# LaRC Shape Memory Polymer Composite for Aerospace Applications

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*All Image Credit: NASA

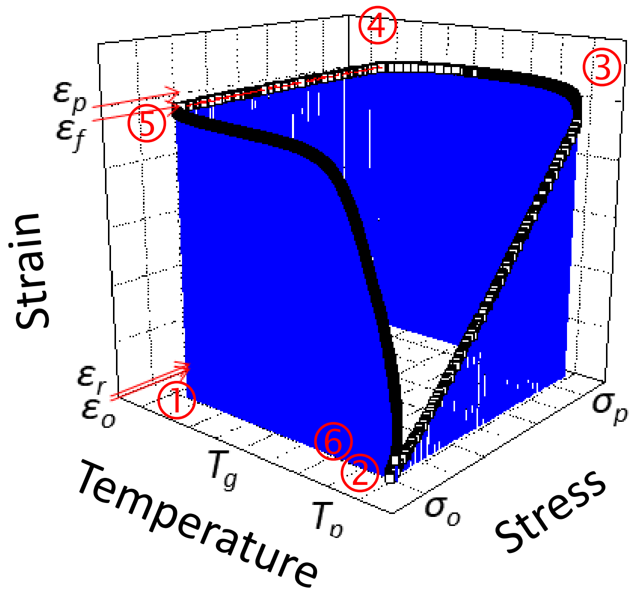
# Outline

1. Introduction : LaRC Shape Memory Polymers
2. Application 1 : Adaptive Air Foil System
3. Application 2 : Origami-Based Deployable Structure
4. Application 3 : Deployable Reflector Antenna
5. Summary and Future Work

# Introduction

## Shape Memory Polymer (SMP)?

- Smart material that has the ability to return from a programmed (temporary) shape to its original (permanent) shape when induced by an external stimulus, such as temperature change and electric field





Original Shape

Programmed (temporary) Shape

Recovered Shape

Demonstration of shape recovery of LSMPC

# Introduction

## Applications of SMPs

- Morphing structures and packaging
- Self-deploying space structures
- Intelligent medical devices
- Smart fabrics, etc.

## Advantages and Disadvantages of SMPs

- SMP Advantages
  - Lightweight
  - Tailorable
  - Conformable
- SMP Disadvantages
  - Low recovery stress
  - Slow response time
  - Complicated process

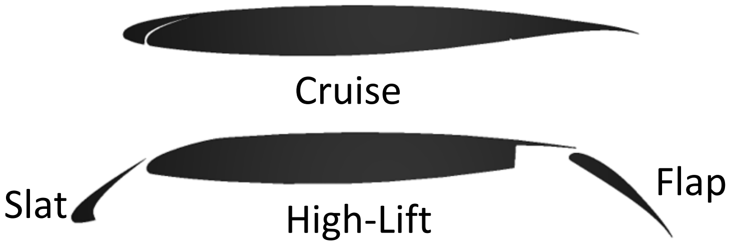
→ ***Series of LaRC SMPs:***
***Carbonaceous Nanoinclusion, Fiber Reinforcement + Thermosetting SMP***

# Application 1 : Adaptive Airfoil System

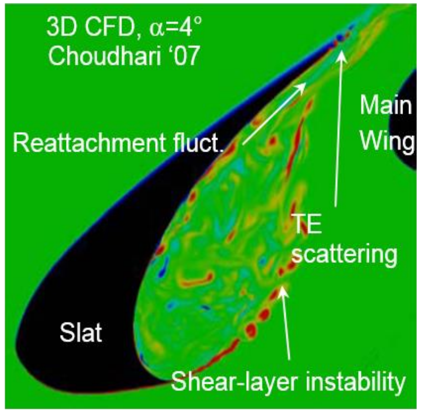
## Motivation

- Slat, leading edge high lift system deploys away from the main wing in the high-lift configuration
- Geometric discontinuities of edge, gap and cavity cause considerable unsteadiness to generate  significant acoustic noise
- Slat cove filler (SCF) reduces the unsteady aerodynamics
- SCF should sustain the aerodynamic load when deployed and remain hidden between the slat and the main wing when stowed for cruise
- Additionally, requires weight-efficiency, passivity (no requirement for auxiliary support systems), durability and fail-safety
- New SMP composite (SMPC) with large stiffness change for the SCF application

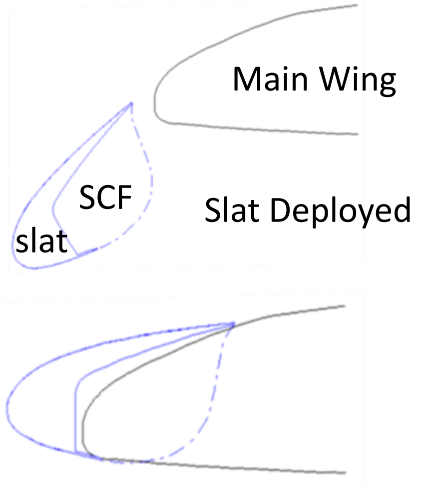
*Project PI: Dr. Mia Siochi




Schematic of a three-element airfoil system in the retracted (cruise) and deployed (high-lift) configurations [1]




Flow vorticity in the vicinity of the deployed, leading-edge slat [1]



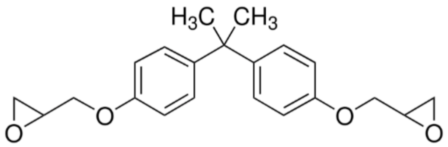

*Ref 1*. Scholten, W.; Patterson, R.; Hartl, D.; Strganac, T.; Volpi, J.; Chapelon, Q.; and Turner, T.: "Noise Reduction in a High Lift Wing Using SMAs: Computational Fluid-Structural Analysis," *Proc. ASME 2016 Conf. on Smart Matl., Adaptive Struct. and Intell. Sys.*, Stowe, VT, September 28-30, 2016

# Materials

**1. Preparation of homogeneous nanocomposite**

- Dispersion interaction
- Donor-Acceptor interaction
- In-situ polymerization under sonication and shear

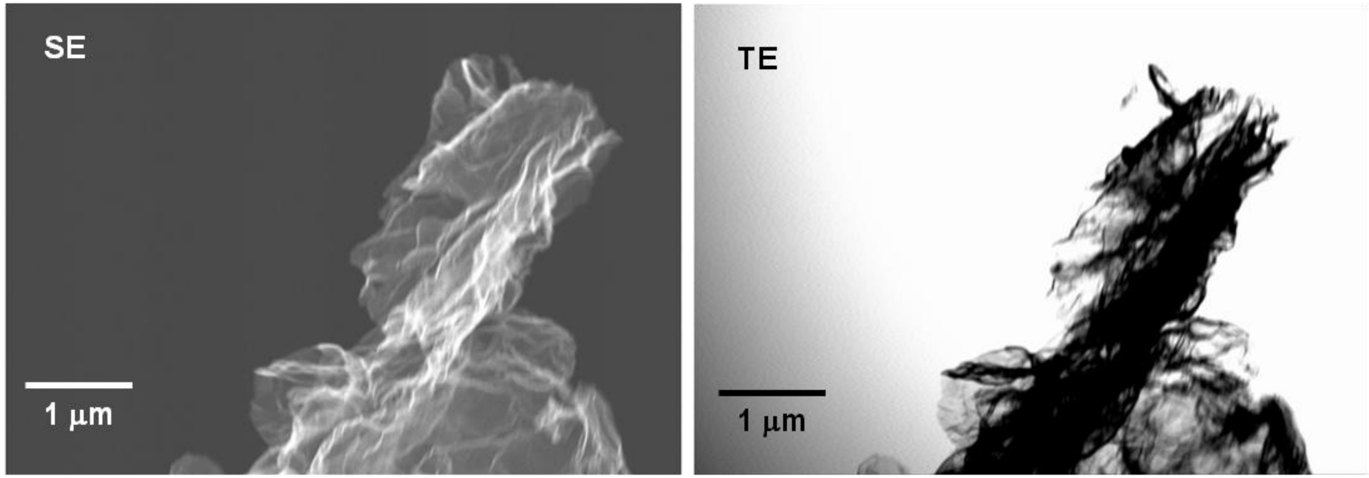
**2. Matrix: Epoxy-based shape memory polymer (LaRC-SMP)**



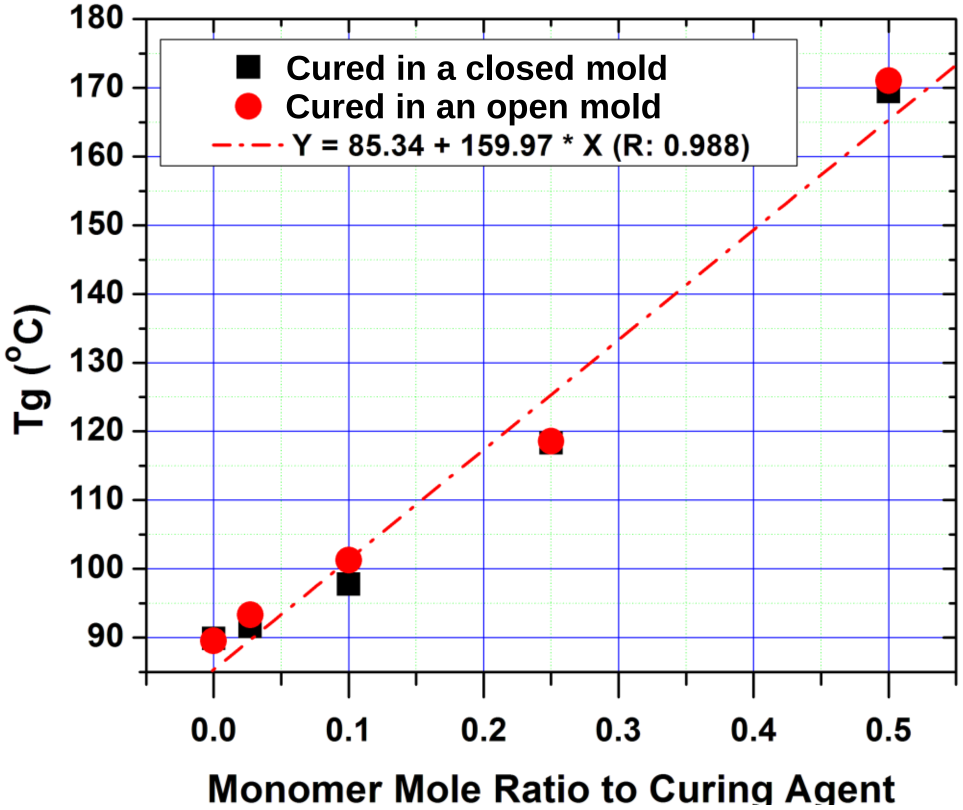

Diglycidyl ether of bisphenol A (DEGBA)
Triglycidyl Ether of p-Aminophenol
4,4'-Methylenebis[N,N-bis(2,3-epoxypropyl)aniline]

**3. Inclusion:** Reduced graphene oxide (RGO), carbon nanotube (CNT), iron oxides

**4. Reinforcing Fabric:** Kevlar®, carbon fiber (CF), carbon nanotube sheet (CNS)



# Tailoring Properties - 1 : Glass Transition Temperature



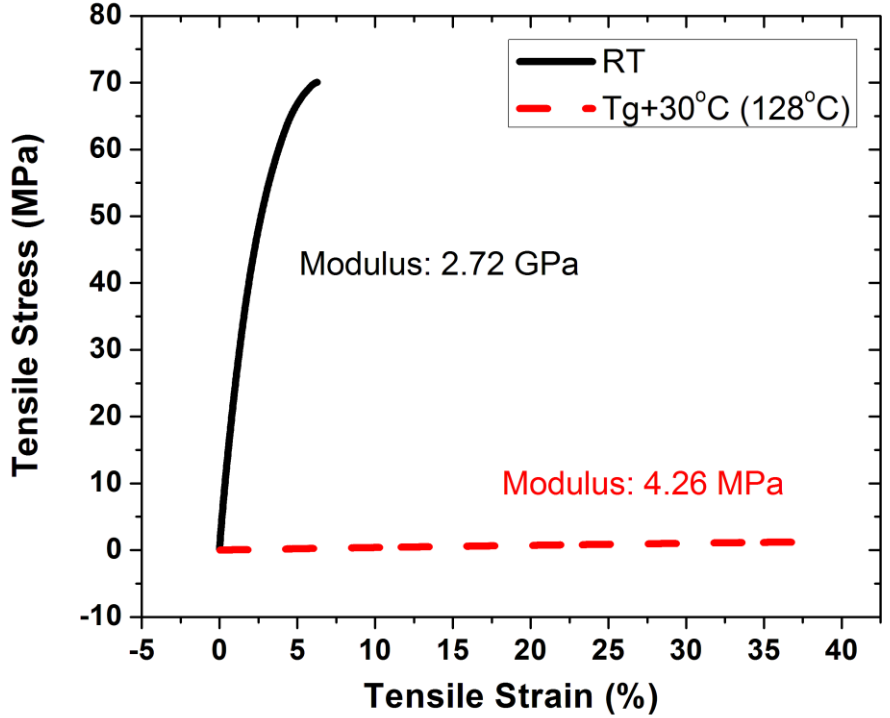

Monomer of matrix resin
→DGEBA (x) based

*Tailoring Tg:*
*from 90°C to 150°C*

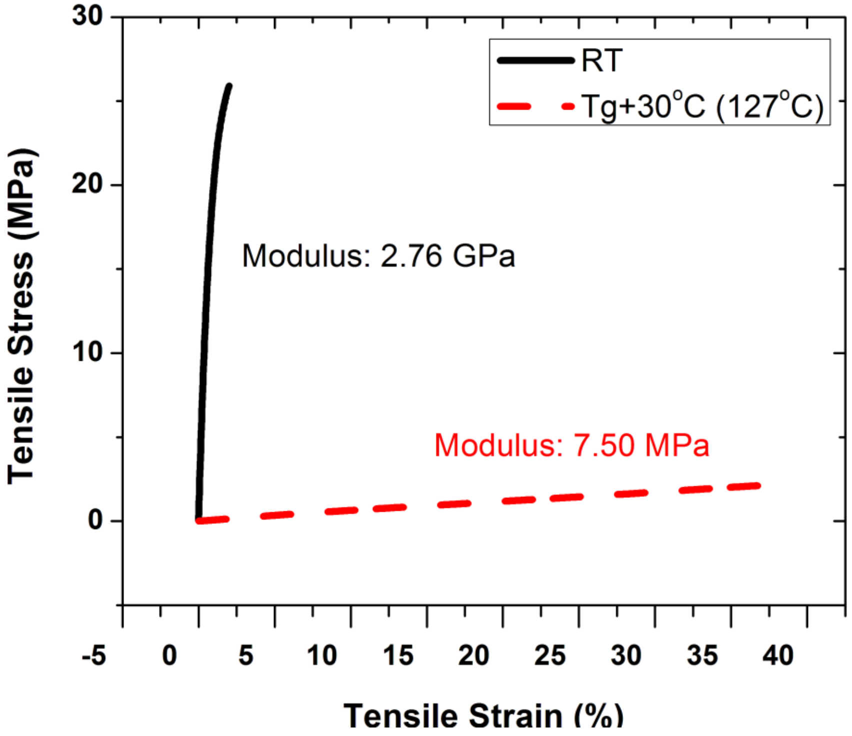
- DSC heating rate of 10 °C/min

# Tailoring Properties - 2 : Mechanical Properties

Pristine LaRC SMP




LaRC SMPC*

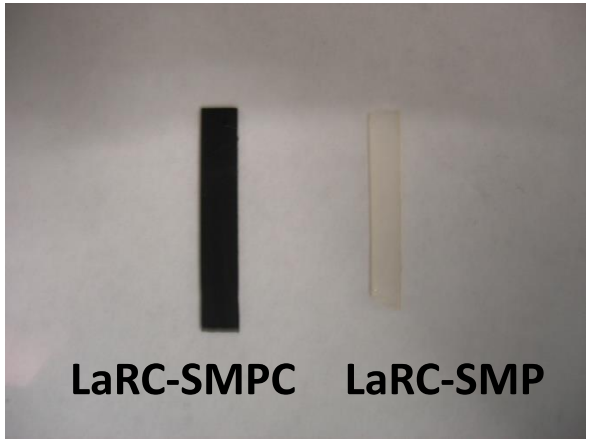



LaRC-SMP has elastic property with large elongation above glass transition temperature

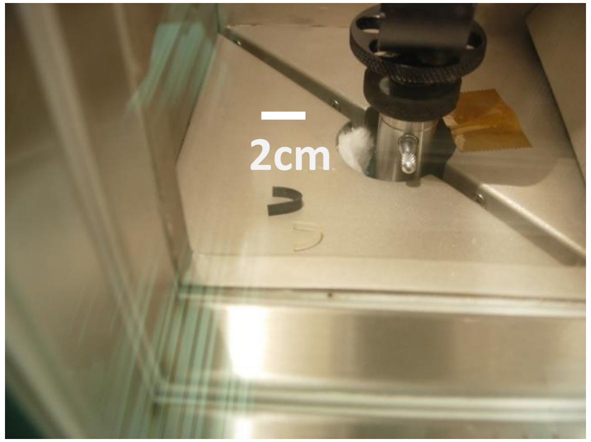
- Strain rate of 10%/min

*SMPC: Shape Memory Polymer Composite

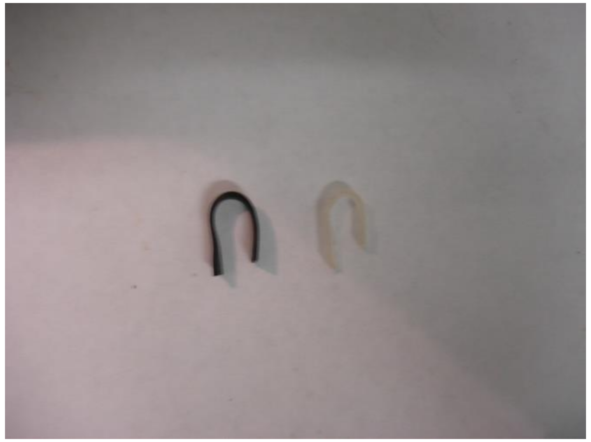
# Thermally Activated Shape Memory Effect (SME)



