Modeling Starshade Petal Dimensional Stability

Starshade to TRL 5 (S5)
Starshade Science and Industry Partnership (SIP)

12/17/2020

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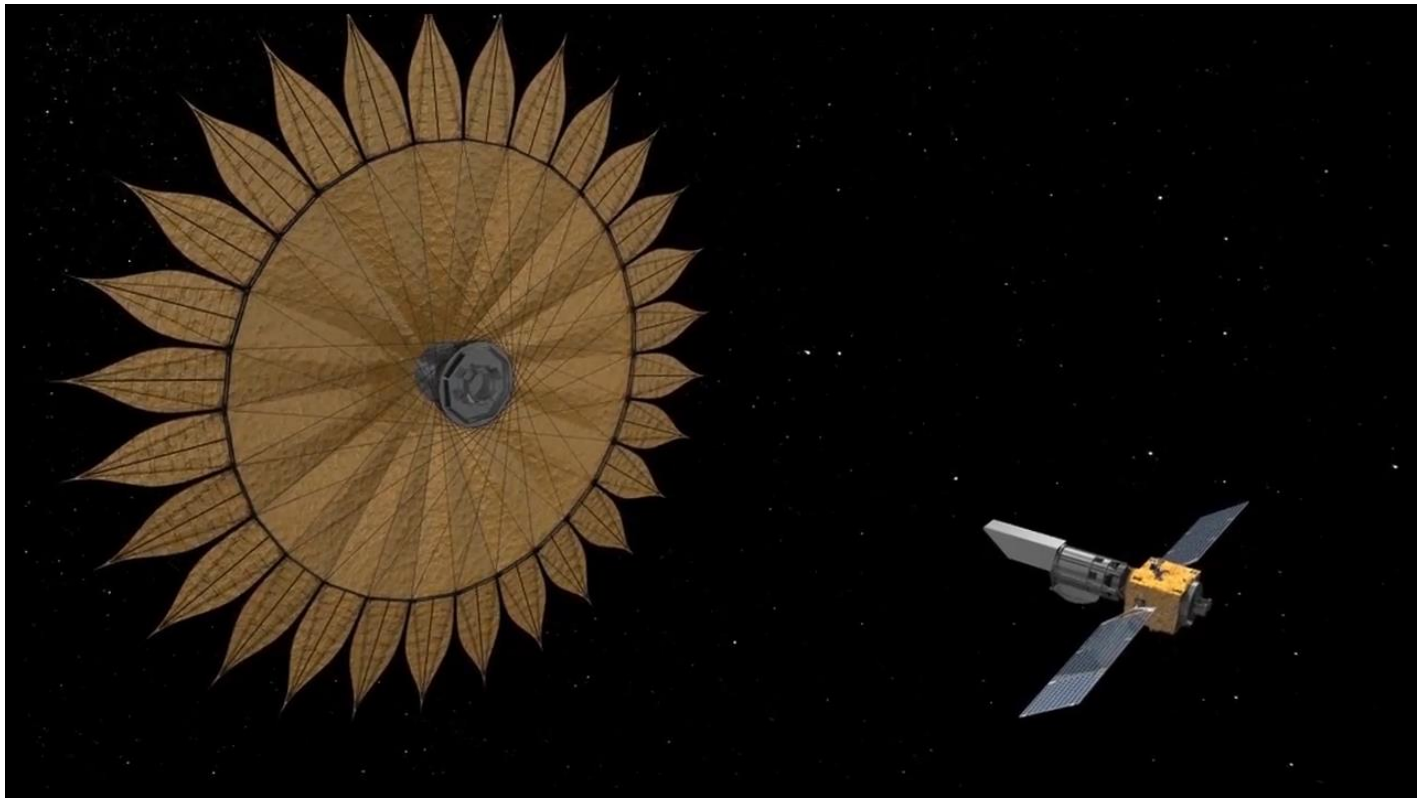
Fixed Price Research & Development Subcontract
Subcontract No. 1631978

Overview

- Key Technology Gaps
- Error Budget Reduction
- Work Scope
  - Preliminary Analyses
  - Material Testing
  - Petal Creep Predictions
- Summary



* jpl.nasa.gov

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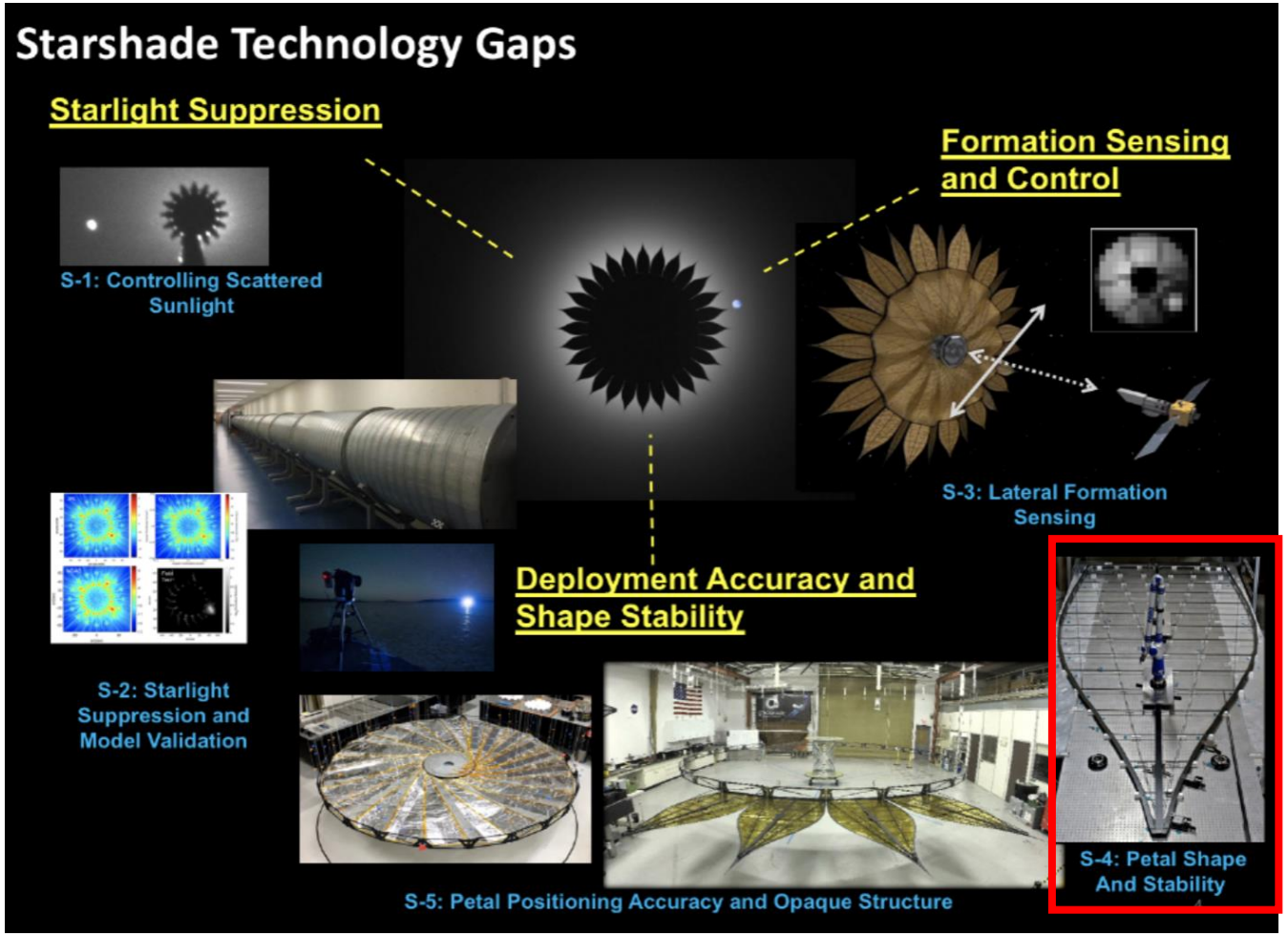
Addressing Key Technology Gaps

