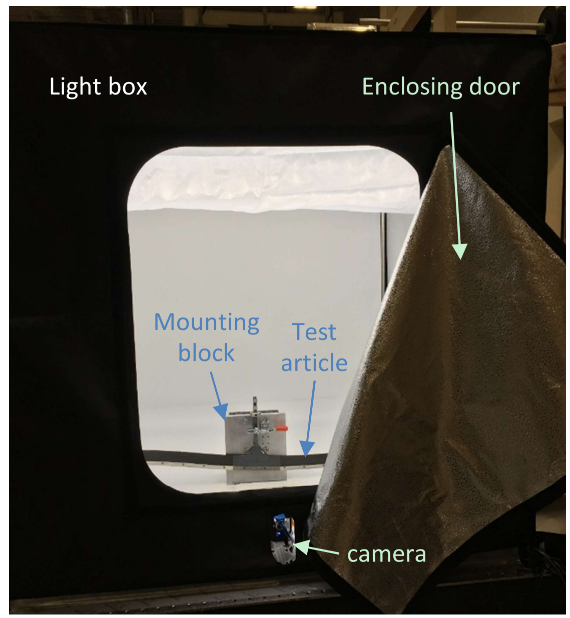
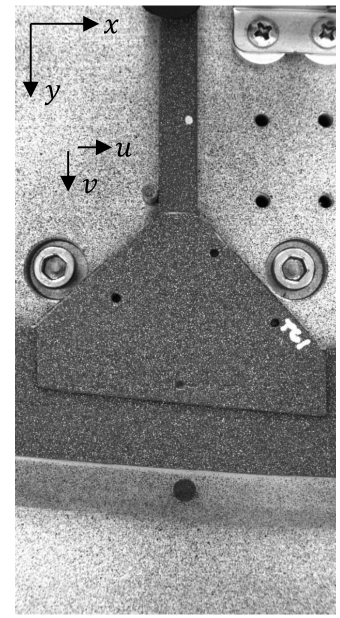
- Thorlabs Kiralux 8.9 MP Monochrome CMOS camera
  - Global shutter
  - 4096 x 2160 px sensor
  - Sensor size: 14.131 mm x 7.452 mm
  - Pixel size: 3.45 µm x 3.45 µm
- Ncorr Processing Software
  - Open source, Matlab GUI
  - Processes images subject to user input parameters, outputs u, v displacement or strain heat maps
  - Static images indicate < 0.015 px error from correlation and noise error
- **Raw DIC error $\epsilon_i = 0.8\ \mu m$**
  - From correlation, out of plane distortions, and µm/px knowledge