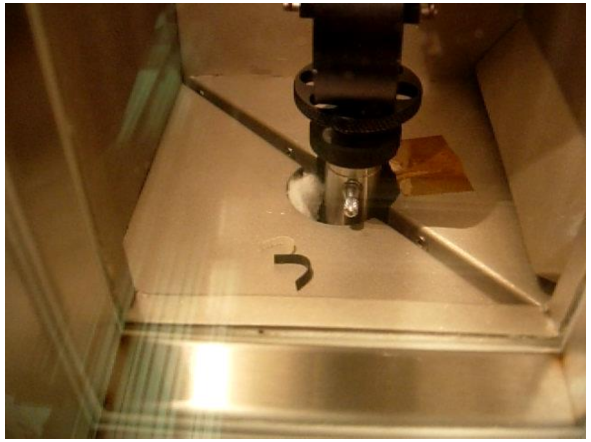

Permanent Shape, $T < T_g$



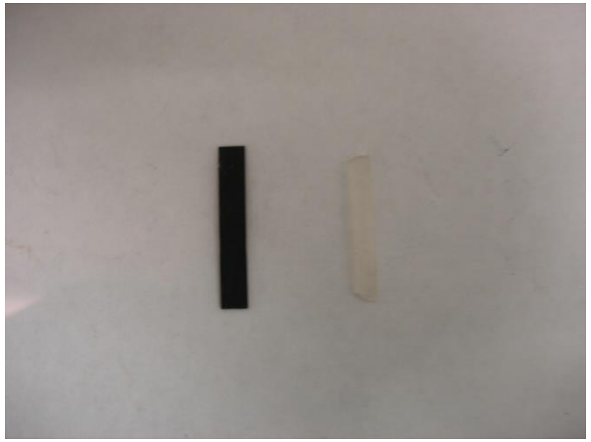

Programming (Deformation), $T > T_g$



Temporary Shape, $T < T_g$

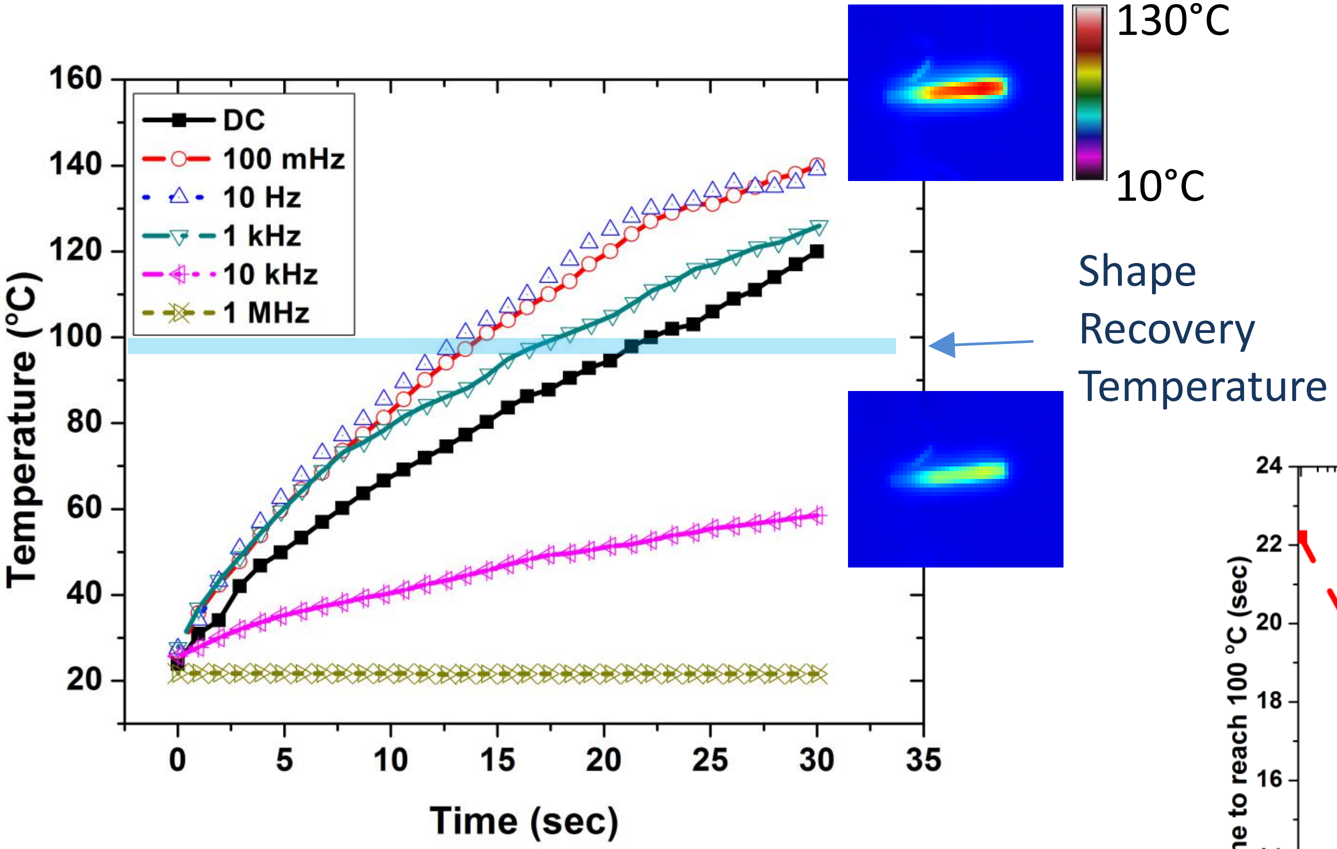


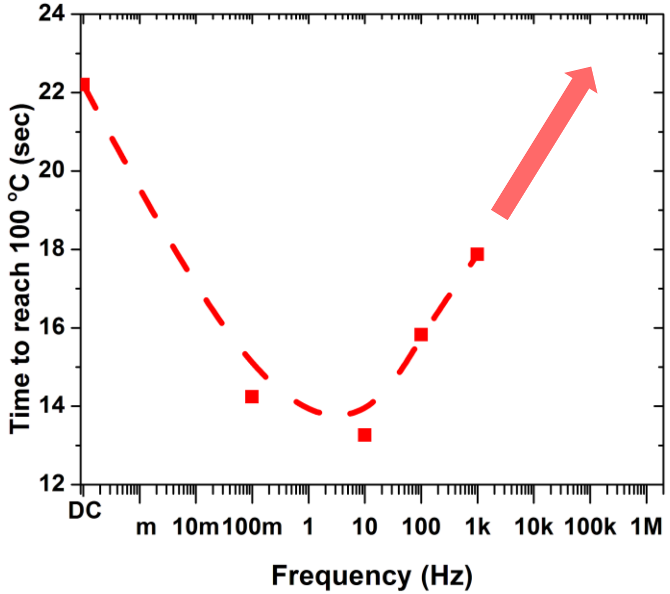
Shape Recovery, $T > T_g$



Recovered Permanent Shape, $T < T_g$

# Tailoring Response Time – 1 : AC Electric Field

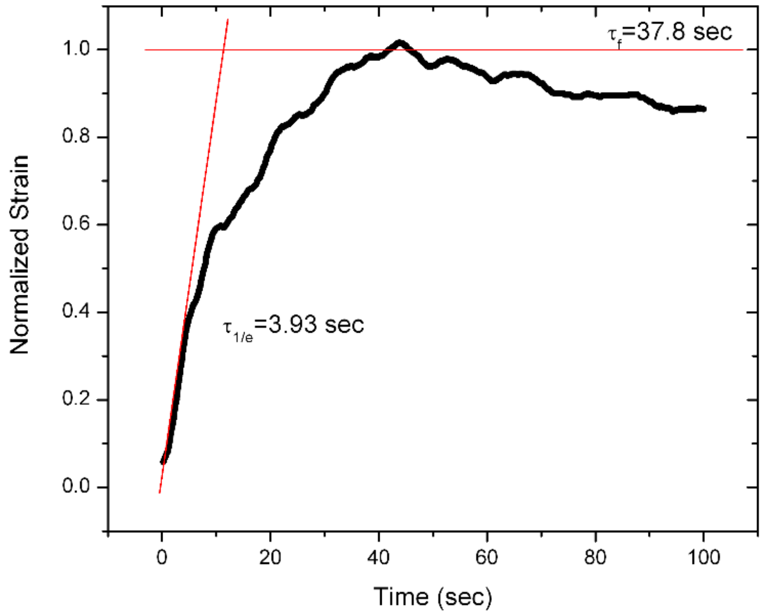


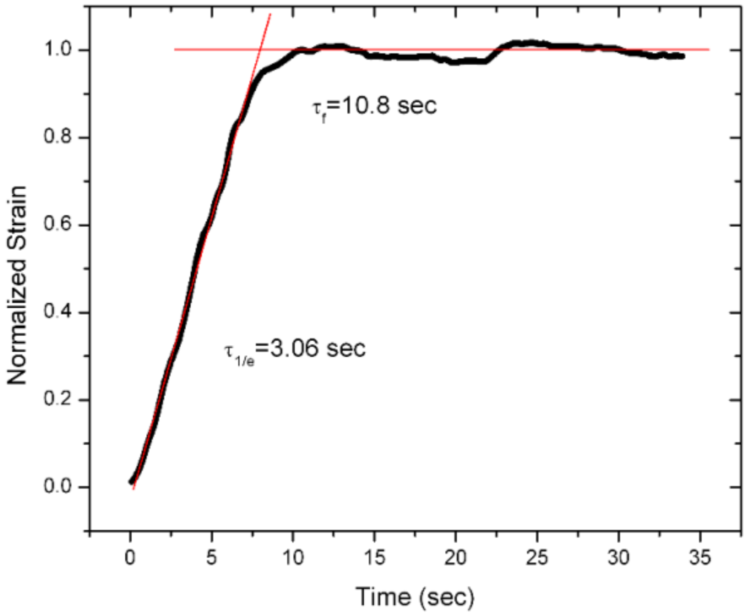

Response time:
22 sec (DC) → 13 sec (10 Hz)

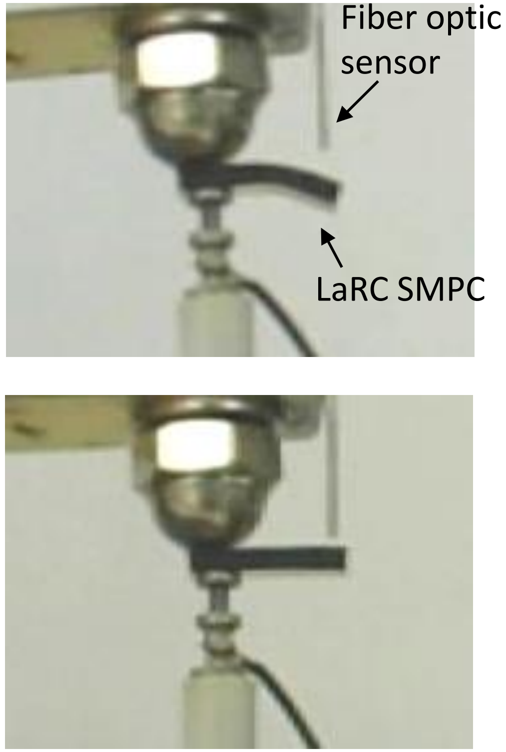
# Tailoring Response Time – 2 : Metal Electrodes

Conventional metal (Au/Cr) electrode LaRC SMPC



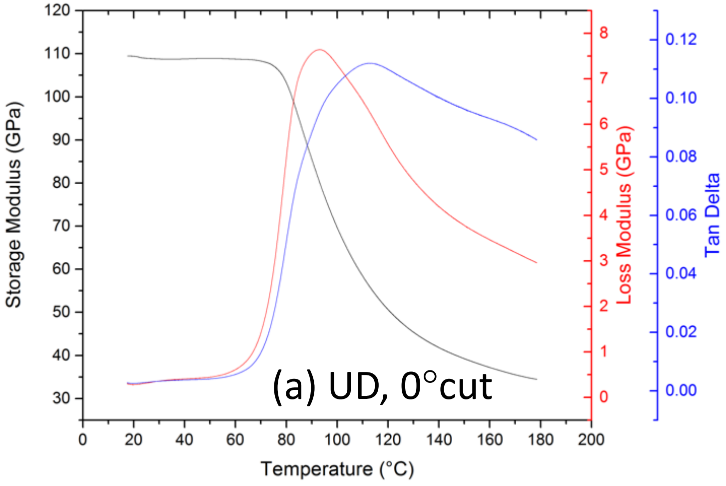

Elastic titanium sheet laminated LaRC SMPC

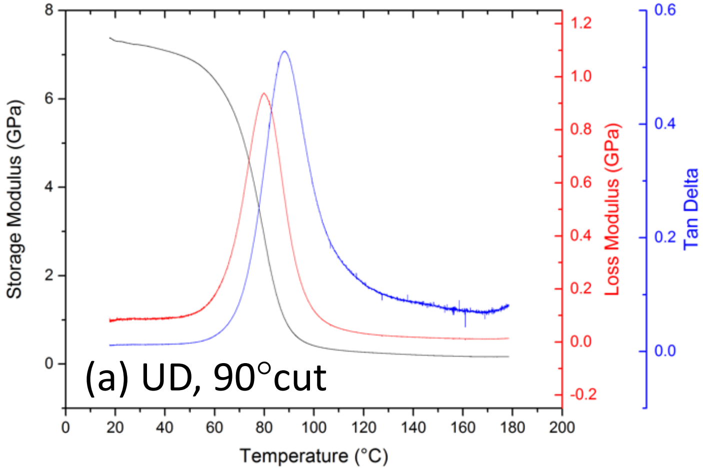



The final recovery time ($\tau_f$) of the LaRC SMPC laminated with the elastic titanium alloy sheet was about 10.8 sec, over 3 times faster than that of unlaminated LaRC-SMPC (37.8 sec)

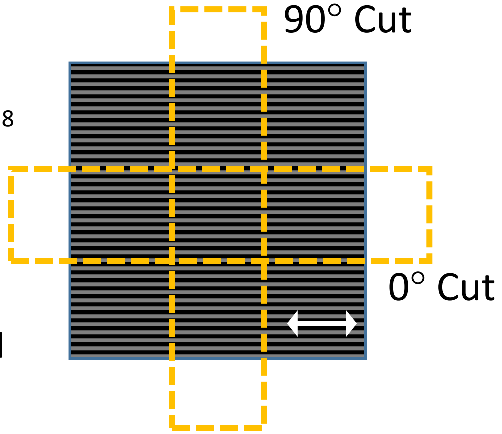
# Tailoring Dynamic Mechanical Properties 1 : Carbon Fiber