- Deployment Accuracy and Shape Stability
  - Combined analysis/test approach
  - Targeting estimates on Starshade petal dimensional stability
  - Petal dimensional stability driven by material dimensional stability



* Starshade to TRL5 (S5) TDP

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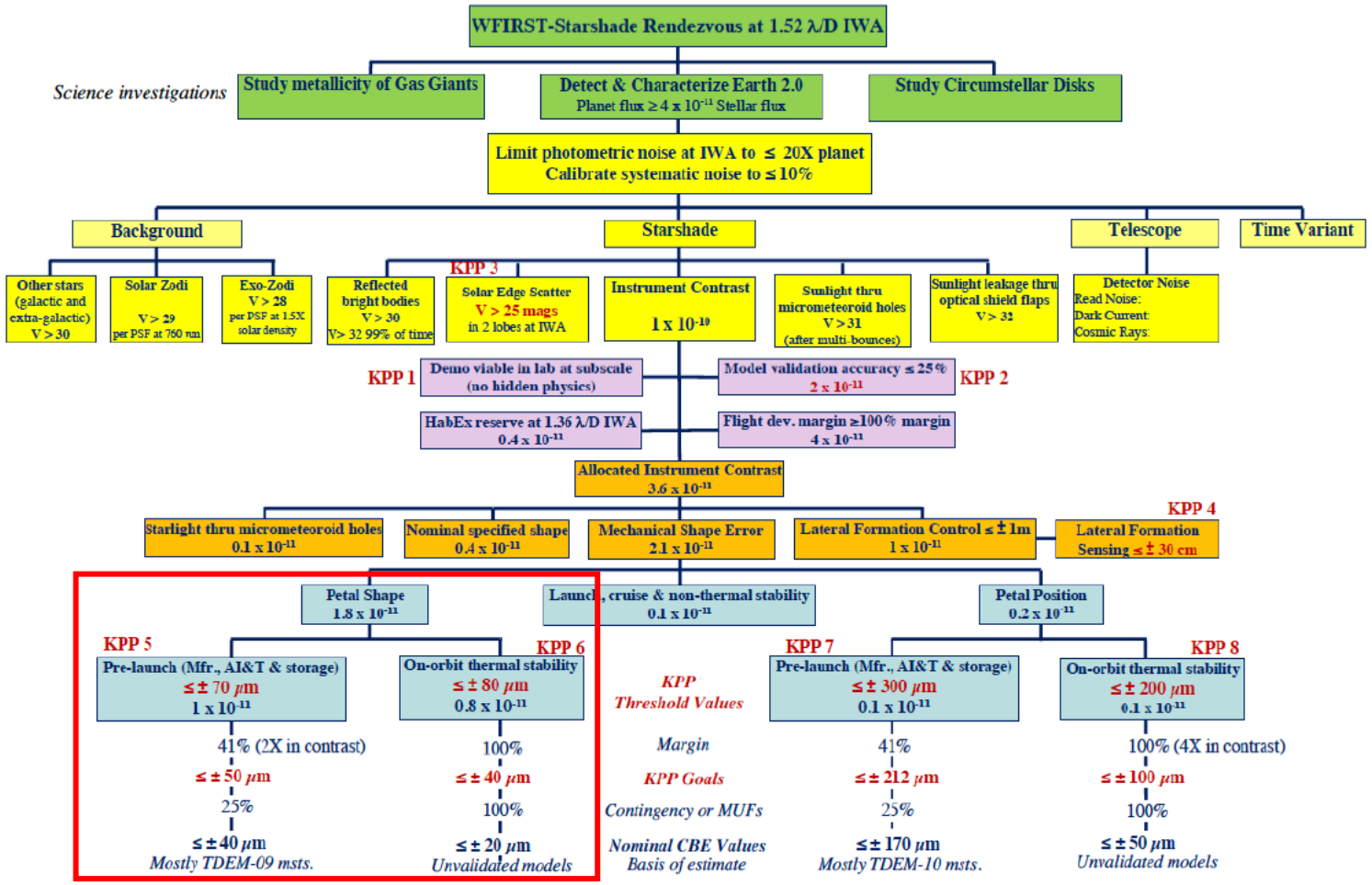
Error Budget Reduction

- Opterus work addresses Petal Shape
  - KPP 5 (≤ ± 40 µm)
  - KPP 6 (≤ ± 20 µm)
- Pre-launch and on-orbit shape stability are relevant
- Efforts focus on pre-launch shape stability of prototype petal design