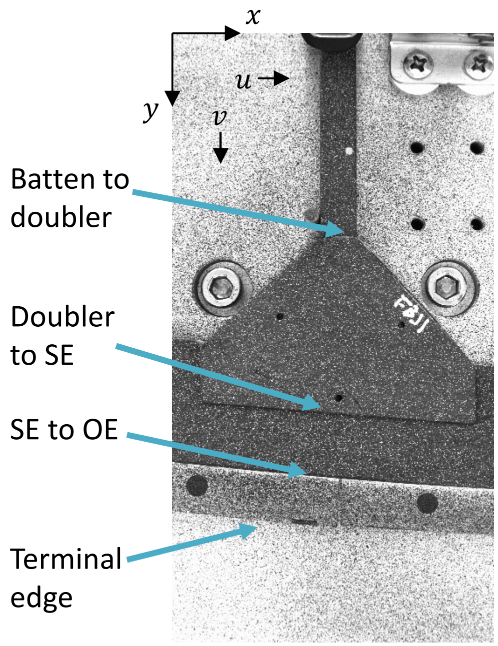
DIC imaging station



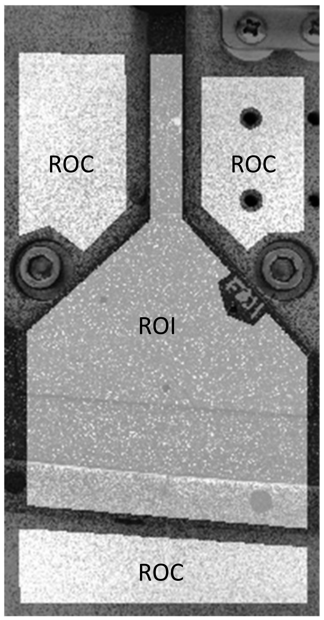
Resulting DIC image

DIC Post Processing for Creep Analysis

- DIC Images are taken with days/weeks between
- Camera drift conditions can change significantly over that time, resulting in pixels of error
- Here we apply the Generalized Compensation Method from Bing Pan's paper, "High-accuracy 2D digital image correlation measurements using low-cost imaging lenses: implementation of a generalized compensation method."
  - Corrects DIC analysis error by evaluating camera drift parameters from undeformed Regions of Compensation (ROC)
  - u is the deformation in x direction
  - v is the deformation in y direction
- Relative displacement differenced in 0.5 mm steps
  - With differencing, $\boldsymbol{\epsilon_d = 2\epsilon_i = 1.6}$ $\mu\boldsymbol{m}$
  - Additionally, the residuals of the postprocessing are $\boldsymbol{\epsilon_{res}} \sim \mathbf{0.1 - 0.7}$ $\mu\boldsymbol{m}$



Reference image



Region of Interest (ROI) and Region of Compensation (ROC) definitions

DIC Results: Test 1 Relative Displacement

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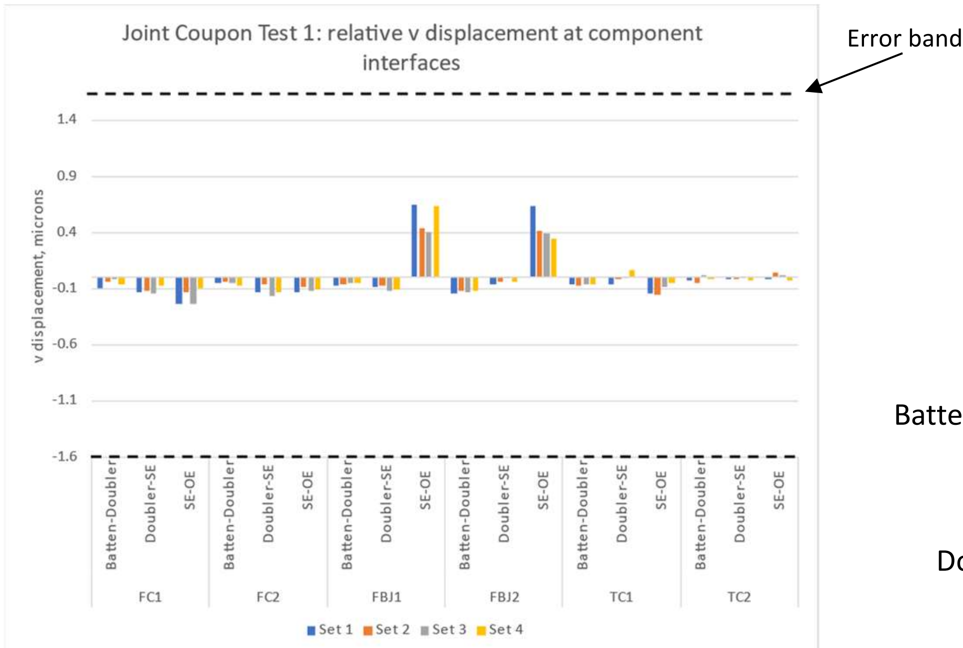
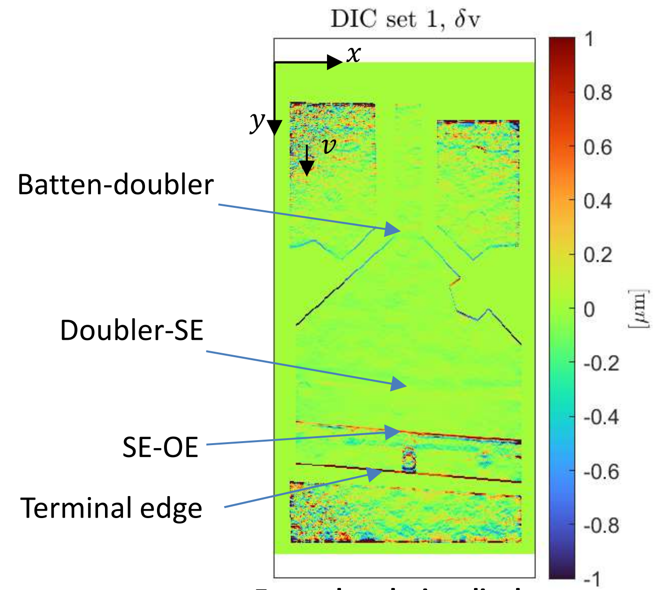