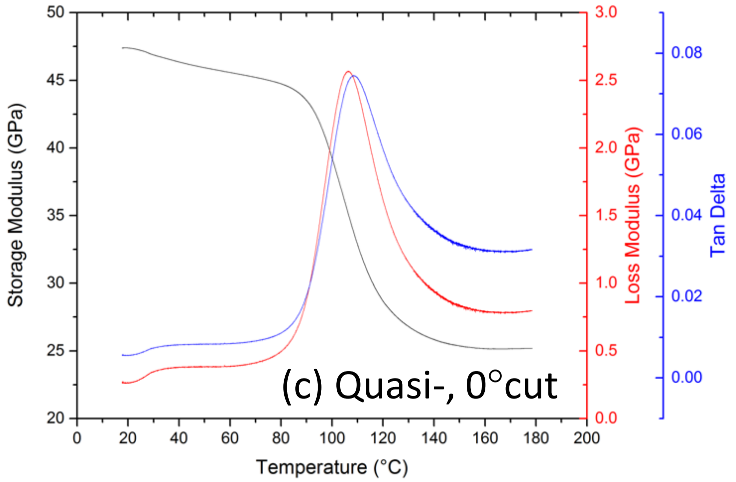


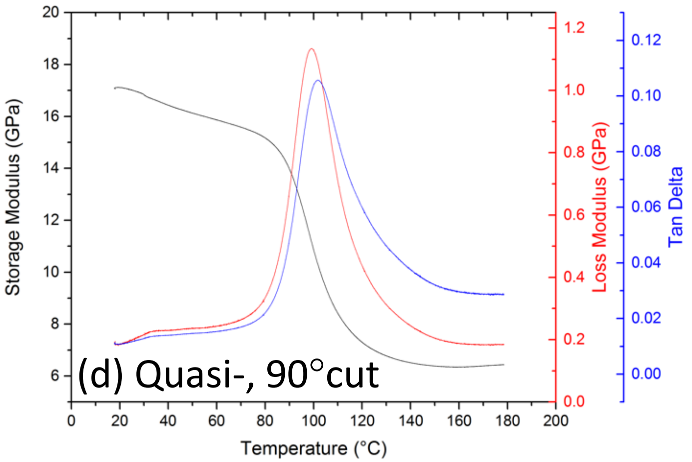



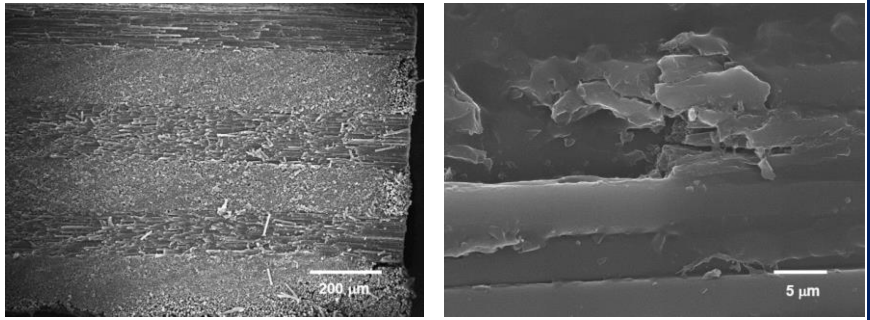

(a-b) CF uni-directional (UD), $[0°]_8$ reinforced SMP composite,

(c-d) CF quasi-isotropic, $[+45°/0°/-45°/90°]_{2s}$ reinforced SMP composite



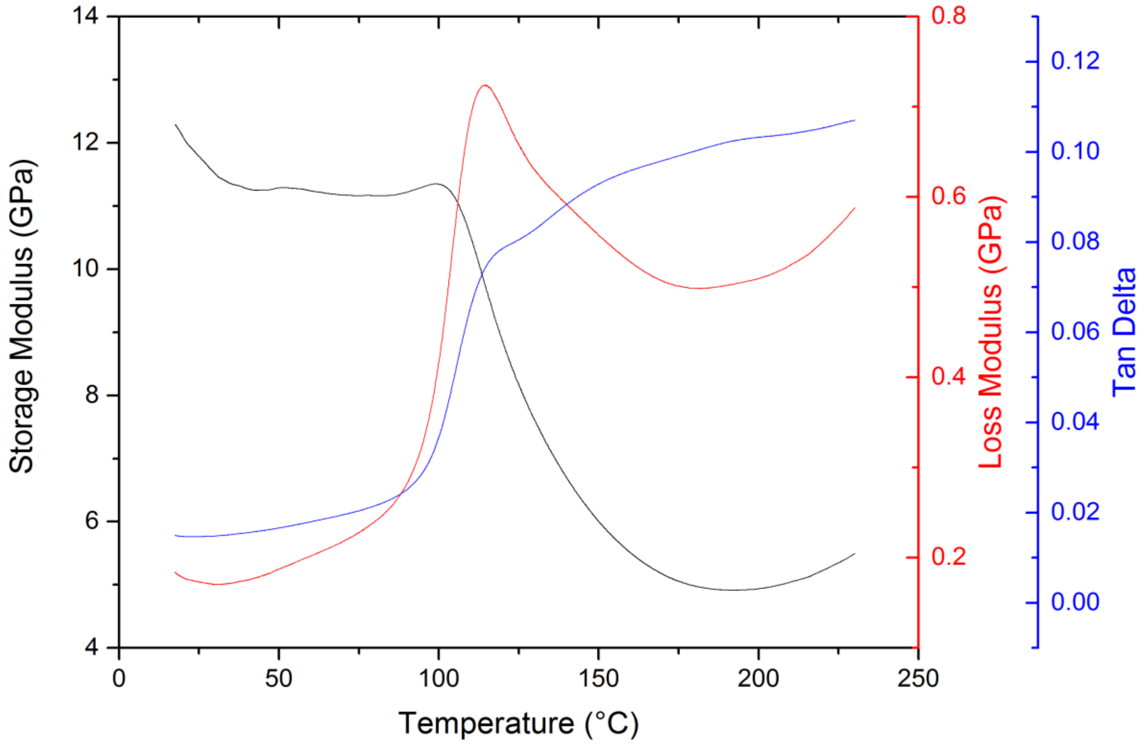



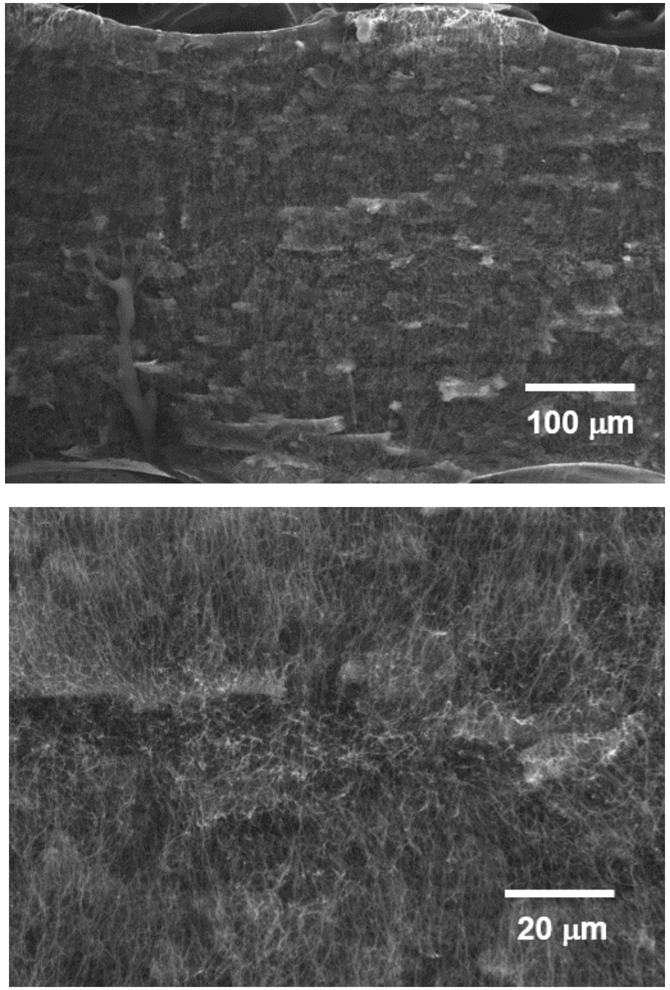

Cross-sectional SEM images of CF fabric reinforced SMPC

CF reinforced SMPC has high elastic modulus of about 50 ~ 110 GPa

# Tailoring Dynamic Mechanical Properties 2 : CNS

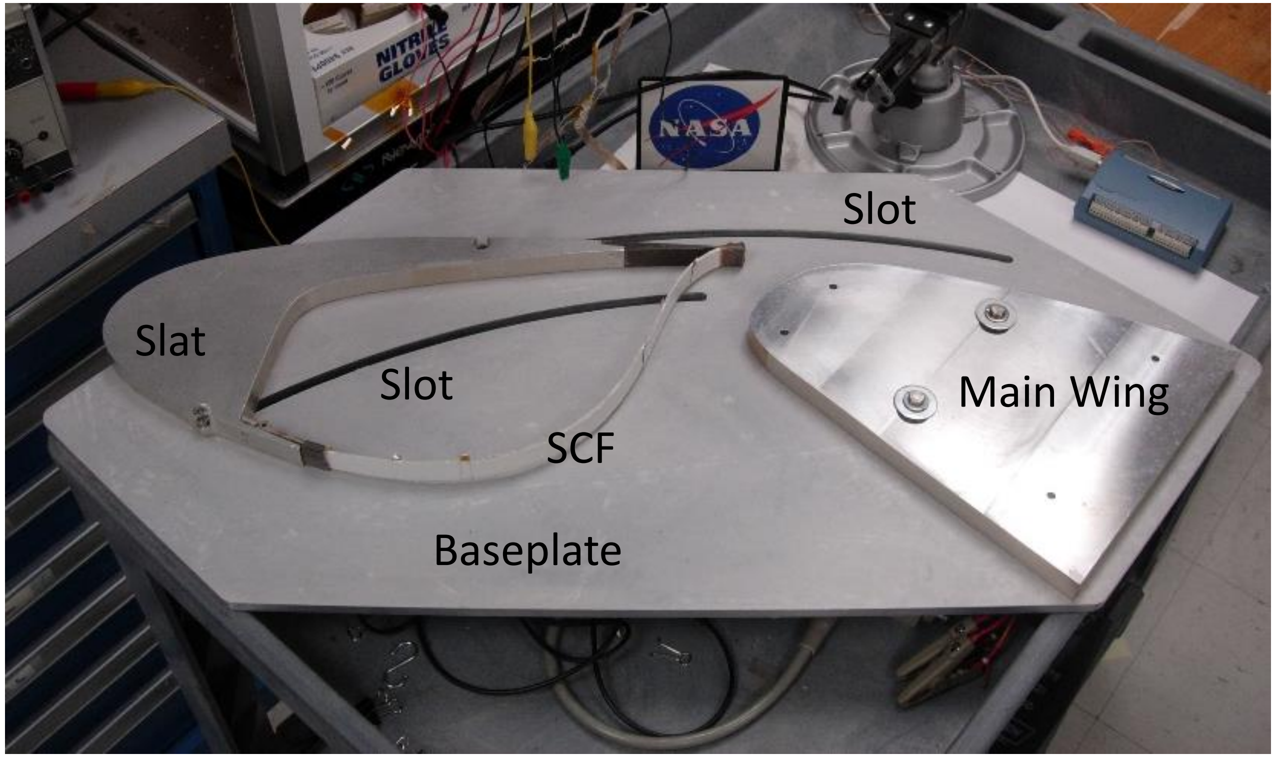



Carbon Nanotube Sheet (CNS) reinforced SMPC has lower elastic modulus than CF reinforced SMPC



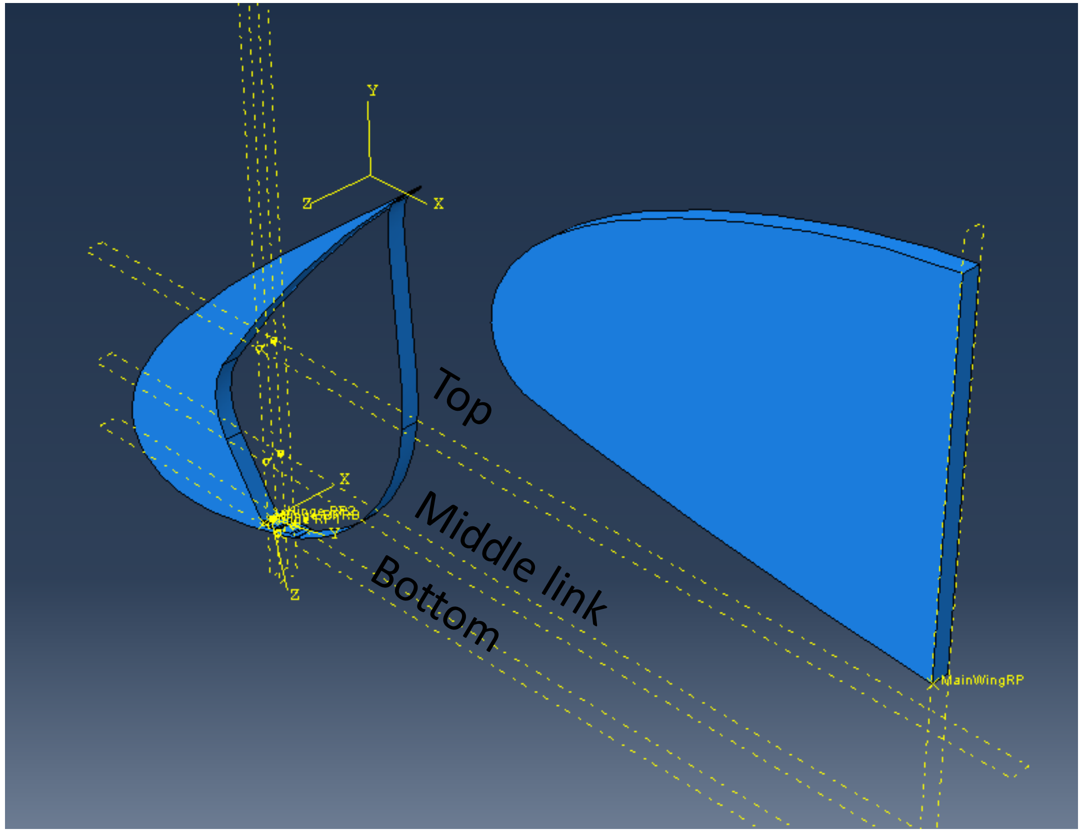

Cross-sectional SEM images of CNS reinforced SMPC

# Bench-Top Demonstration Model




A bench-top test apparatus, based on the 30P30N airfoil, was developed at 75% scale to assess the operational viability of the LaRC SMPC based slat-cove filler (SCF) prototypes

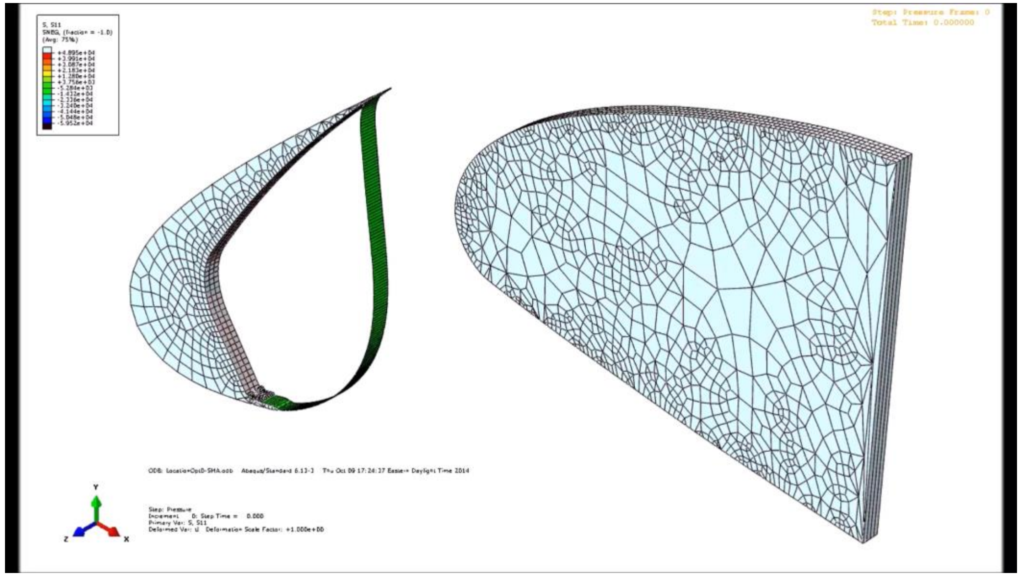
# Designing SCF Conformation by Computational Modeling




Using the Abaqus finite element analysis program, SCF dimensions and the segmented (top, mid-link and bottom section) configuration from previous work, the design of the SCF incorporating the SMP material was studied

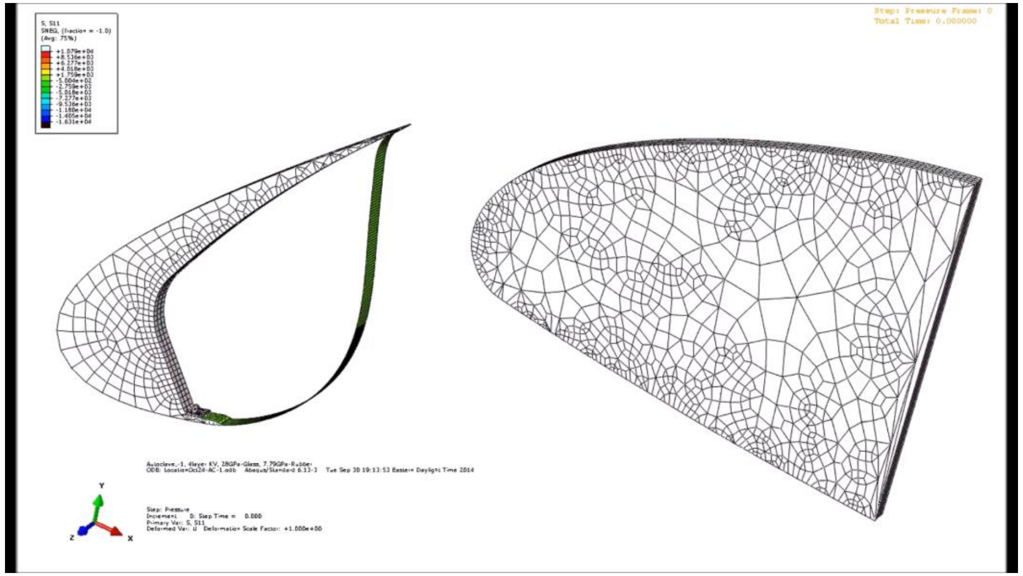
# Designing SCF Conformation by Computational Modeling

Computation modeling of SMP SCF actuation shows **unsuccessful** deployment with no mid-link



No mid-link → Deployment failed

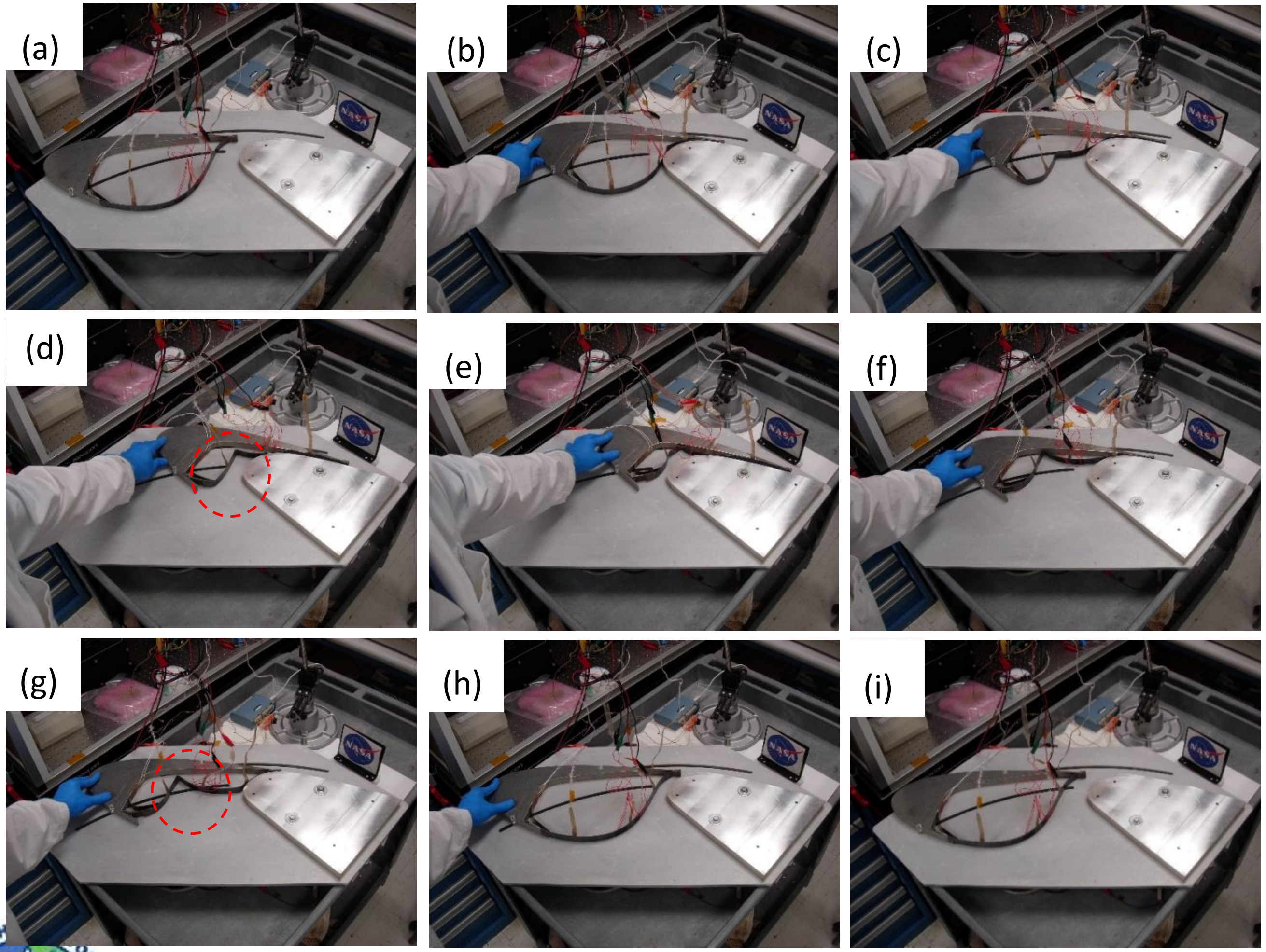
Computation modeling of SMP SCF actuation shows **successful** deployment with a mid-link



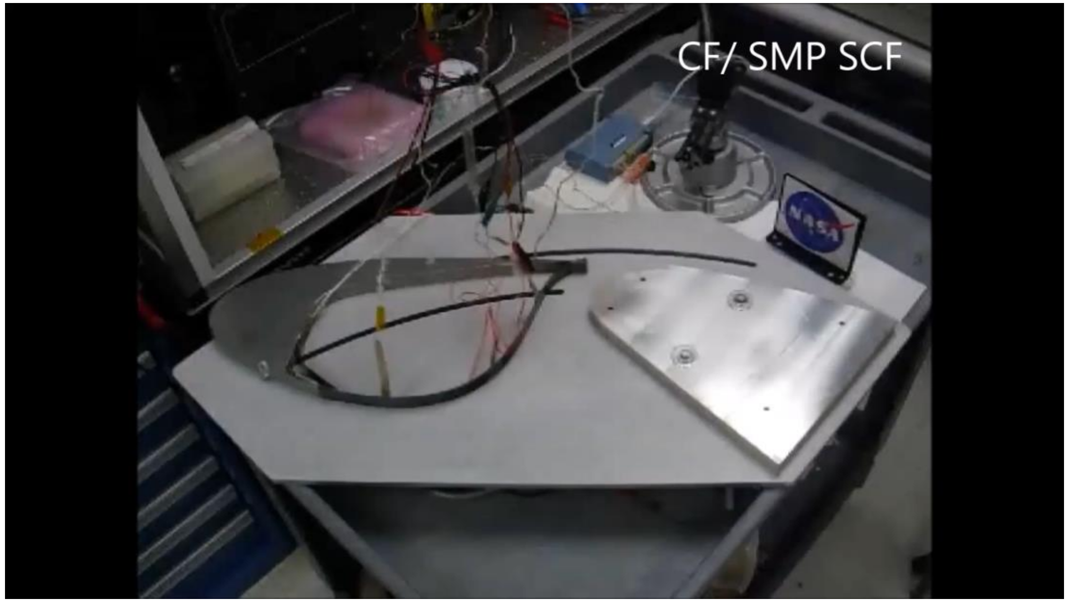
A mid-link (Length: 3”, mean location from bottom: 6.5”)

→ Successful deployment

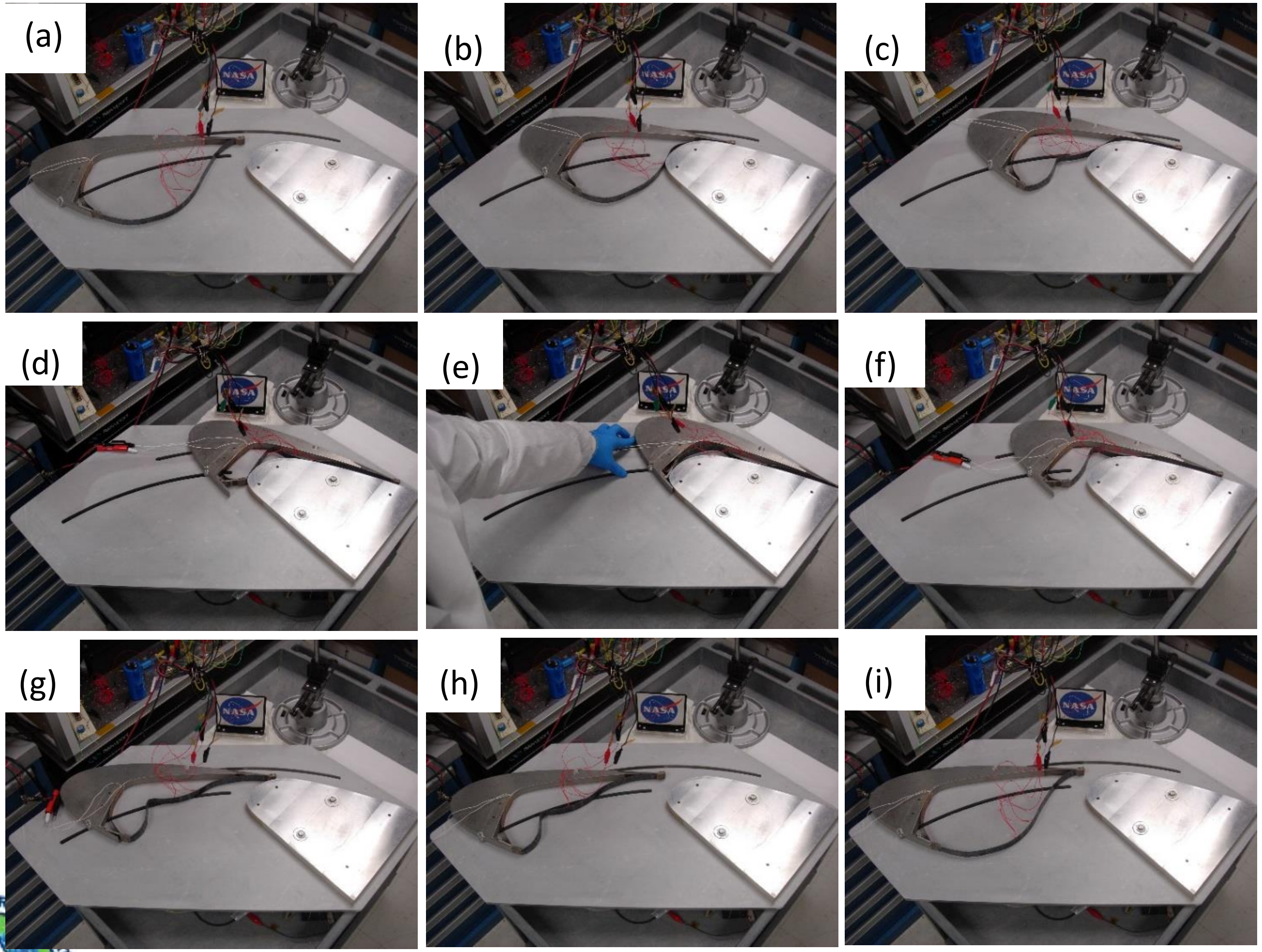
# Bench-Top Demonstration of SCF Fabricated with SMPC-1