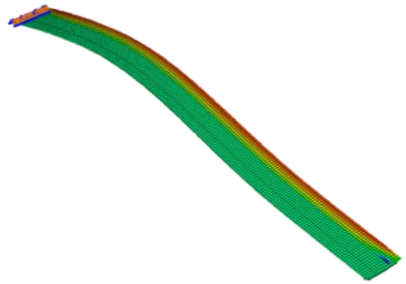
* Starshade to TRL5 (S5) TDP

Work Scope

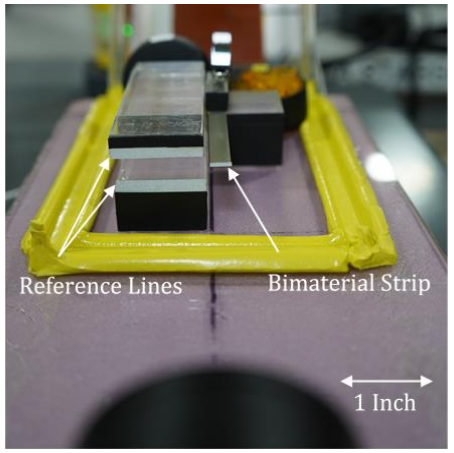
Goal: Evaluate Starshade petal dimensional stability as a function of materials and stowage

Technical Progression

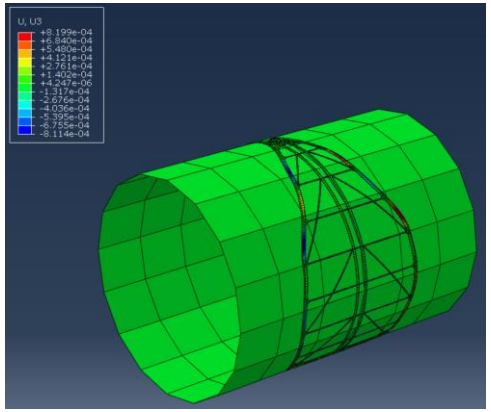
1. Preliminary Petal Edge Analyses



2. Coupon Level Material Testing



3. Petal Stowage Creep Predictions



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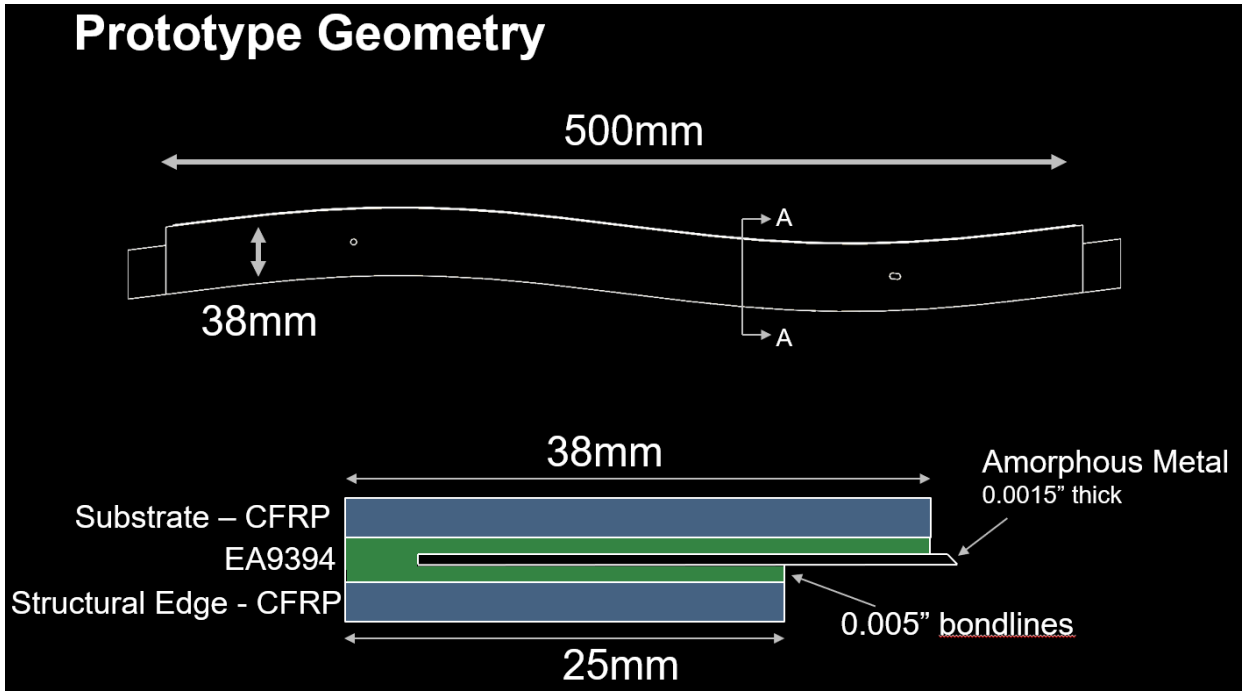
Preliminary Petal Edge Analyses

- How does material selection influence time-dependent response to stowage?
- CFRP laminates and epoxy adhesive are time-dependent!
- Lots of CFRP resin systems out there…how does varying the resin impact time-dependent deformations?
  - Neat resin?
  - Toughened?
  - Filled?
  - Toughened and filled?



* 2019 Optical Edge SPIE Presentation - Advancements in precision edges for a starshade external occulter

#	Resin Identifier	Resin Description	Nanosilicate	Toughener
1	F7C	Pure epoxy	No	No
2	F7	Epoxy with toughener	No	Yes
3	Epoxy (38% NS)	Epoxy with nano-silicates, no toughener	38%	No
4	F7 (10% NS)	Epoxy with toughener and nano-silicates	10%	Yes
5	F6	Cyanate ester	N/A	N/A