Relative displacement in the y axis at component interfaces for test 1 data

Image reference name	Date imaged
Pretest	2/12/2021
Set 1	2/22/2021
Set 2	2/24/2021
Set 3	2/26/2021
Set 4	3/1/2021

Imaging dates for Test 1 DIC images

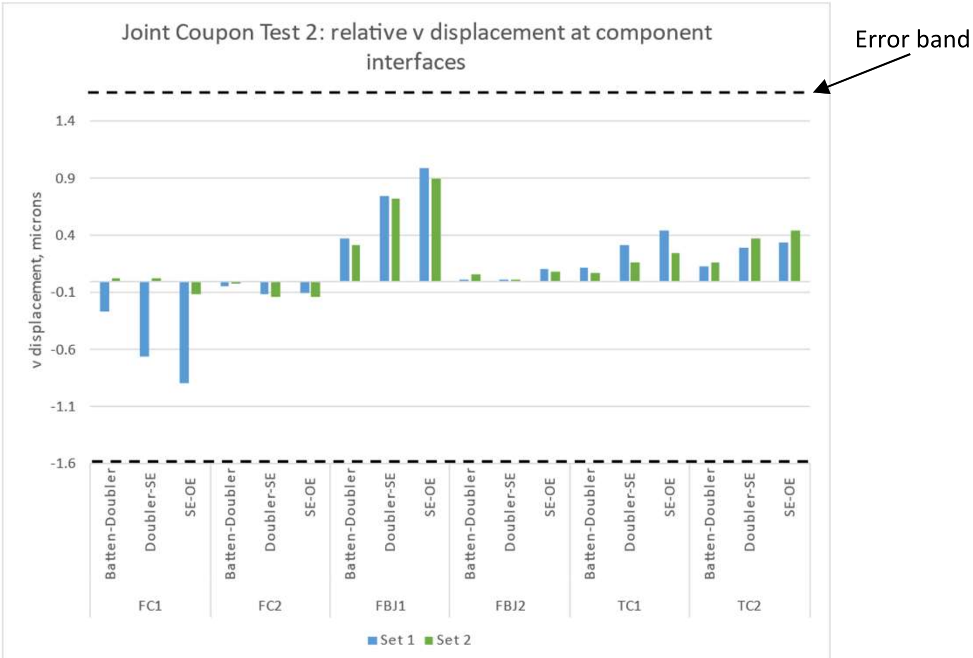


Example relative displacement DIC results for FBJ1 Test 1

All changes measured at **≤ 1 micron** – Joint design does not drive creep in petal width!

DIC Results: Test 2 Relative Displacement

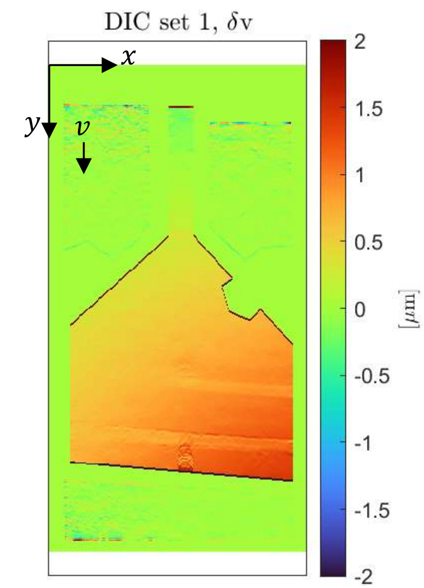
TENDEG



Relative displacement in the y axis at component interfaces for test 2 data

Image reference name	Date imaged
Pretest	3/1/2021
Set 1	3/19/2021
Set 2	3/26/2021

Imaging dates for Test 2 DIC images



Example relative displacement DIC results for FBJ1 Test 2

All changes measured at **≤ 1 micron** – Joint design does not drive creep in petal width!