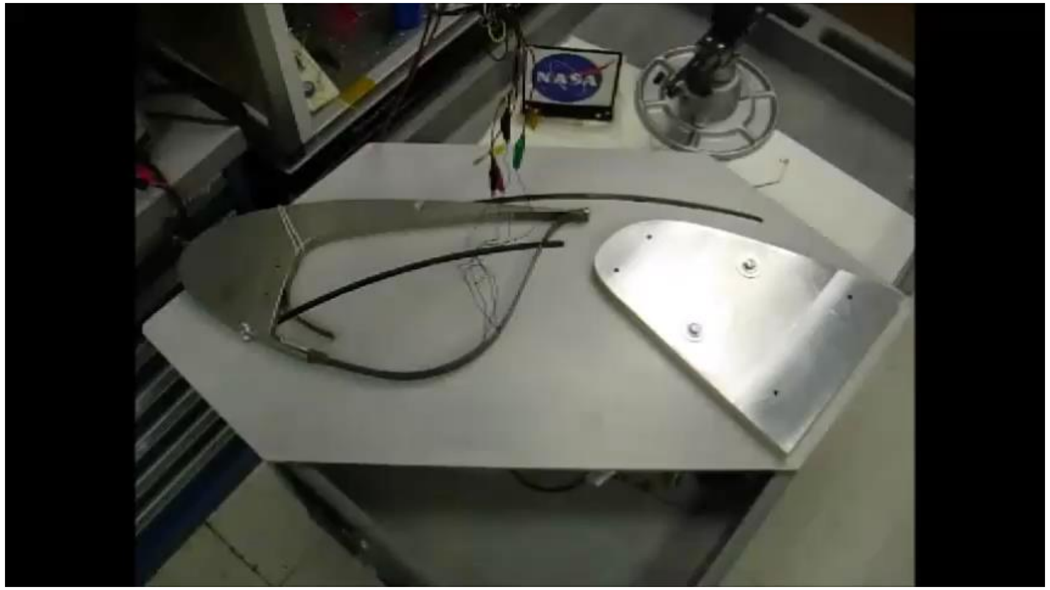

Bench-top demonstration of SCF fabricated with **CF/SMPC**. (a) before retraction, (b-h) full process of stowage and deployment, and (i) yielding **no permanent damage** after runs. However, there were **kinks** in bending



# Bench-Top Demonstration of SCF Fabricated with SMPC-2




Bench-top demonstration of SCF fabricated with **Carbon nanotube sheet (CNS)/SMPC**. (a) before retraction, (b-i) full process of stowage and deployment with **no damage and no kink**. However, deployment was **sluggish**



# Lessons from Adaptive Airfoil System Application

1. A new series of shape memory polymer composites (LaRC SMPC) fabricated with elastic layers and different fibers [Kevlar®, carbon fiber (regular and thin ply), carbon nanotubes sheet] was developed for adaptive airfoil system application to reduce aircraft noise.

2. The performance of slat-cove filler prototypes fabricated using various LaRC SMPC compositions was investigated with a bench-top apparatus that was representative of modern transport-class airframe geometry.

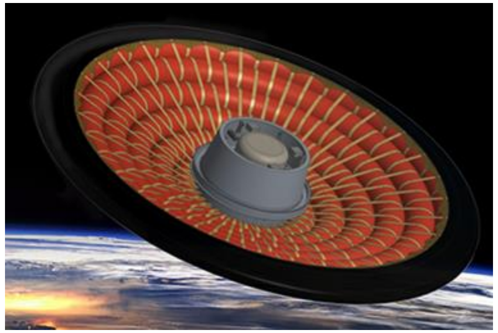
3. The SCFs made of Kevlar® fiber fabric or CF fabric infused SMPC kinked in simulated operation, which can be a critical mechanical problem for this application. The SCF made of CNS/SMP composite can be autonomously deployed and stowed without kinking, but deployment was sluggish compared to the CF/SMP composite.

4. A balance of strain capability, redeployment speed and steady aero-load sustainment remained elusive in this study. Among the lessons learned in this materials development effort is the need to assess material properties in simulated use conditions. In this case, investigation of the SCF fabricated with LaRC SMPC under simulated aerodynamic load exposed shortcomings in the material that would not have otherwise been noted.

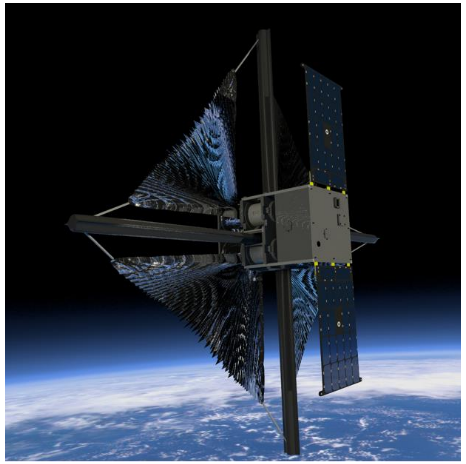
# Application 2 : Origami-Based Deployable Structure

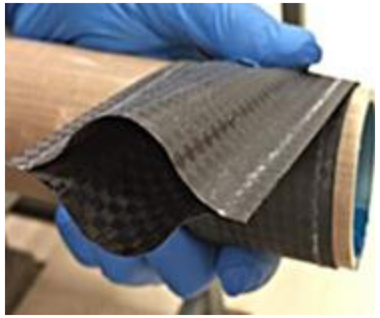
## Motivation

- Due to the confined volume of standardized launch vehicle cargos, large space structures are needed to be packed in a small volume and footprint before launch and are deployed or inflated into required geometry at the mission location.
- Inflatable structures need a continuous gas supplement to replace slow leakage of gas used for inflation or temperature adjustments to maintain required inflation pressure. High kinetic energy micrometeoroids can cause a catastrophic failure.
- Deployable composite tubular boom is an excellent lightweight system to hold relatively low mass payloads such as solar sails or solar arrays. However, its buckling load is not sufficient for load bearing structures like surface habitats.
- New origami-based SMP composite (SMPC) was developed for deployable load bearing structures.


Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID)


Inflatable habitat


Deployment of solar sail membranes and composite booms


Collapsible tubular mast boom rolled up for storage

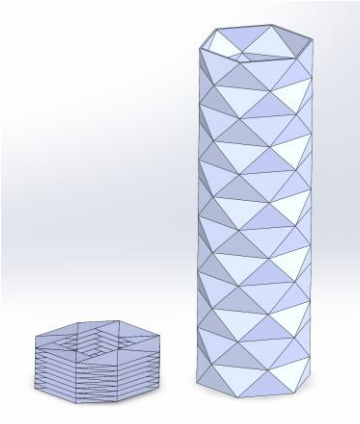
*Project PI: Drs. Keith Gordon/Jin Ho Kang

# Potential Applications

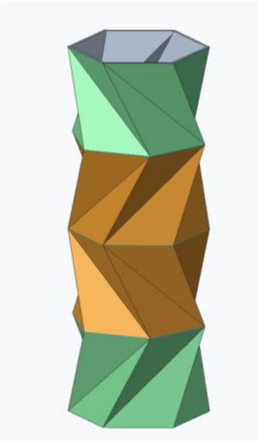
## Origami Patterns

*"Ori" meaning to fold and "Kami" meaning paper in Japanese*

- Miura-Ori pattern, Square twist pattern, Radial Flash Pattern, Tachi-Miura Polyhedron Pattern, Yoshimura Pattern, Kresling Pattern



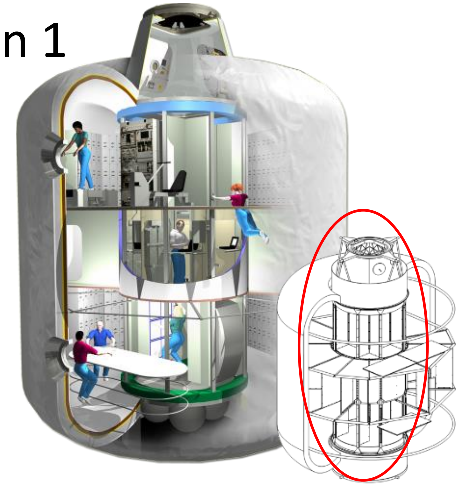
Yoshimura



Kresling

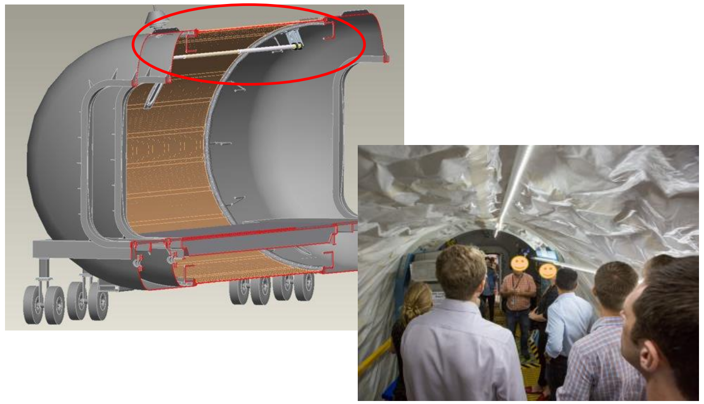
## Potential Target Applications

Application 1 (core structure)



Application 2 (legs)

Application 3 (beam)

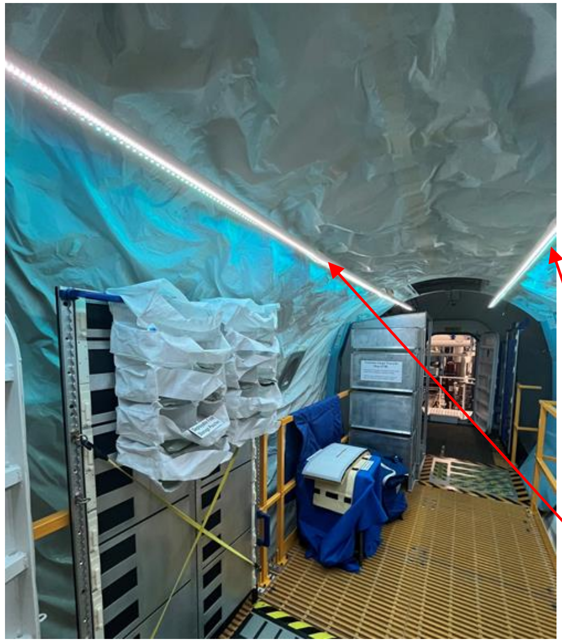


# Potential Applications

## Potential Application

- Support beams for habitat

xHab



Support Beams

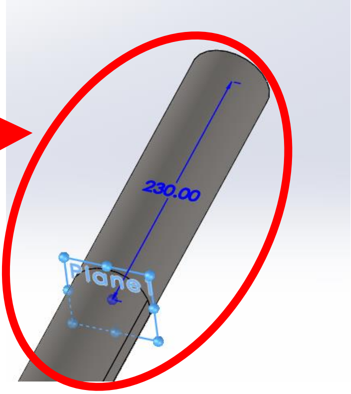
- Currently, beams are installed after expansion, but origami beams would deploy together with the habitat deployment.
- Beams need to hold their own weight and the weight of the heat blanket + restraint layer in case of >90% pressure drop, causing sagging.
- Will be replacing the function of both the light emitting diode (LED) beams on the inside and the exterior aluminum beams that hold the heat blanket.

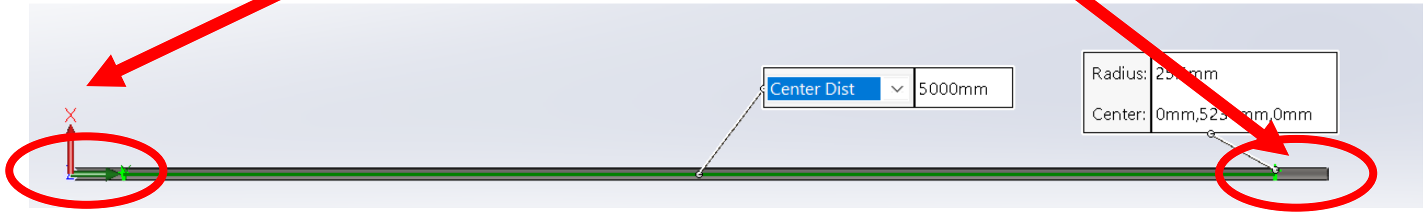
# Design Optimization

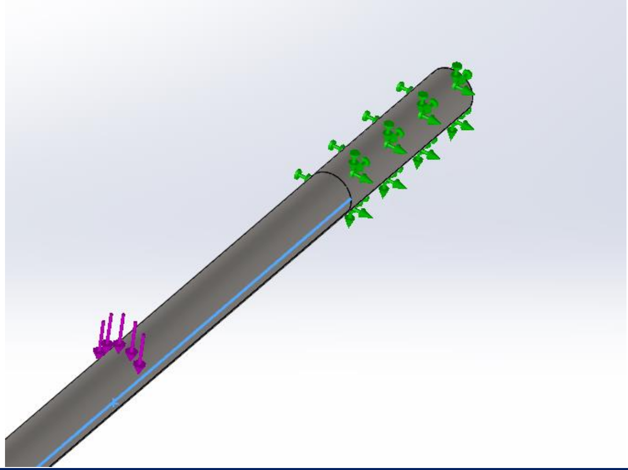
## Design Optimization by Finite Element Analysis (FEA) model

- Material comparison - simplified pipe

| Dimension | Value | Unit |
|---|---|---|
| Length between grips | 5 | m |
| Grip length | 0.23 | m |
| Total length | 5.46 | m |
| Outer diameter | 0.051 | m |
| Thickness | 0.001 | m |



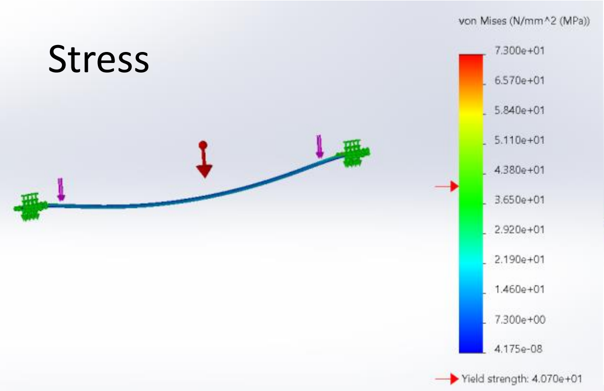



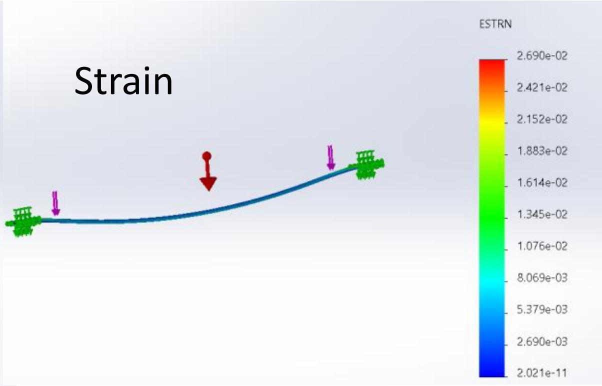
- Split line along middle of model (blue) – force from soft goods pressing down all of top half, which is worst case.
- 1180 N force applied along the 5 m area between grips
- 1.62 m/s gravity applied to whole model
- 12 mm mesh size

# Design Optimization

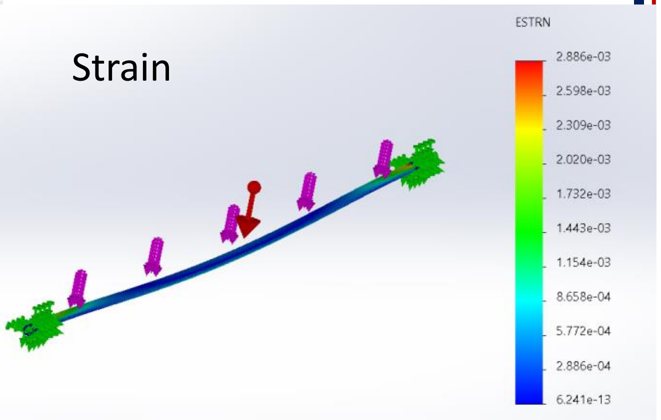
## Design Optimization by FEA model

| Materials | Analysis | Simulation Max Value | Material Yield Properties | Safety factor (SF) | Optimized Weight |
|---|---|---|---|---|---|
| Polyvinyl Chloride (PVC, current) | Stress | 65 MPa | 40.7 MPa | 0.6 | 12.9 kg (SF ~ 2.0) |
| | Strain | 2.4 % | 6% | 2.5 | |
| Aluminum 6061 T6 | Stress | 175 MPa | 275 MPa | 1.6 | 3.22 kg (SF ~ 2.2) |
| | Strain | 0.22 | 7.87% | 35.8 | |
| CF/Epoxy SMP (*IM7/8552) | Stress | 163 MPa | 2538 MPa | 13.5 | 0.164 kg (SF ~ 5.3) |
| | Strain | 0.3 % | 1.5% | 5 | |



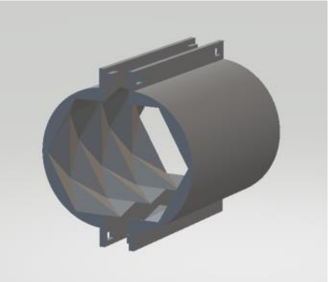

PVC Pipe (current)

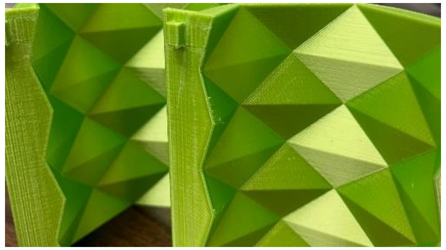



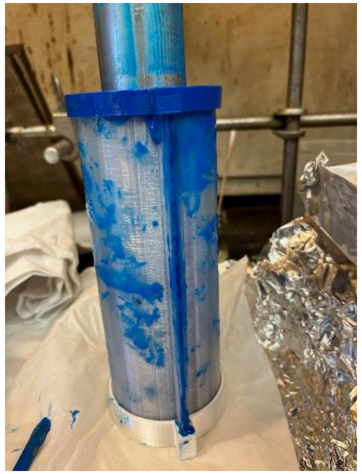

CF / Epoxy Pipe

# Fabrication of Prototype

Yoshimura Pattern Beam








2.4"D x 4.6" H x 0.017“T

# Evaluation of Deployment (Shape Memory Effect)

## Yoshimura Patterned SMPC Beam

Original Shape

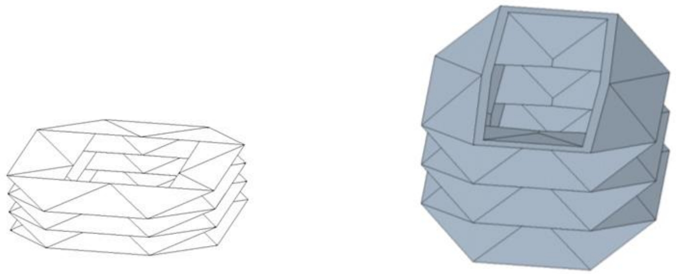
Programmed Shape
(Stowed)

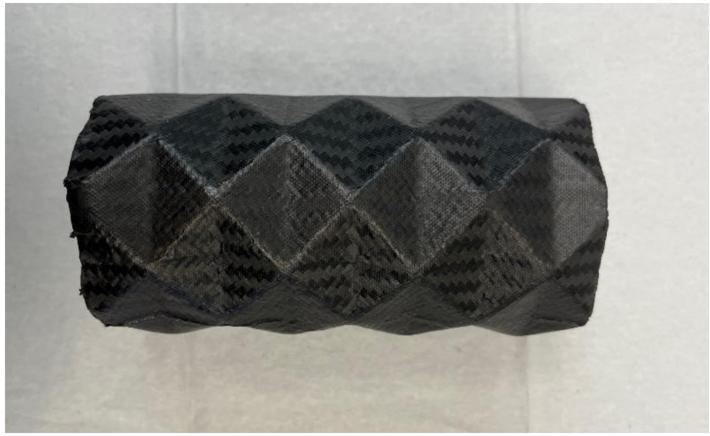

Recovered Shape
(Deployed)

Packing Efficiency ~ 13%

# Lessons from Origami-Based SMPC

1. Novel origami-based deployable and rigidizable shape memory composite was developed for load bearing space structures.
2. Potential applications include core structure or floor beams, anti-sagging ceiling beam and supporting legs.
3. Sub-scale size origami SMPC beam was fabricated and deployment was demonstrated.
4. There was technical difficulty to fold in designed folding lines.
5. Hybrid resins system may solve the folding issue.