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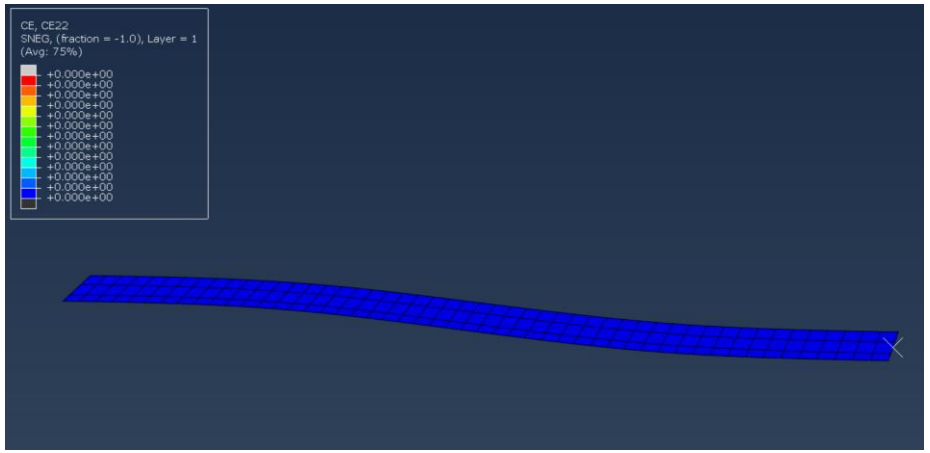
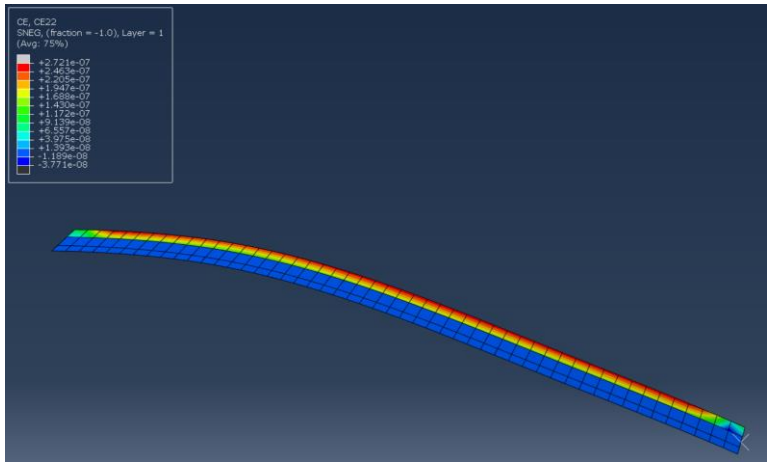
Preliminary Petal Edge Analyses

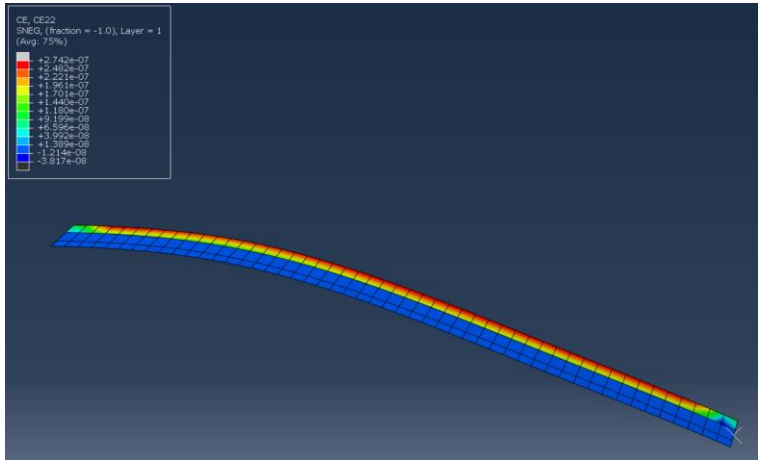
Petal Edge: Unloaded



Petal Edge: Load Applied



Petal Edge: Load Held for Time



Stow petal edge (constant load) – observe time-dependent deformations

Preliminary Edge Analyses: Results & Outcomes

#	Resin Identifier	Resin Description	Tip Displacement (m)	Edge Elastic Strain (με)	Edge Creep Strain (με)	CFRP Visco.
1	F7C	Neat epoxy	0.121	286.4	0.274	On
2	F7	Epoxy w/ T	0.121	286.4	0.274	On
3	F3GHT	Epoxy w/ NS	0.120	284.6	0.273	On
4	F7 10%	Epoxy w/ T and NS	0.122	289.7	0.277	On
5	F6	Neat cyanate ester	0.120	284.3	0.272	On
6	***F7***	***Epoxy w/ T***	***0.122***	***283.8***	***0.274***	***Off***
*T = toughener, NS = nanosilicates, all reported values correspond to 5 minute stow (i.e. load still applied)						

Key Outcomes

1. Time-dependent deformations small compared to elastic deformations
2. Time-dependent deformations minimally influenced by changing CFRP resin
3. Time-dependent deformations dominated by epoxy bond lines (EA9394)