In Summary

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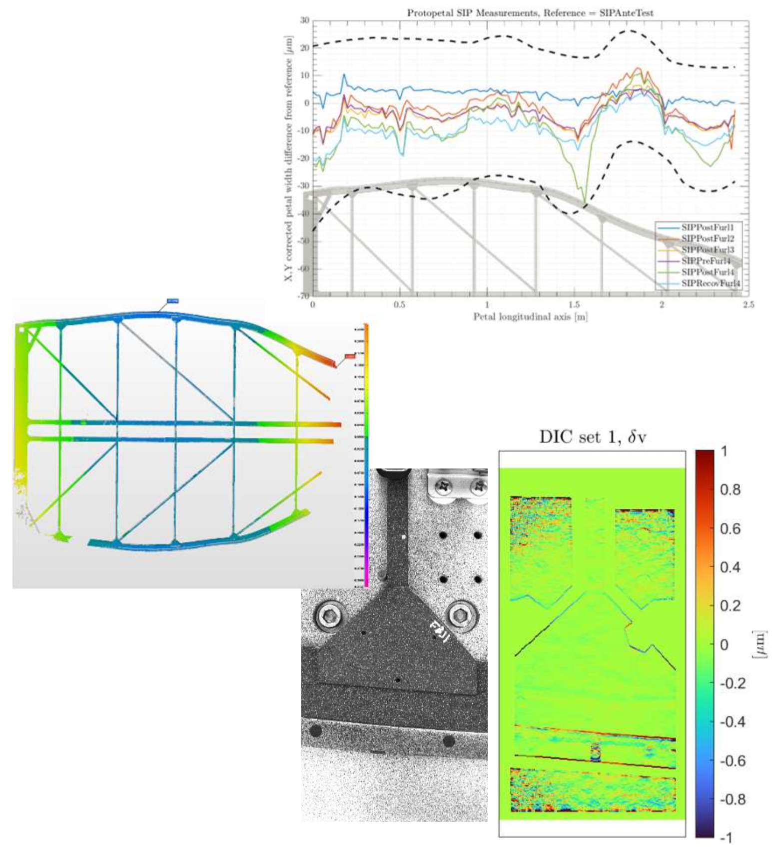
1. Petal width changes measured throughout test campaign are **within the KPP5 Budget of ± 70 microns (manufacturing, AI&T, storage)**
   - Suballocation for creep is ± 20 ppm (ground stowage)
     - **Measured median petal width bias equals -8 ppm**
   - Greatest petal width changes may be due to bowing in off-the-shelf, non-flight, pultruded battens and braces
   - Greatest petal width changes also show signs of rapid **creep recovery**
2. Joint design is determined **to not be a driver** of petal width creep, despite additional adhesive layers
   - Local joint coupon width change measured **≤ 1 micron**
3. Out-of-plane creep from furling is measured at both the petal and coupon level
   - Pop-up ribs will counteract this effect
4. Analysis **successfully correlated** petal and joint stiffnesses, as well as the petal interface forces



Future Work and Recommendations

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- This empirical study was focused on adhesive layers at joints, edges and spines and the results suggest testing and characterization are required for the battens and braces
- Future creep testing should include:
  - Carts and batten snubbers
  - Pop-up ribs
  - Optical shield
- Creep effects in the flight petal should be understood and **verified to be within budget**
  - To be addressed in Milestone 5B
  - A detailed viscoelastic analytical model should be correlated to system level test results

4-meter Protopetal

Thank you for your attention.

QUESTIONS?