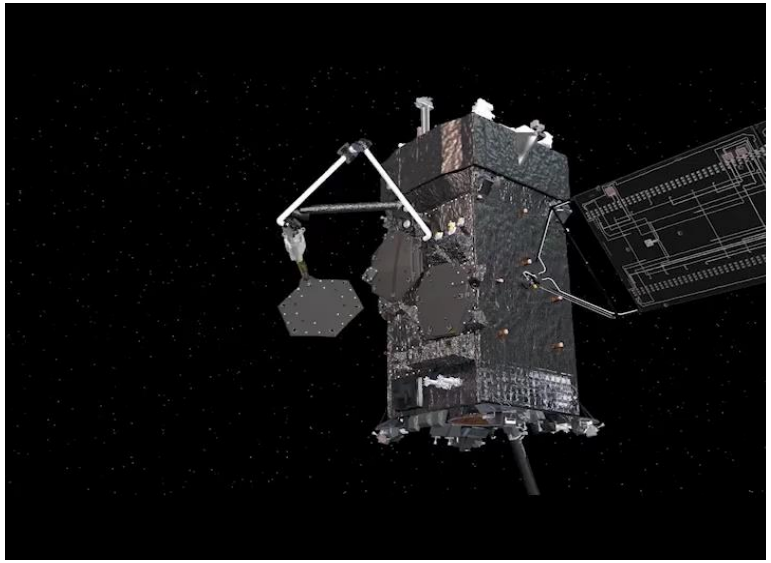




# Application 3 : Deployable Reflector Antenna

## Motivation

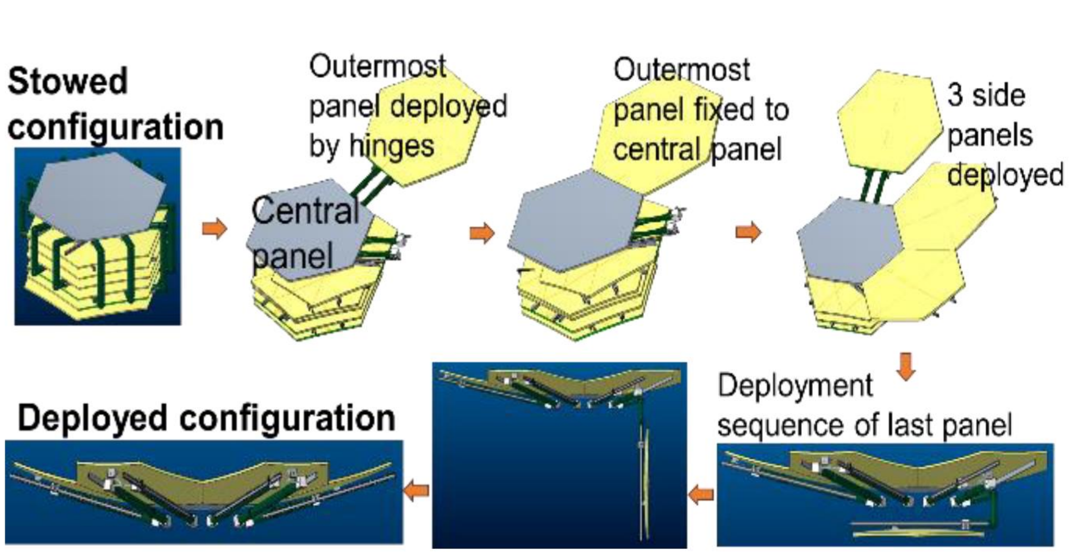
- Current launch vehicle fairing can accommodate fixed solid reflector antennas of 4-meter diameter.
- Typical architecture of deployable solid surface reflector is to have a central hub surrounded by a series of petals or gores supported on a deployable metering structure
- Those designs limit size to less than 10 meters in diameter due to high mass and mechanical complexity.
- An on-orbit servicing, assembly and manufacturing mission (OSAM-1) is planned to demonstrate in-space assembly of a 3-meter reflector antenna from seven 1-meter size hexagonal rigid panels using Space Infrastructure Dexterous Robot (SPIDER) by MAXAR Technologies.
- LaRC and MAXAR established a new collaboration effort of new advanced packaging method using flexible composite technology.
- A shape memory polymer composite tubular hinge was developed for this application.



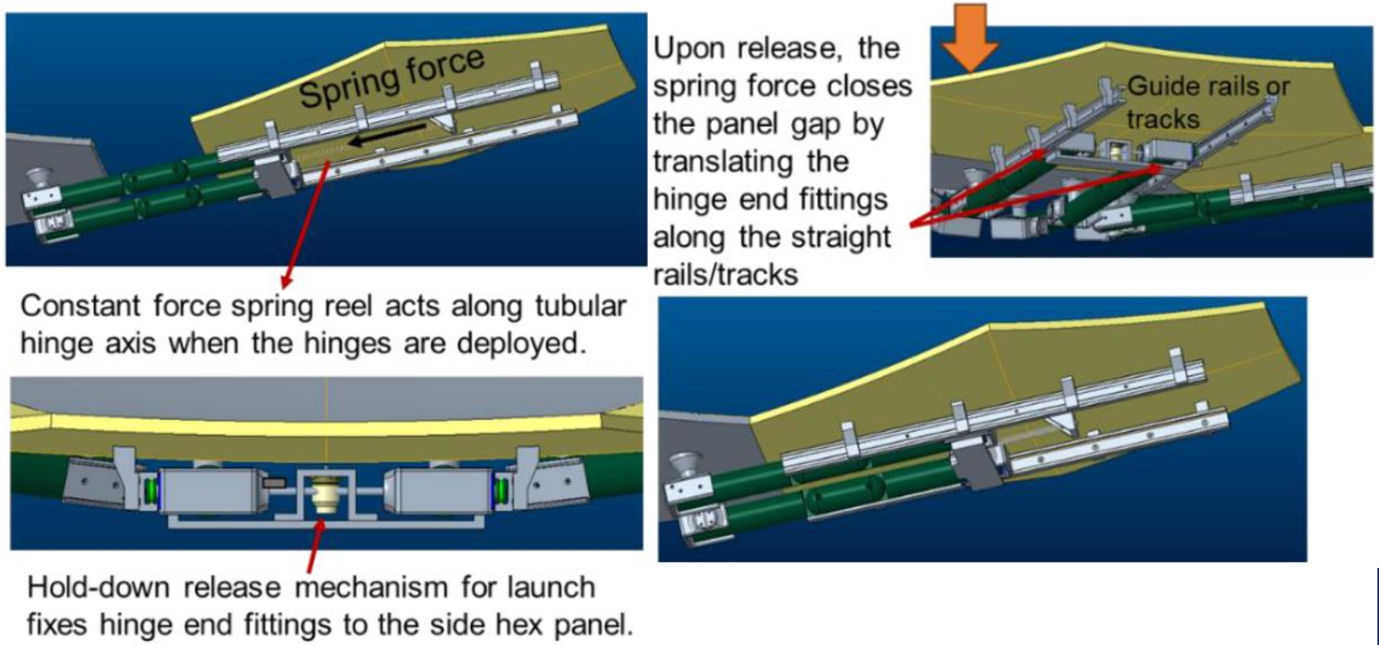
Space Infrastructure Dexterous Robot (SPIDER) in the OSAM-1 spacecraft

*Project PI: Dr. Juan Fernandez

# Architecture Design




Deployment sequence of a concentrically stacked seven-panel reflector by SMC hinges. Side panel deployment occurs one at a time from the outmost panel until all are fixed to the central panel.

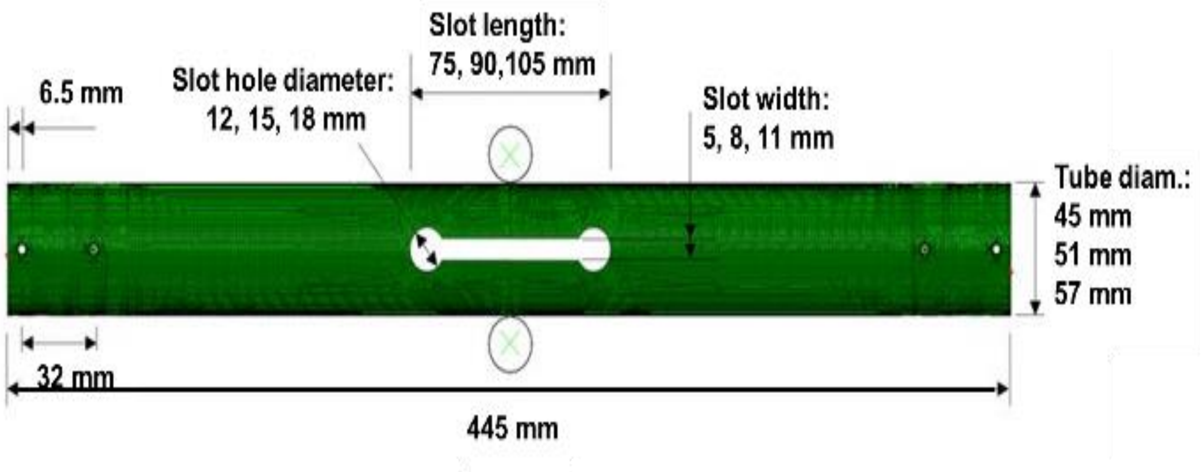


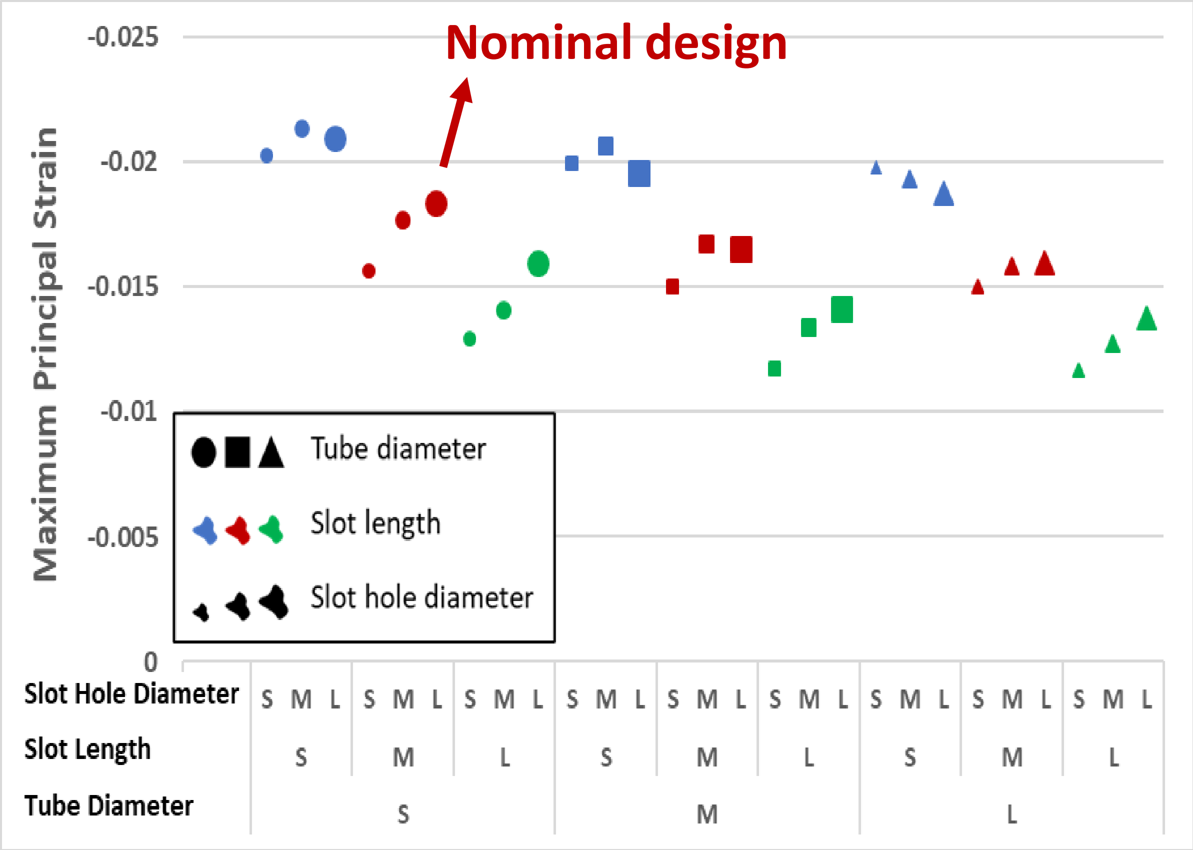

Secondary spring-loaded mechanism to close the initial inter-panel gap left by the pair of hinges.

The use of a new SMPC with integrated heating and sensing capabilities was developed to reduce part count (complexity), power requirements, and cost of larger antenna reflectors, while enabling a high deployed stiffness solution with predictable and controlled deployment dynamics

*Ref.* J. M. Fernandez et al., 41st ESA Antenna Workshop on Large Deployable Antennas, Sept. 2023, ESA-ESTEC in Noordwijk, The Netherlands

# SMPC Tubular Hinge Design and Test



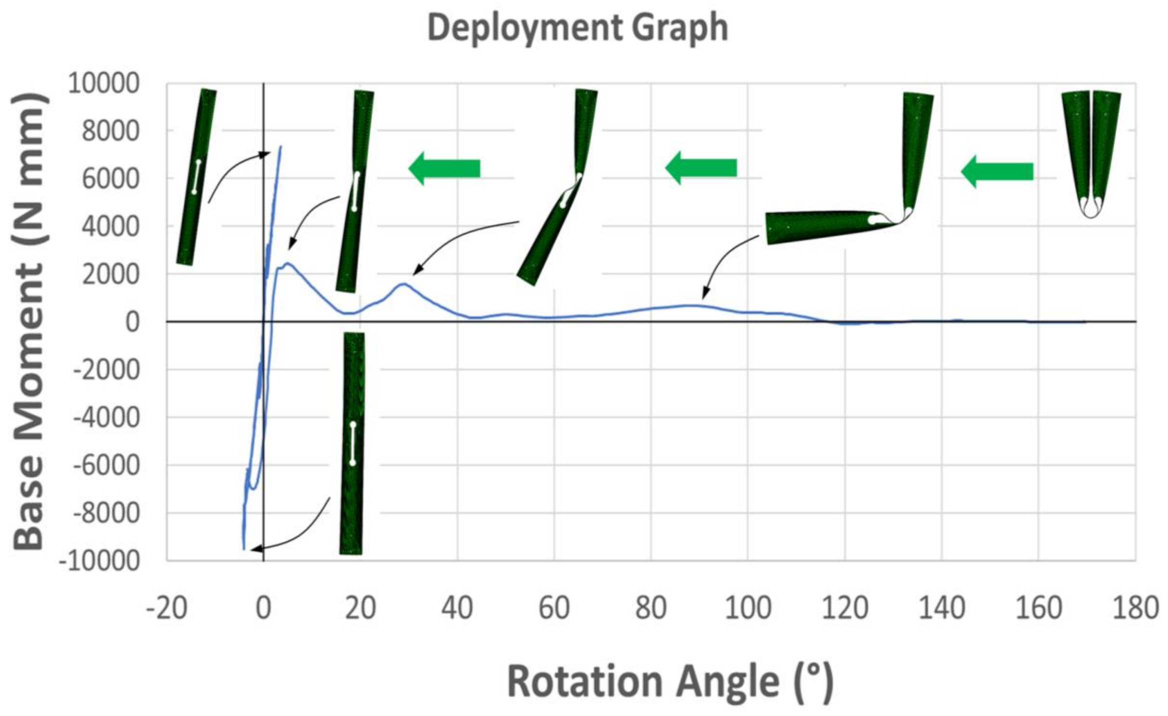




Three independent parameters: tube diameter, hinge slot length, and the diameter at the end of the dogbone slot (with the slot width being proportional to it) with three different dimensions (small, medium and large) generated a total of 27 analysis cases.

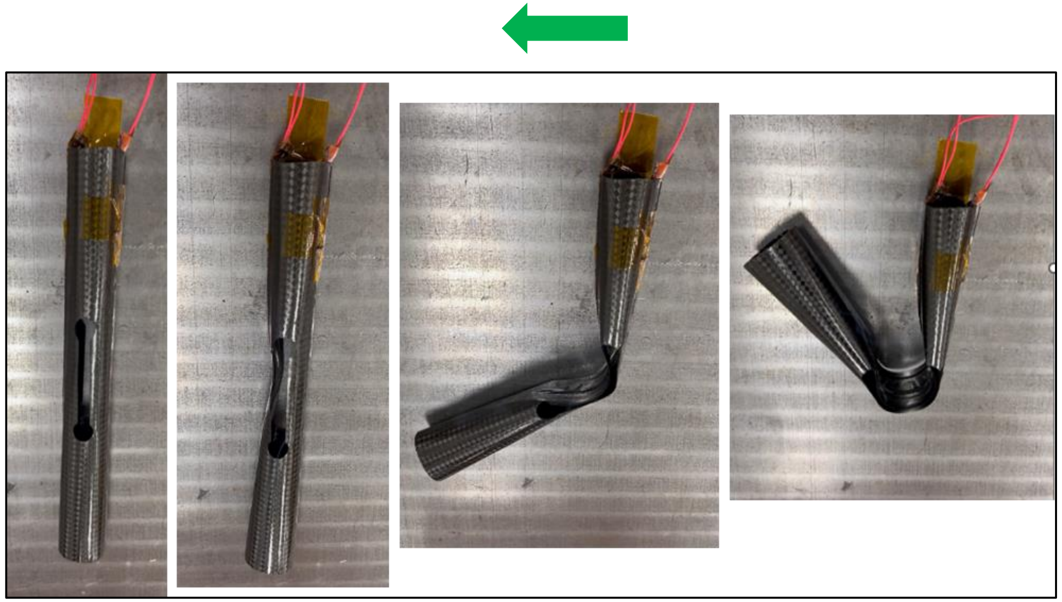
Folded strains between 1.2% to 2.2% are expected, suggesting the use of intermediate modulus CF laminates with high strain to failure or elastomeric-like resin

*Ref.* J. M. Fernandez et al., 41st ESA Antenna Workshop on Large Deployable Antennas, Sept. 2023, ESA-ESTEC in Noordwijk, The Netherlands

# SMPC Tubular Hinge Design and Test




Deployment moment-rotation relationship graph showing final moment peaks when the hinge snaps through



Test article deployed using the embedded heaters locking into the final straight configuration

Large peak moments after hinges reach final straight configuration at 0° angle
Hinge vibrates back and forth until the kinetic energy dissipates

*Ref.* J. M. Fernandez et al., 41st ESA Antenna Workshop on Large Deployable Antennas, Sept. 2023, ESA-ESTEC in Noordwijk, The Netherlands

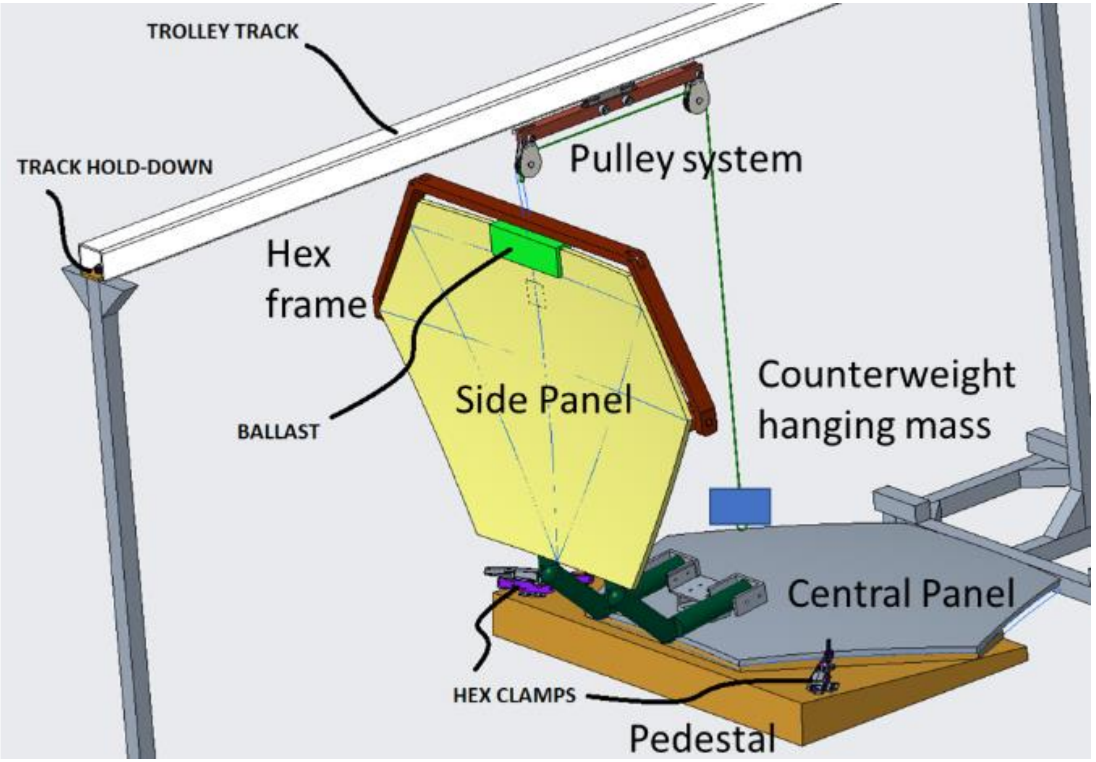
# Lessons from Deployable Reflector Antenna

1. New architecture for solid surface antenna reflector that combines deployment of unit cells of vertically-stacked, seven-hexagonal panel sub-reflectors compatible with robotic assembly into larger version.