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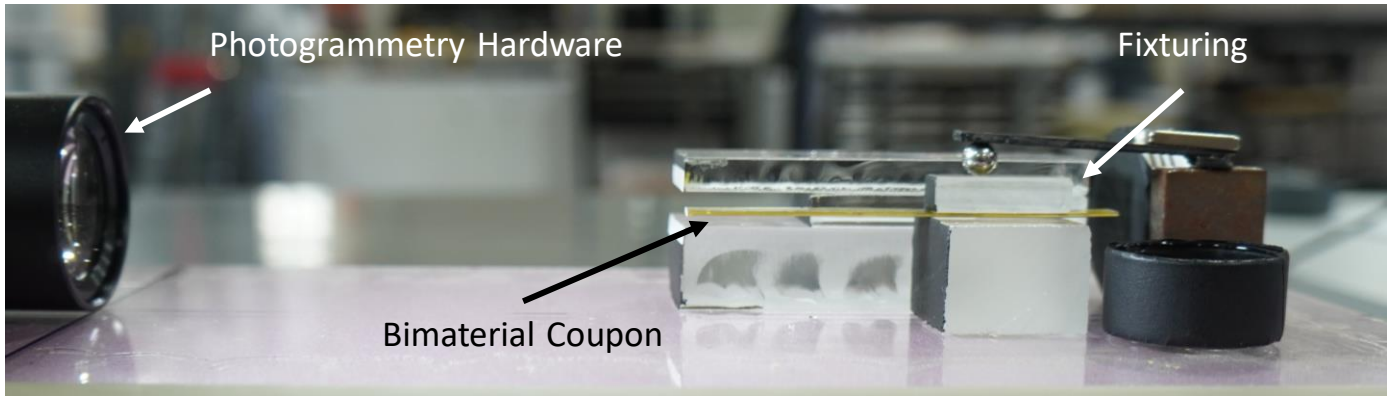
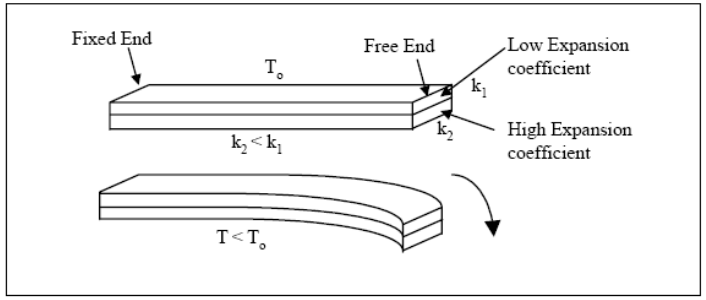
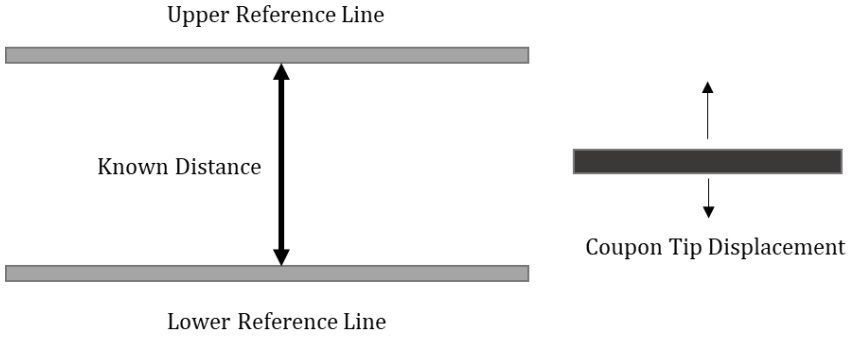
Coupon Level Material Testing

- CFRP time-dependency has little impact on edge creep under load
- What about changes in environment?
  - Time
  - Temperature
  - Moisture
- Candidate materials narrowed for testing
  - Toughened epoxy (F7)
  - Cyanate ester (F6)
  - Epoxy adhesive (EA 9394)



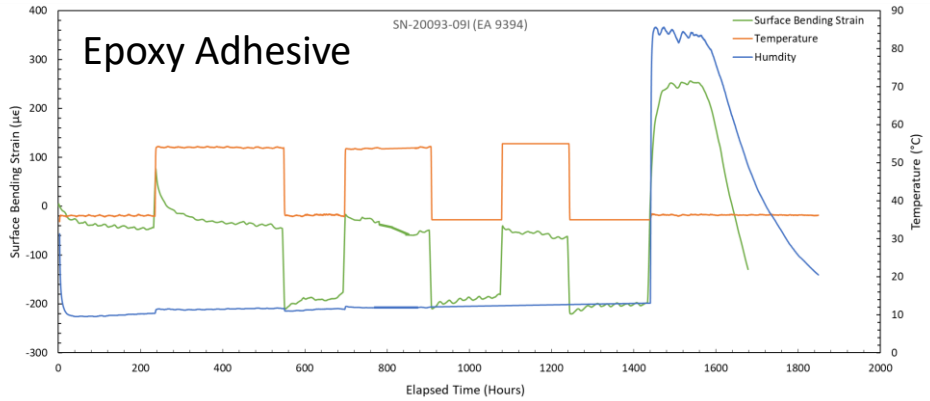


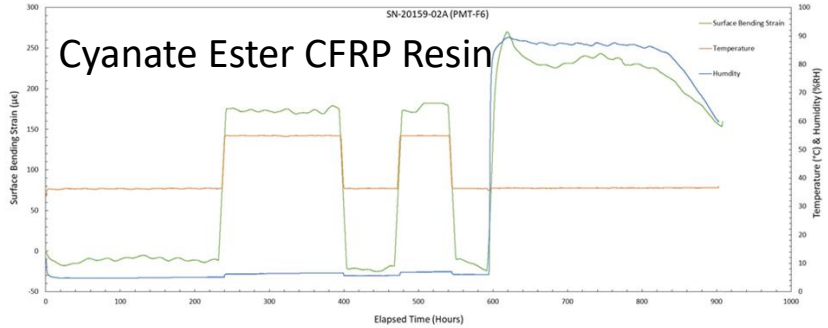
* https://sites.google.com/site/simplestudyiti/instrument-mechanic/theory/measurment-of-tempetrature

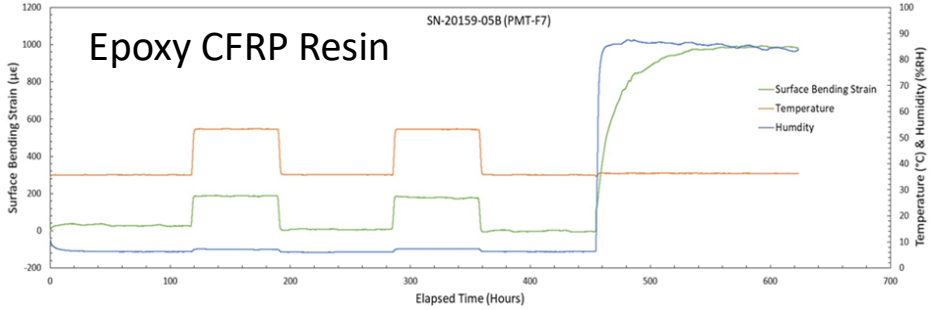


Coupon Level Material Testing

- Testing carried out over several weeks
  - How much do the polymers expand/contract?
  - How time dependent is that response?
- One coupon tested per material (3)
- Multiple thermal cycles, single moisture exposure