2. Parametric study helped in SMC hinge design with baseline case showing acceptable folding strains, sufficient stiffness and low deployment dynamics.

3. There was an interfacial delamination issue between the heater tape and SMPC layer.

4. Final 3-m scale test article and test configuration presented will be used to demonstrate efficient stowage with minimal constrains, controlled deployment, and maintain necessary shape accuracy of < 3 mm root mean square (RMS) error in a relevant environment.



# Summary and Future Works

1. Series of novel LaRC shape memory polymer composites (LaRC SMPC) were developed for various applications from terrestrial to space applications, such as adaptive airfoil system (slat cove filer), origami-based SMPC beam in a space habitat and deployable reflector antenna.

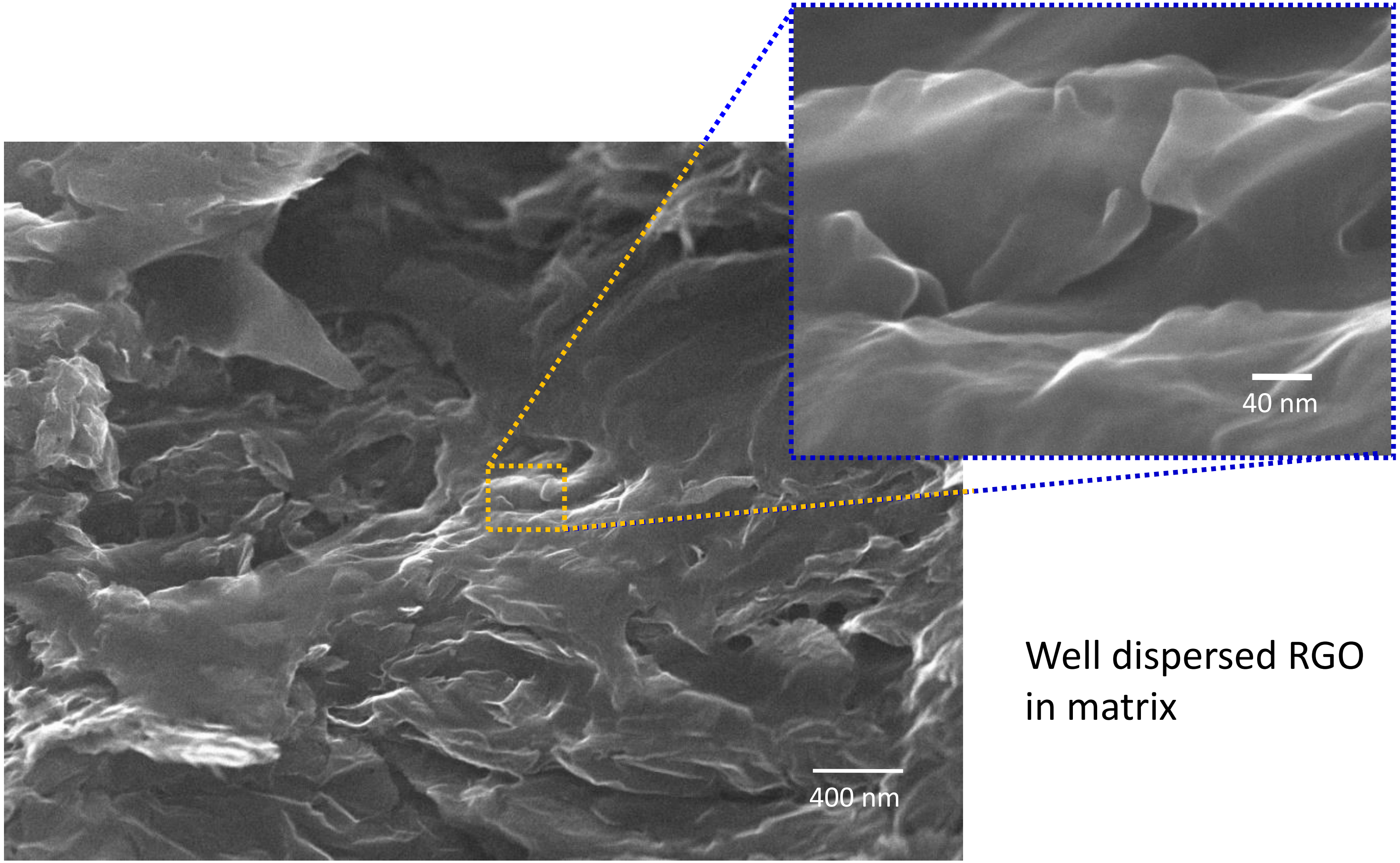
2. The exotic properties of shape memory effect, stowage/deployment capabilities, relatively fast response time, large recovery stress, tailorability were successfully characterized.

3. Some promising demonstration tests of application were achieved, but there still remains room to solve the engineering problems such as long-term durability of multiple deployments.

4. Improved interfacial strength between CF and SMP or between SMP and heater may mitigate the current issues.

# Backup

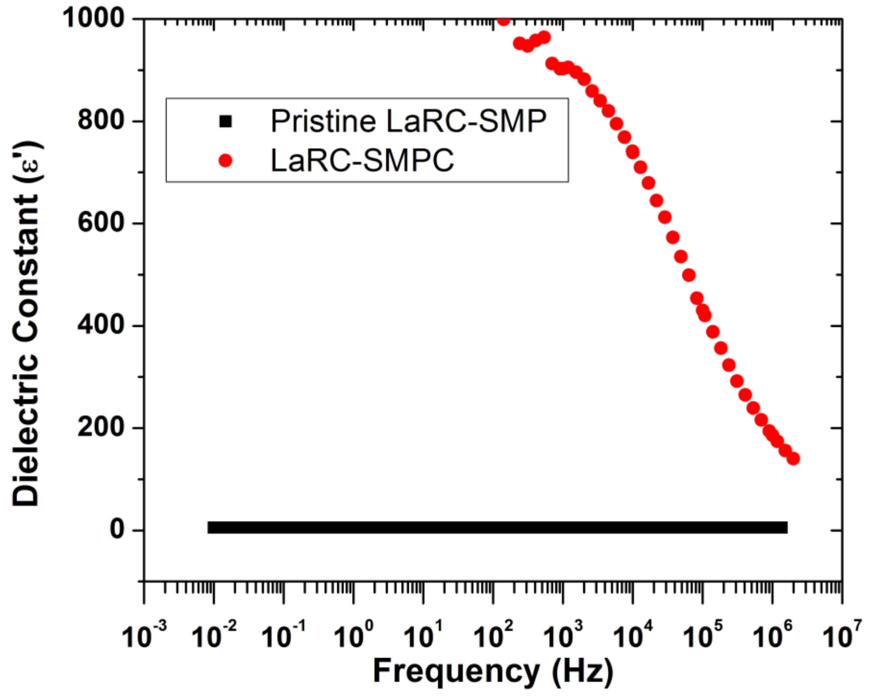
# Morphology of LaRC SMPC (2% RGO)



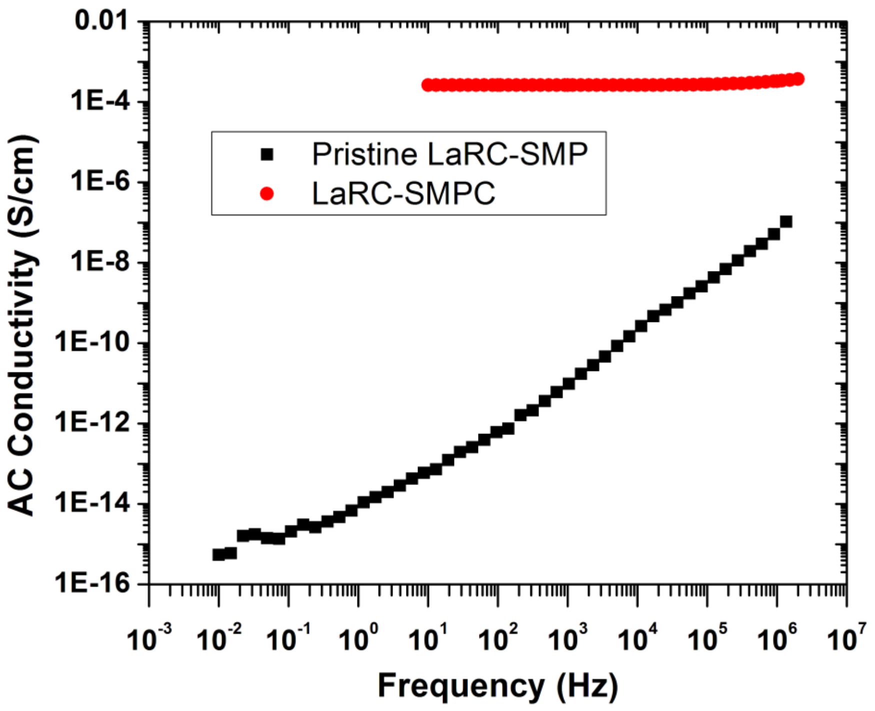

Well dispersed RGO in matrix

# Tailoring Properties – 3 : Electrical Properties

Dielectric constant

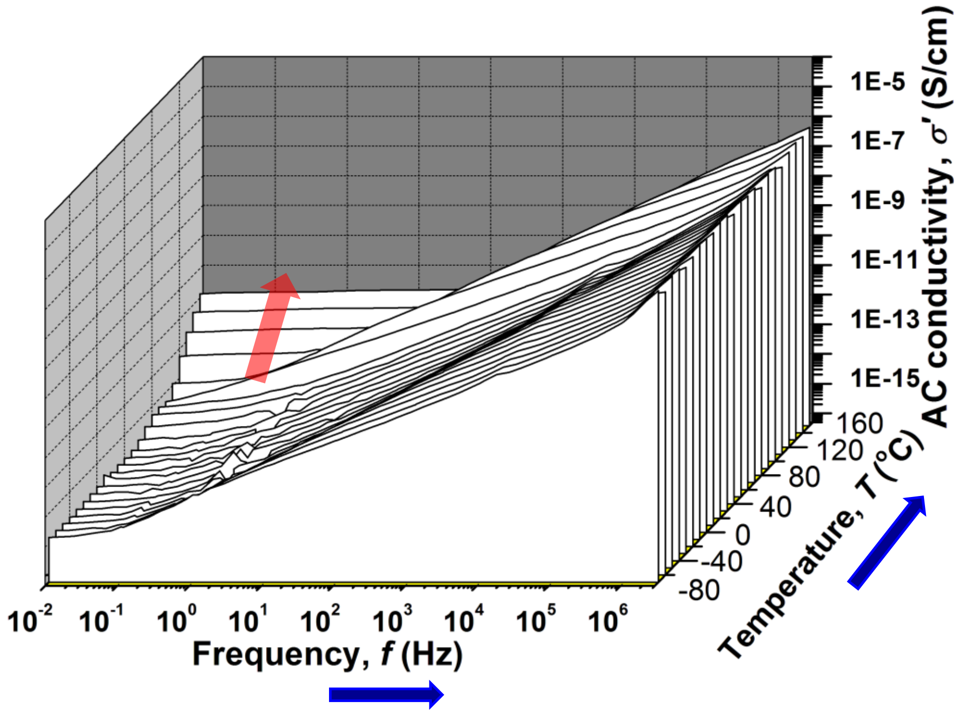


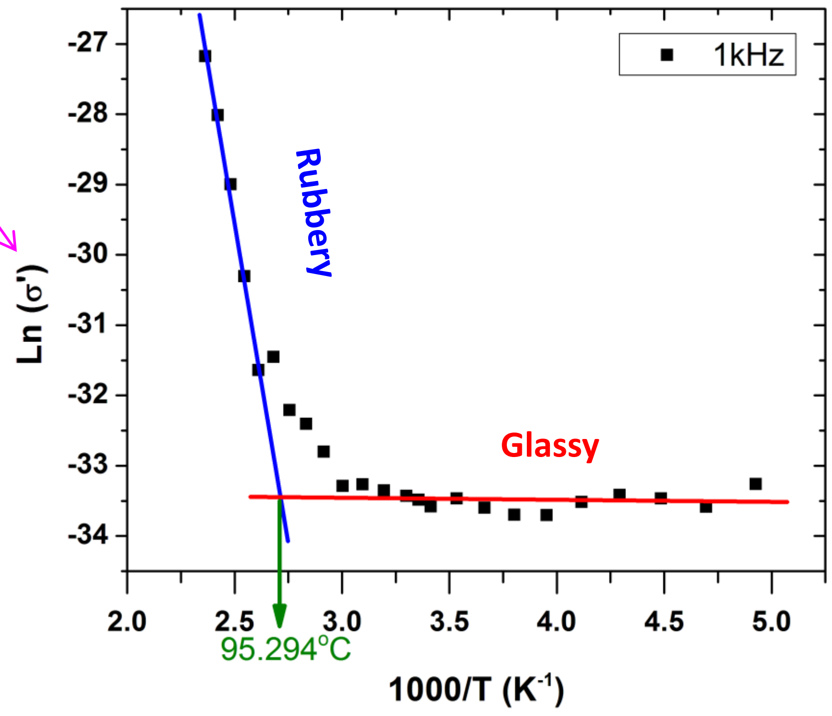

AC conductivity




LaRC SMPC has high electrical conductivity and high dielectric constant

# AC Conductivity of LaRC SMP

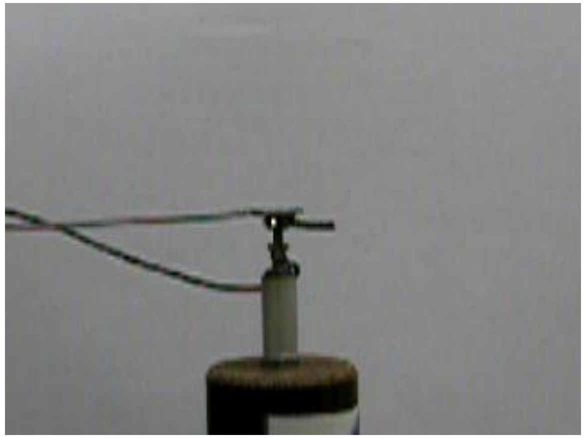



LaRC SMPC has high electrical conductivity and glass transition temperature of about 95°C

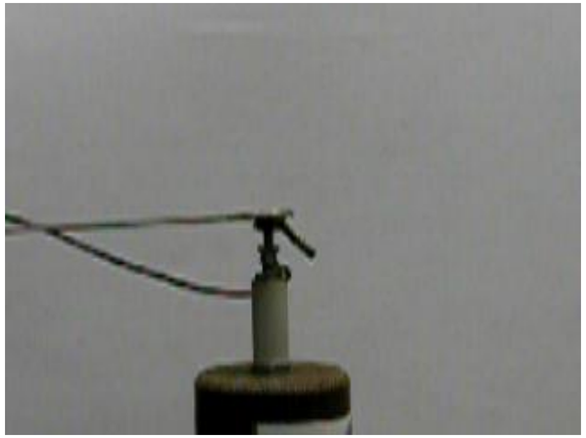
# Electric Field Activated Shape Memory Effect

Voltage ON

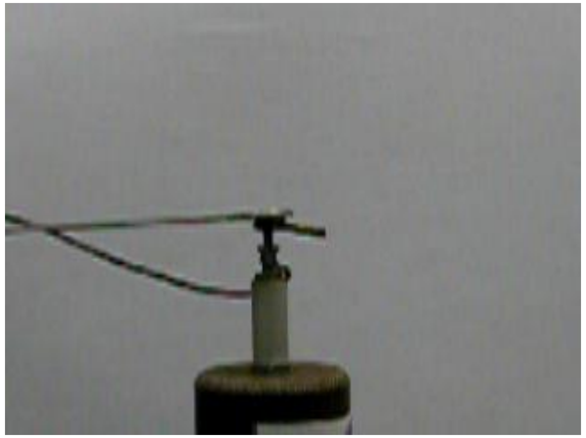


Voltage OFF - Cooling

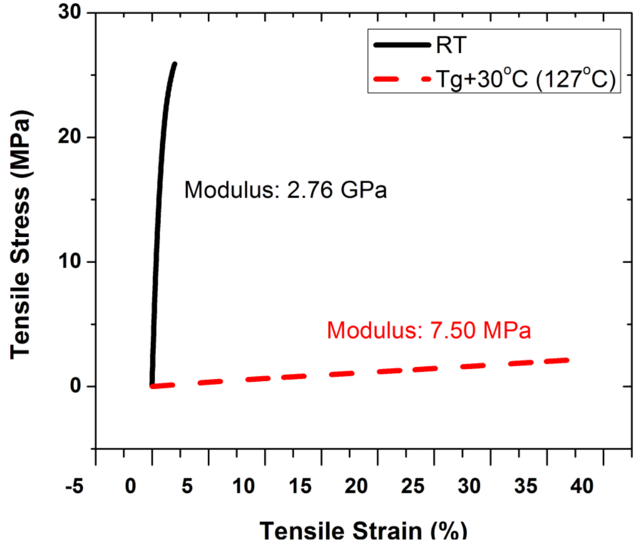
Cooling → Voltage ON again



Voltage OFF - Cooling

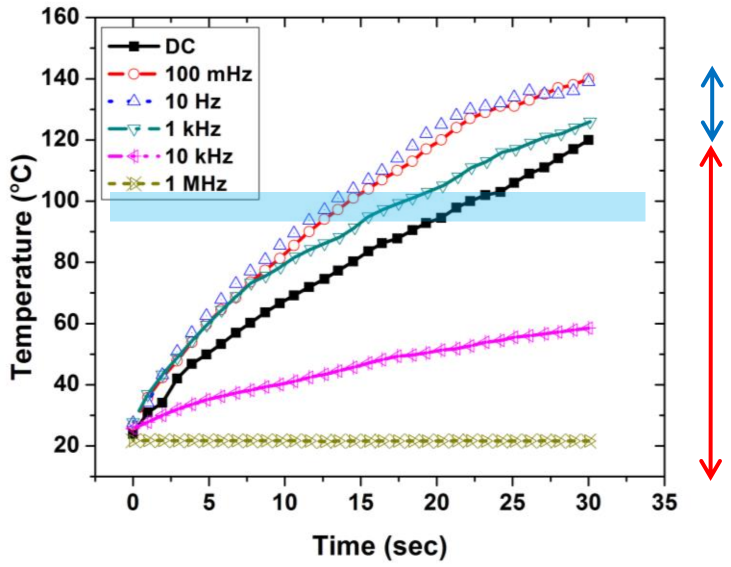


DC 13V (0.01 MV/m)
Cr/Au Electroded




***Joule Heating ($Q = I^2Rt$ )***

# Mechanism of Effect of AC Electric Field on SME



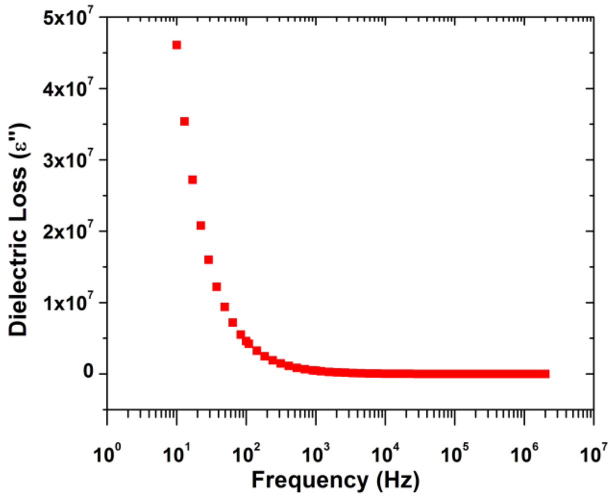

Loss Heating from dipole orientation

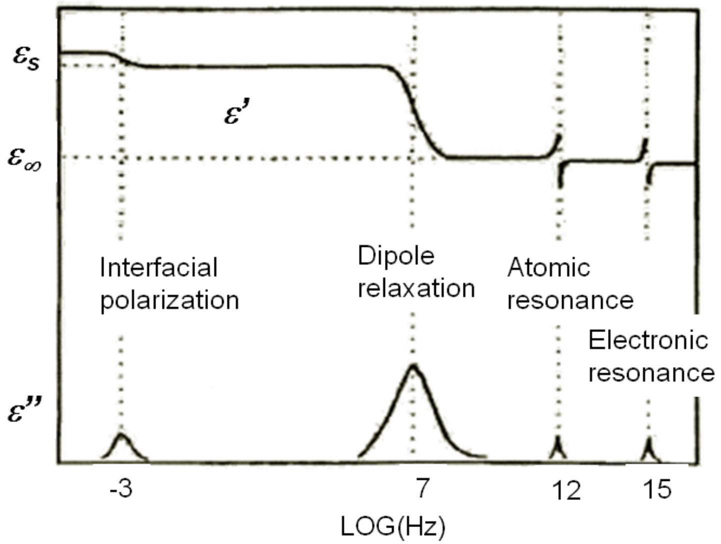
$$P = K f E^2 \varepsilon''$$

Joule heating from DC

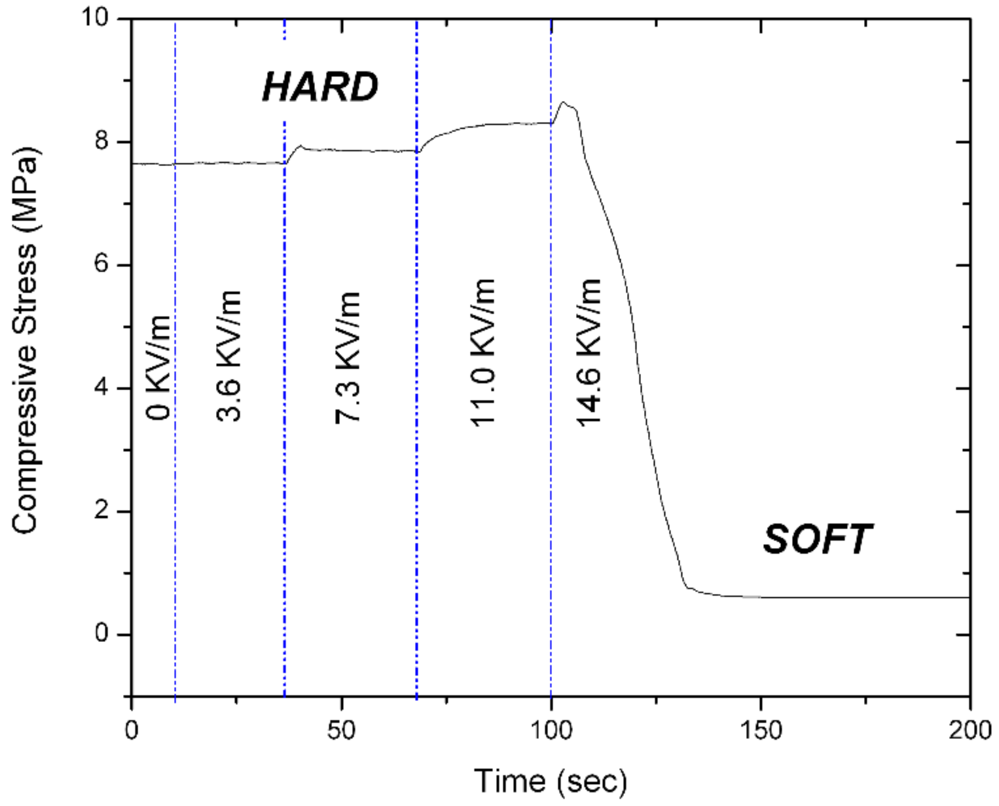
$$Q = I^2 \cdot R \cdot t = V \cdot I \cdot t = \frac{V^2}{R} \cdot t.$$

$$P = V \cdot I = \frac{V^2}{R}.$$



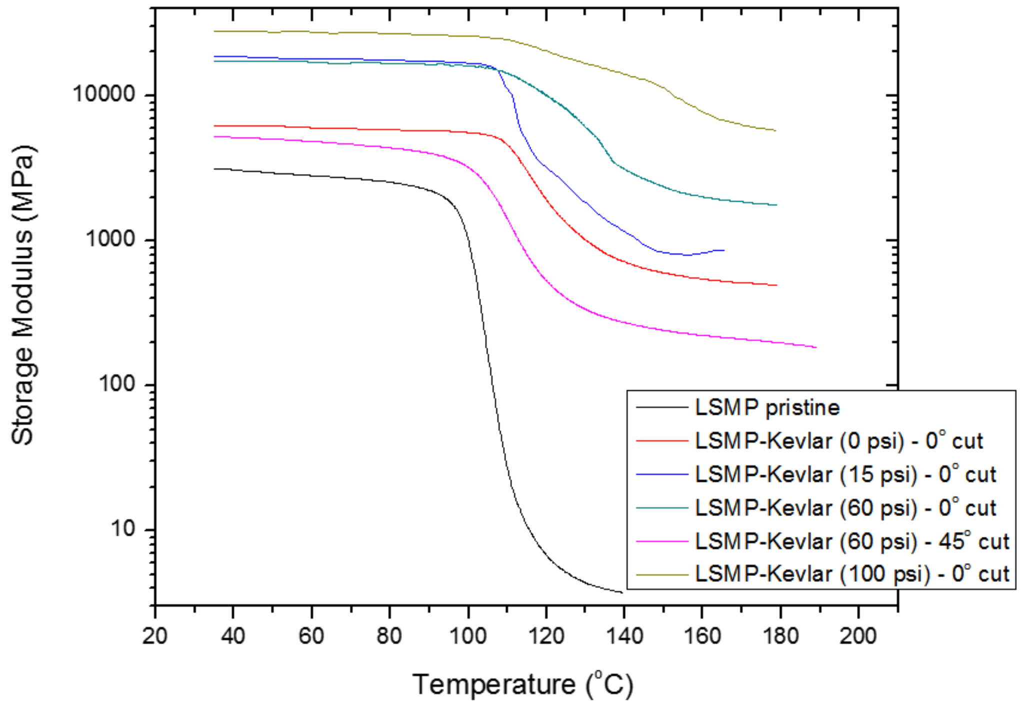



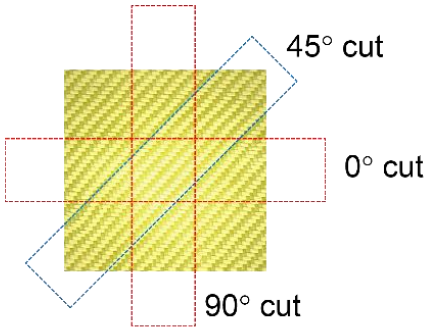
# Effect of DC Electric Field on SMPC

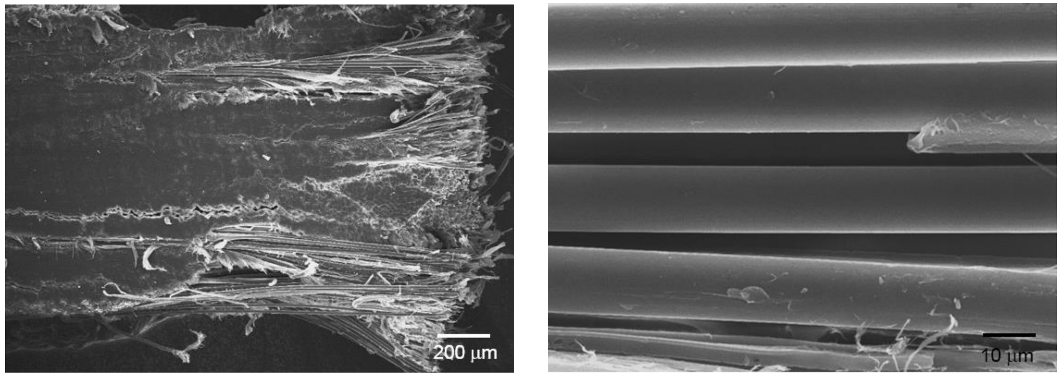



Mechanical stiffness change of LaRC-SMPC under applied DC electric field

# Dynamic Mechanical Analysis of Kevlar® Reinforced SMPC

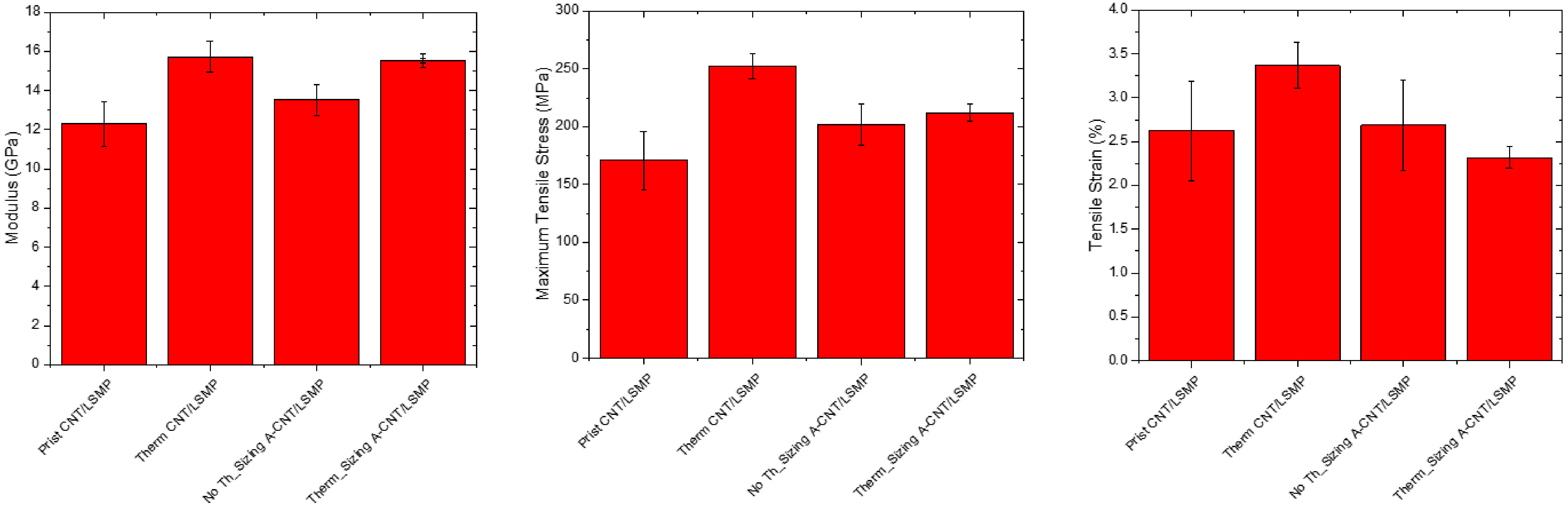


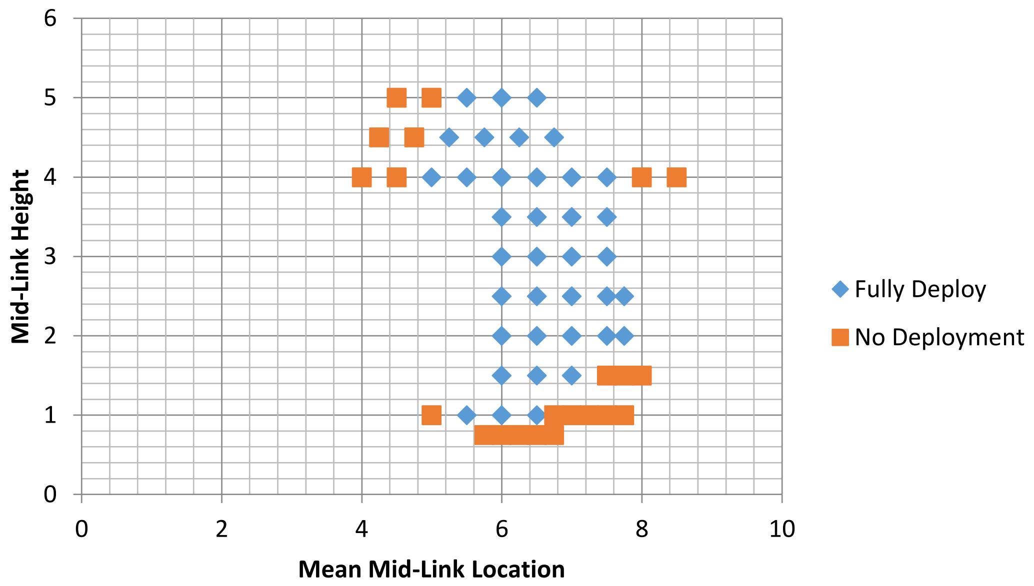

Cross-sectional SEM images of Kevlar® fabric reinforced SMPC

# Mechanical Properties of CNS Reinforced SMPC

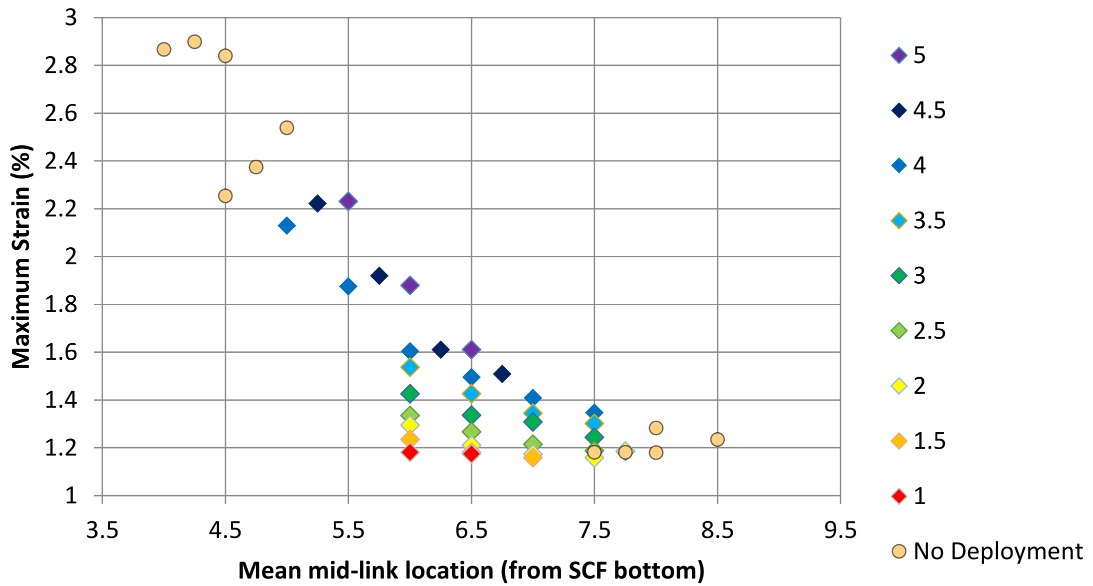



In order to increase interfacial strength between CNTs and SMP resin, CNT sheets were modified by three different methods: (1) thermal treatment at 250°C for 1 hr, (2) sizing treatment (epoxy based sizing material) without thermal treatment, and (3) sizing treatment (epoxy based sizing material) after thermal treatment at 250°C for 1 hr.

# Designing SCF Conformation by Computational Modeling



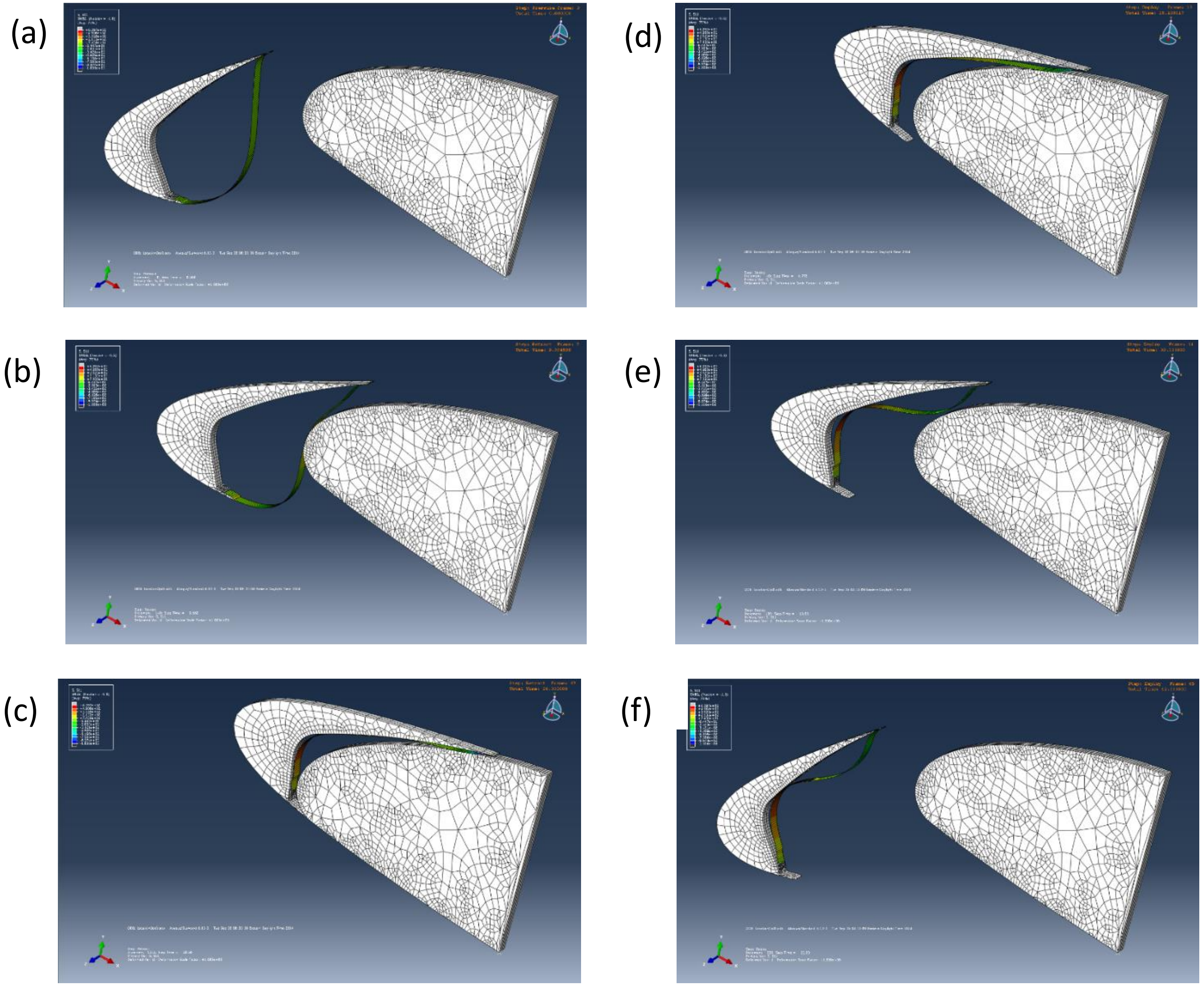

Optimization of mid-link height and location for successful deployment.