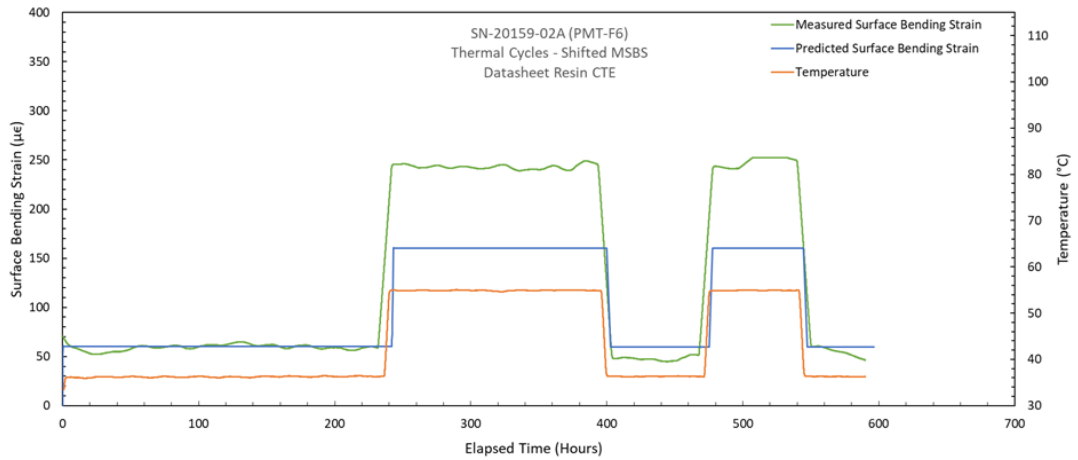


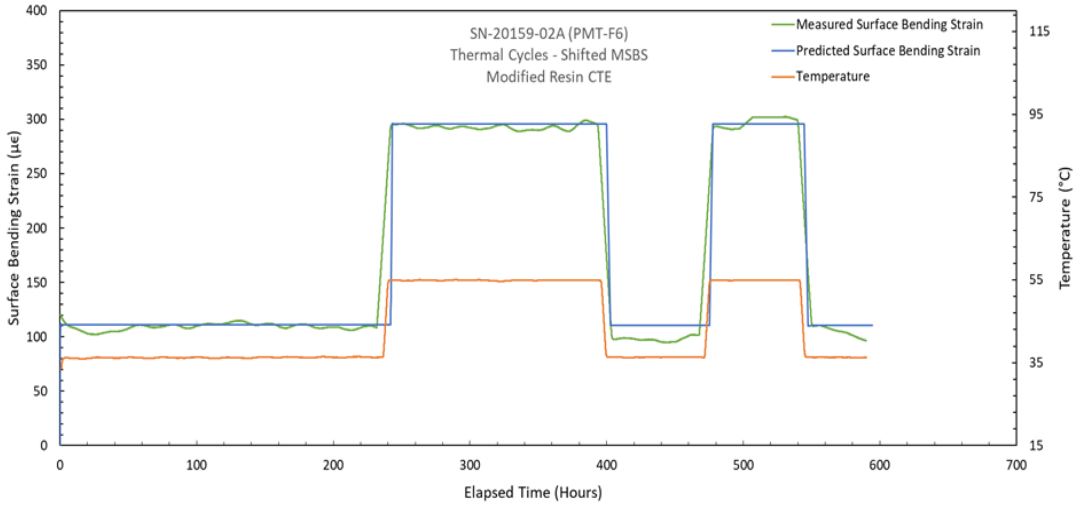




Coupon Level Material Testing

- What's the coupon test data for?
  - Predictions of coupon response, using datasheet material properties, compared to test data
  - Predictions tuned to accurately capture material life history
- Coupon testing agrees with edge analyses
  - EA 9394 adhesive relatively unstable compared to CFRP resins
  - Cyanate ester most stable in terms of time/temp & moisture

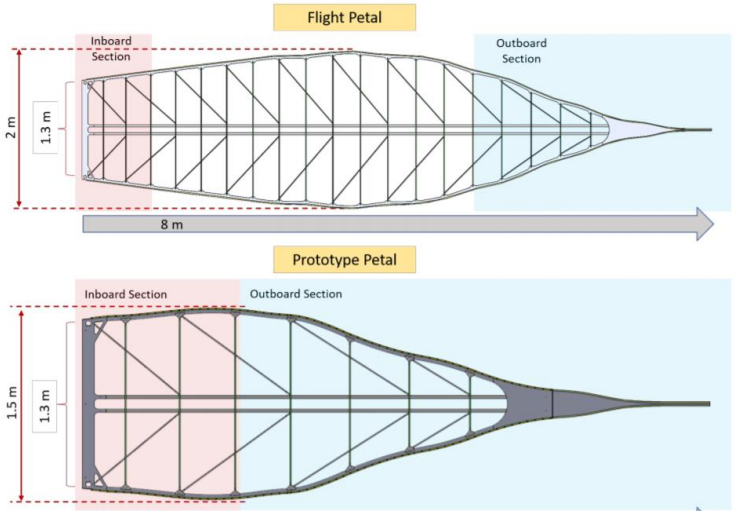




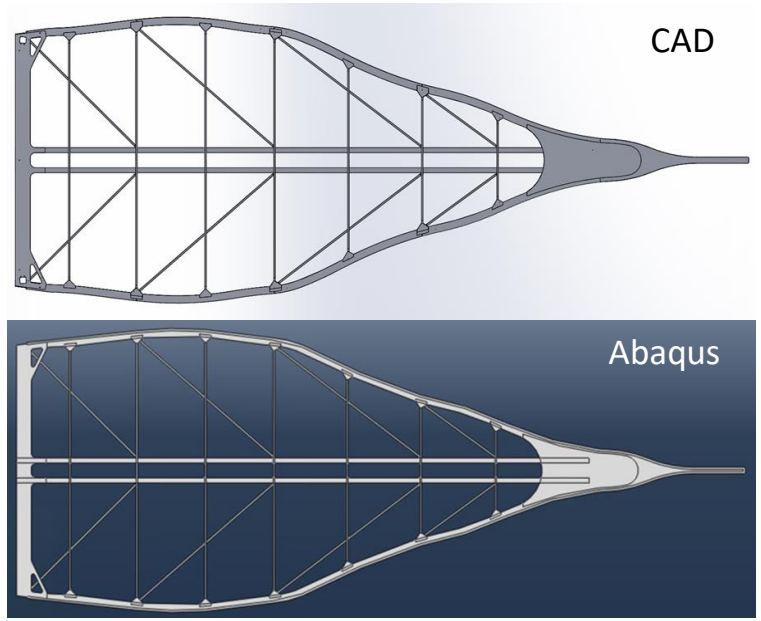
Resin Identifier	Assumed CTE (ppm/°C)	Calibrated CTE (ppm/°C)	Calibrated CME (ppm/%RH)
EA 9394	55.6	100	85
PMT-F6	42	63	35
PMT-F7	48	68	98

Prototype Petal Stowage

- Coupon test results informed the petal model
- All CFRP petal components and epoxy adhesive bondlines modeled
- Multiple time/temp stowage scenarios simulated
- How shape stable is the petal as a function of time/temp stowage?



* Starshade Technology Development Activity Milestone 5A: Verify Petal Pre-launch Accuracy

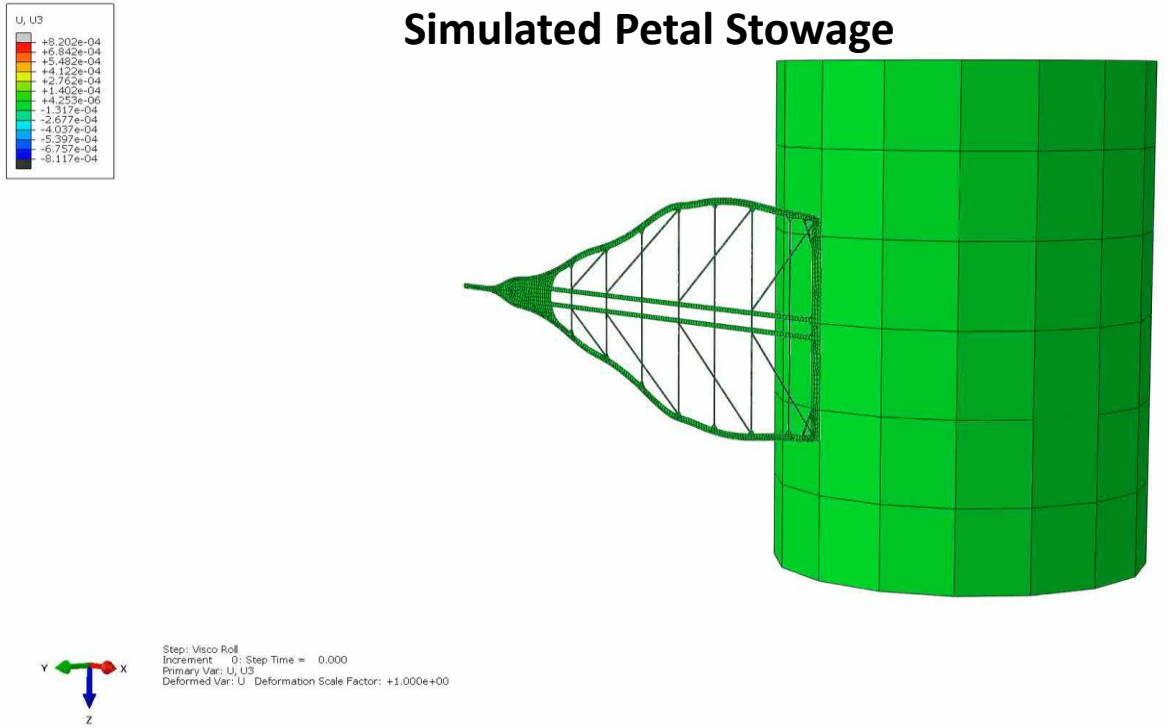


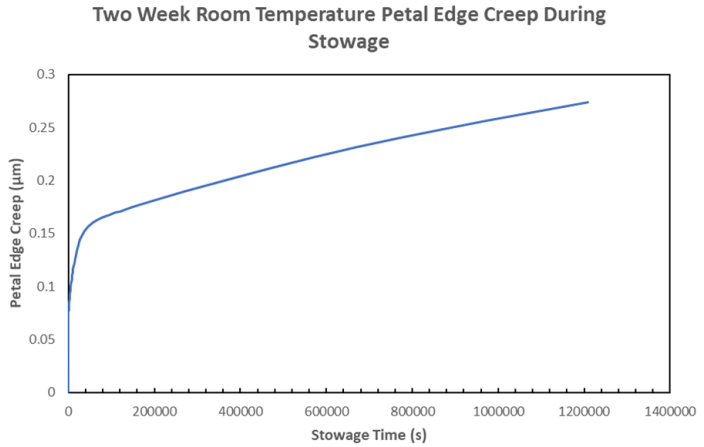
Prototype Petal Stowage

Petal Stowage at Tendeg

* Starshade Technology Development Activity
Milestone 5A: Verify Petal Pre-launch Accuracy

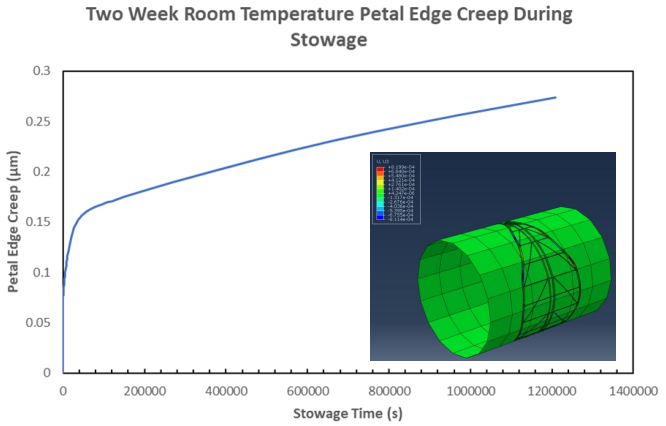
Simulated Petal Stowage

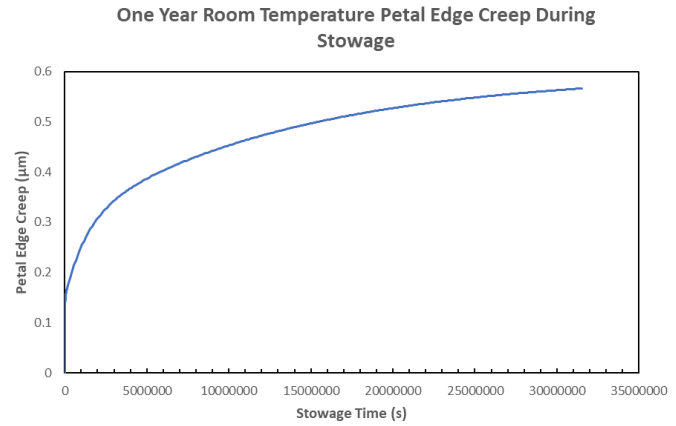


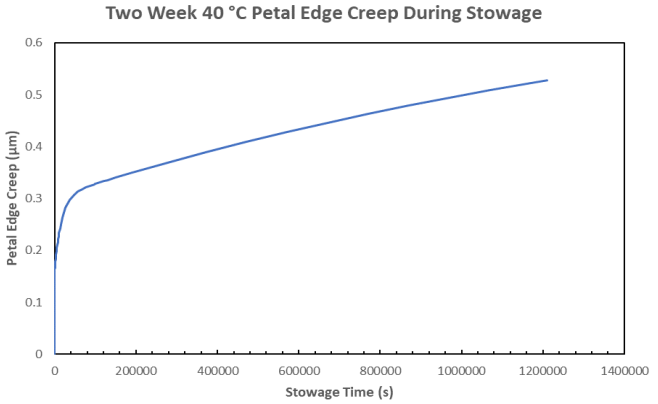


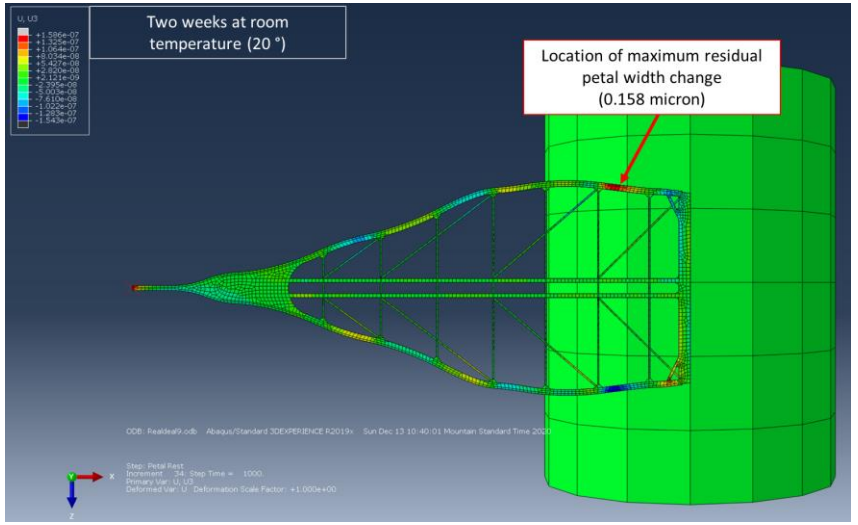
Prototype Petal Stowage

- Three time/temp stowage sequences simulated
  - 2 weeks at room temp (20 °C)
  - 1 year at room temp (20 °C)
  - 2 weeks at 40 °C
- How much does the edge creep during stowage?
- How much creep is recovered?

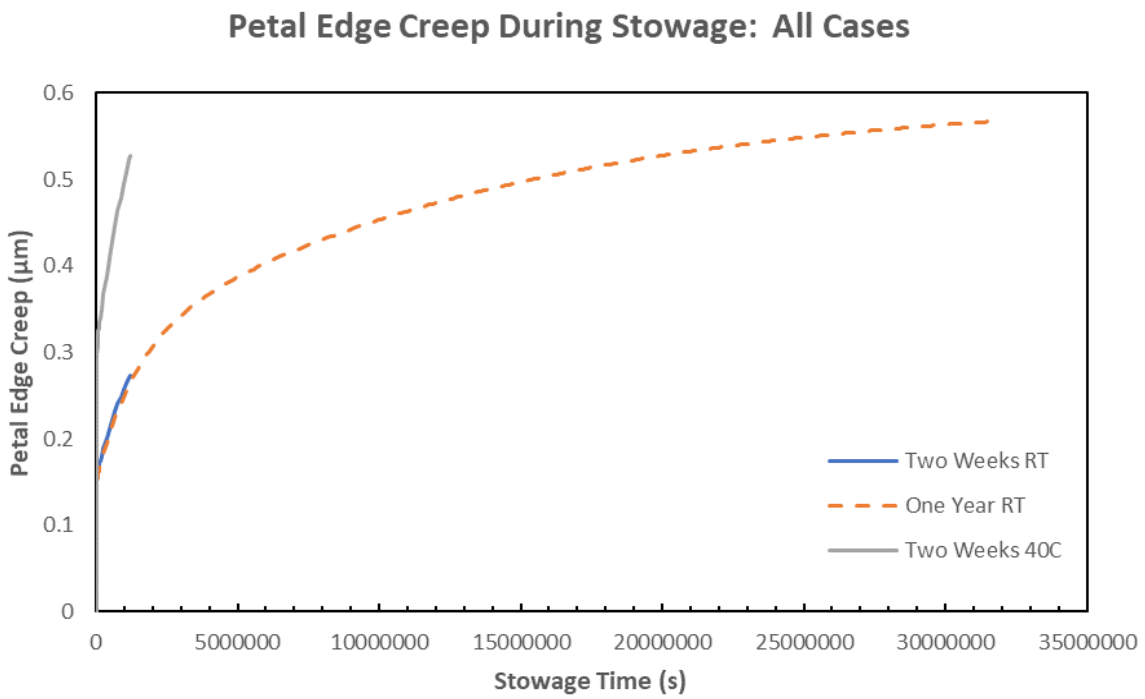








Prototype Petal Stowage



Remaining Edge Creep after Deployment

Analysis Case	Max Predicted Residual Edge Creep (µm)
Two Weeks at Room Temperature (20 °C)	0.158
One Year at Room Temperature (20 °C)	0.415
Two Weeks at 40 °C	2.93

Key Outcomes

- Petal edge creep has a clear time and temperature dependency
- Short times/low temps = more elastic response = more recovery
- Long times/high temps = more viscous response = less recovery

Opterus SIP Summary

Goal: Evaluate Starshade petal dimensional stability as a function of materials and stowage

- Edge analyses showed CFRP creep orders of magnitude smaller than adhesive creep
- Coupon testing of candidate materials supplemented edge analyses
  - Most time-dependent material = epoxy adhesive (EA 9394)
  - Least time-dependent material = cyanate ester CFRP resin system
- **Petal stowage simulations, using test validated material properties, predicted residual edge deformations after deployment on the single micron scale**

Remaining Edge Creep after Deployment

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