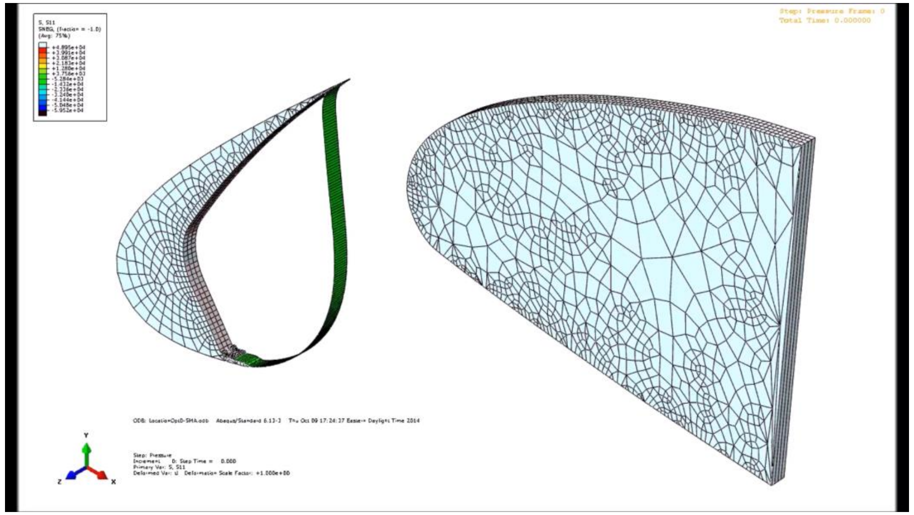

Maximum strain verses mid-link location for various mid-link sizes

Because the preferred maximum strain is below 2% for composite materials, the optimized mid-link location and size was about 15.24 to 19.05 cm (6 to 7.5 inches) and about 3.81 to 12.7 cm (1.5 to 5 inches), respectively. The optimized parameters were employed for the fabrication of SCF.

# Designing SCF Conformation by Computational Modeling

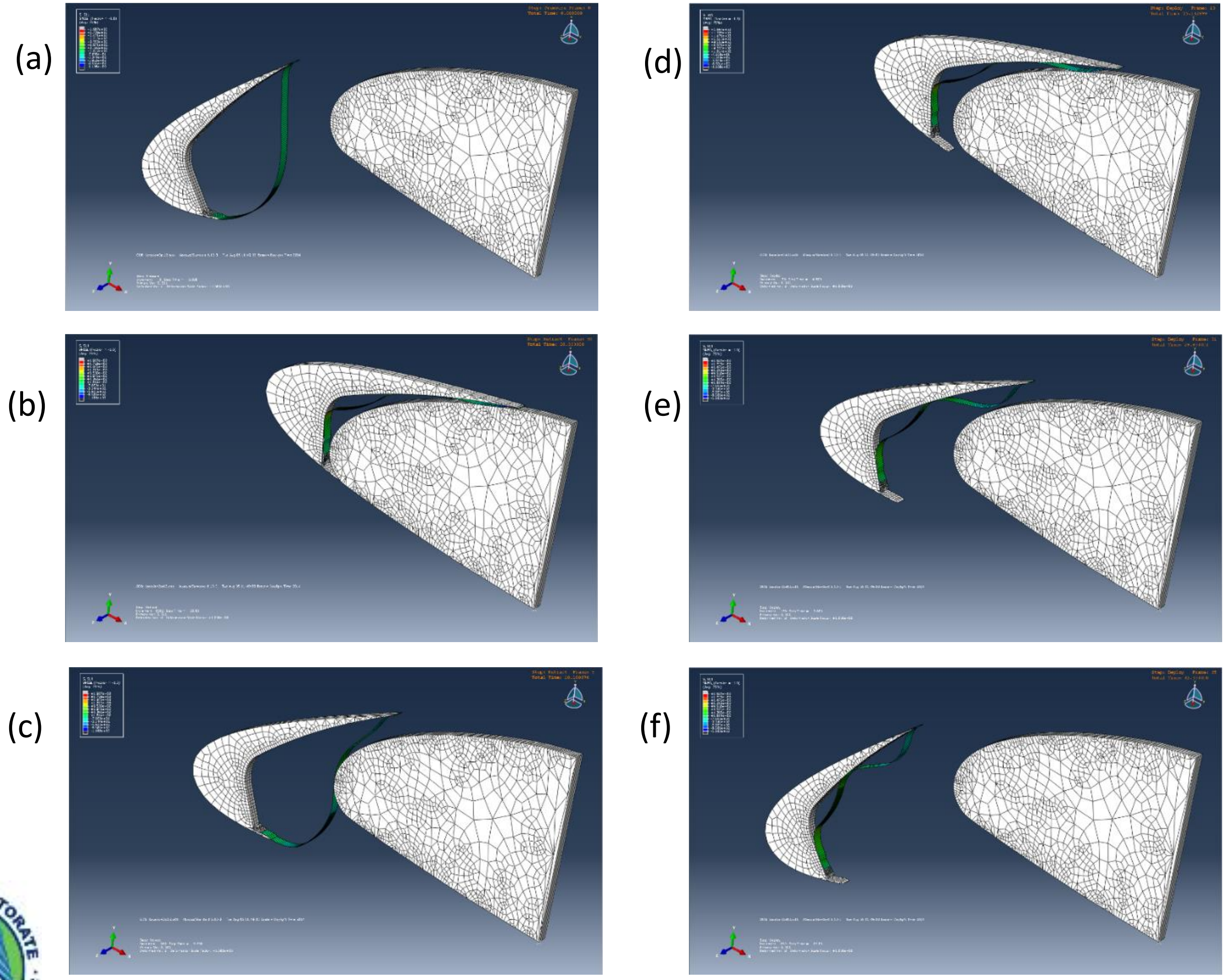



Computation modeling of SMP SCF actuation shows unsuccessful deployment with no mid-link. (a –c) retraction, and (d-f) deployment.

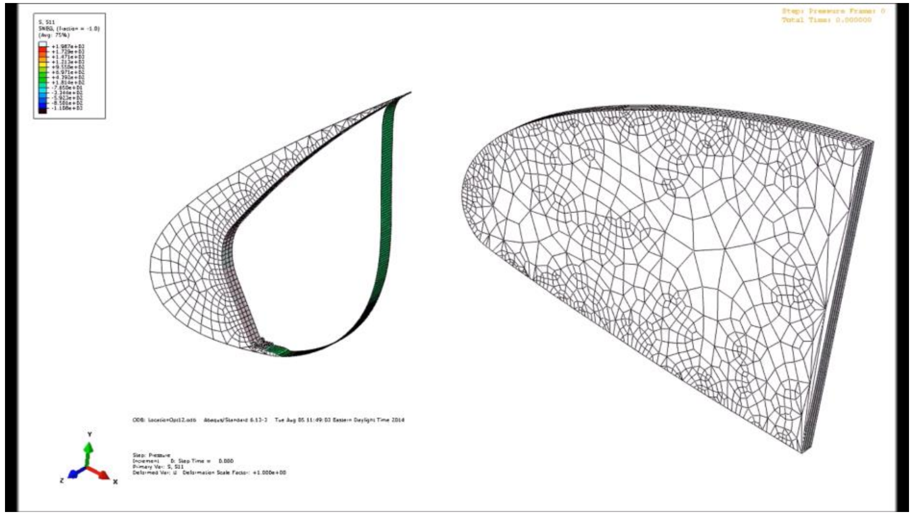


No mid-link → Deployment failed

# Designing SCF Conformation by Computational Modeling



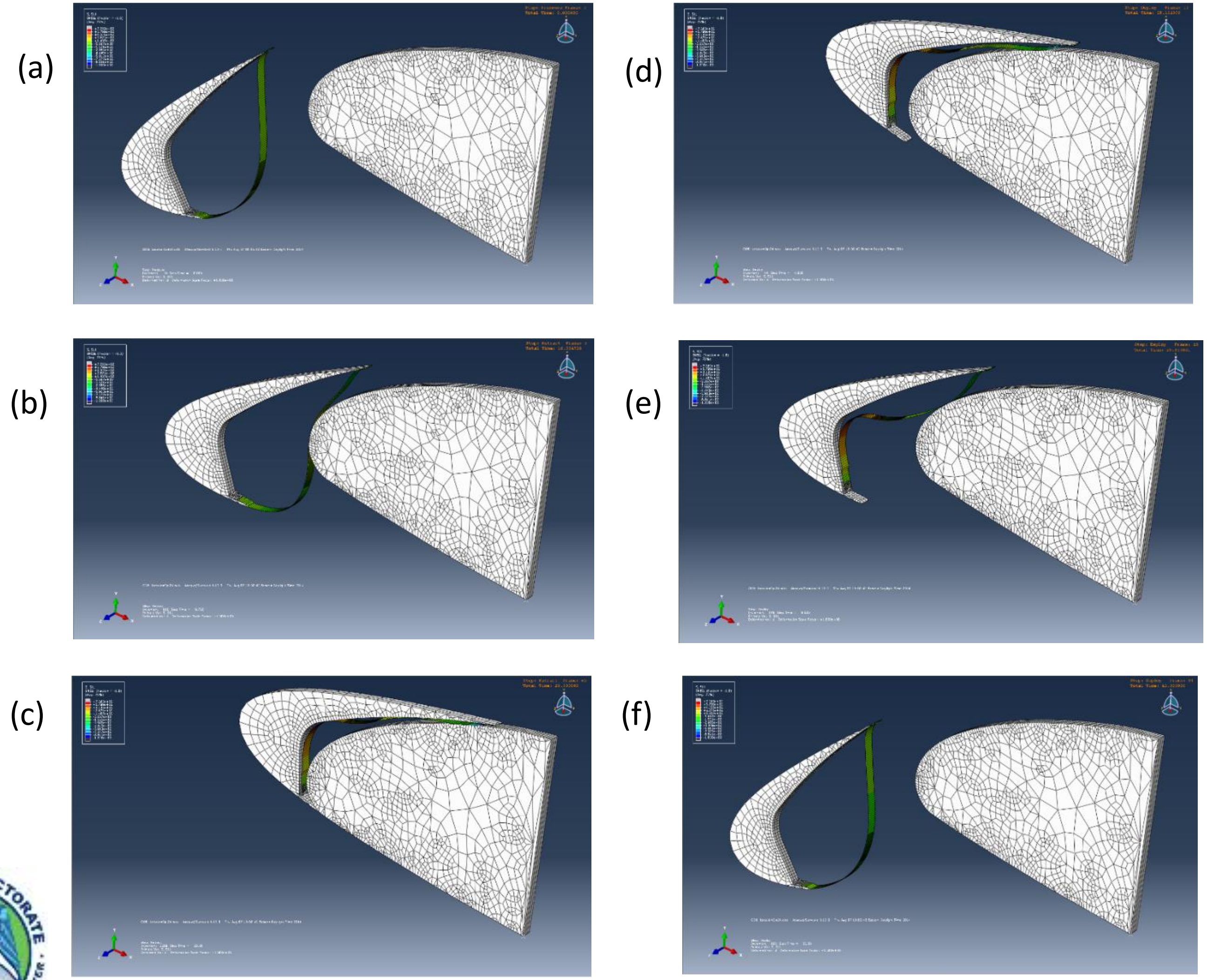
Computation modeling of SMP SCF actuation shows unsuccessful deployment with a mid-link (Length: 4”, mean location from bottom: 4”). (a –c) retraction, and (d-f) deployment.



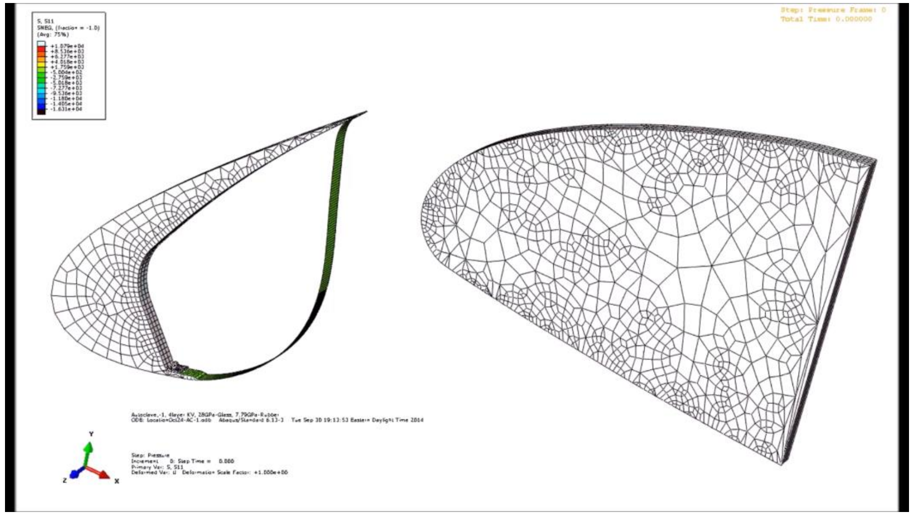
A mid-link (Length: 4”, mean location from bottom: 4”)

→ Deployment failed

# Designing SCF Conformation by Computational Modeling



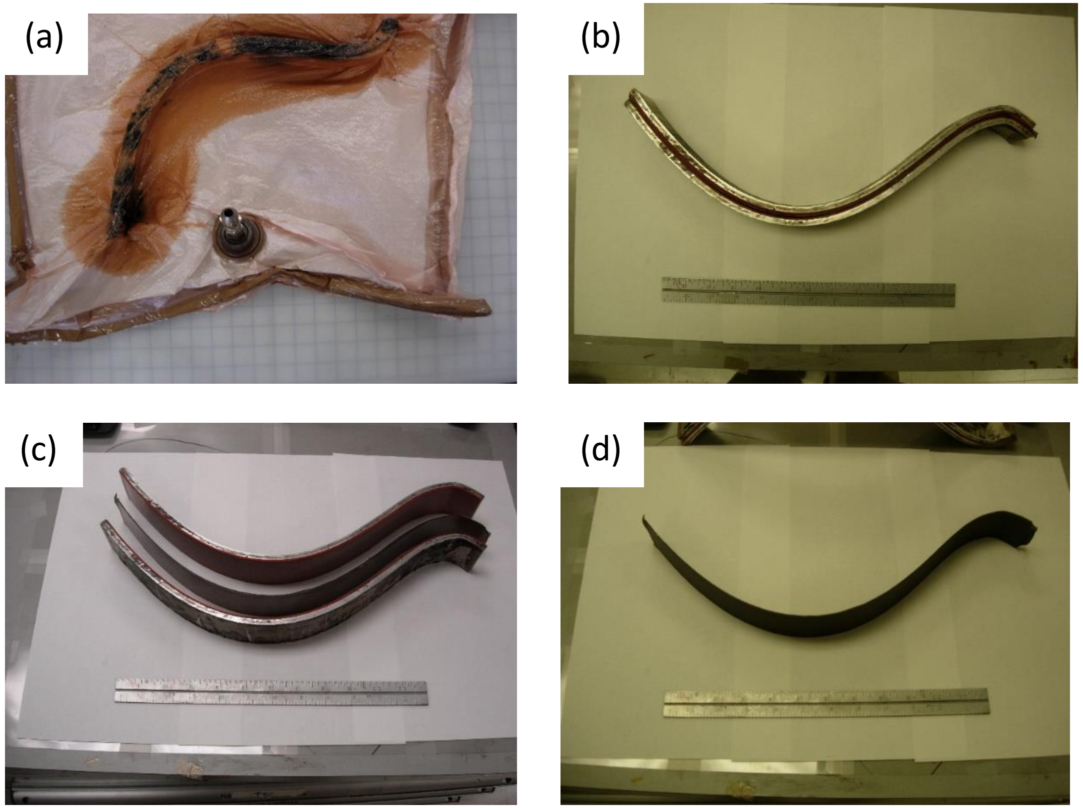

Computation modeling of SMP SCF actuation shows successful deployment with a mid-link (Length: 3”, mean location from bottom: 6.5”). (a –c) retraction, and (d-f) deployment.



A mid-link (Length: 3”, mean location from bottom: 6.5”)

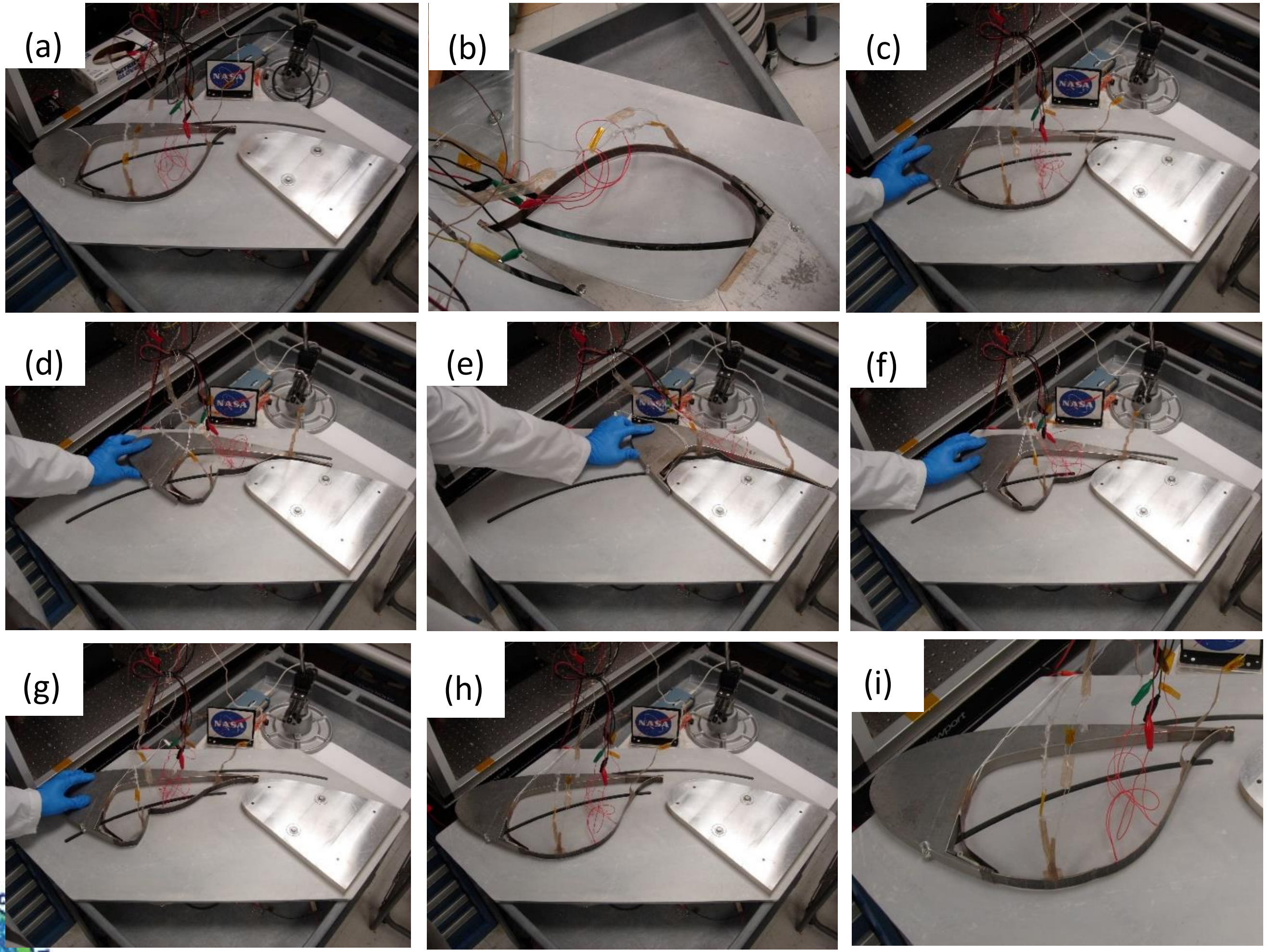
→ Successful deployment

# Fabrication of SCF using SMPC

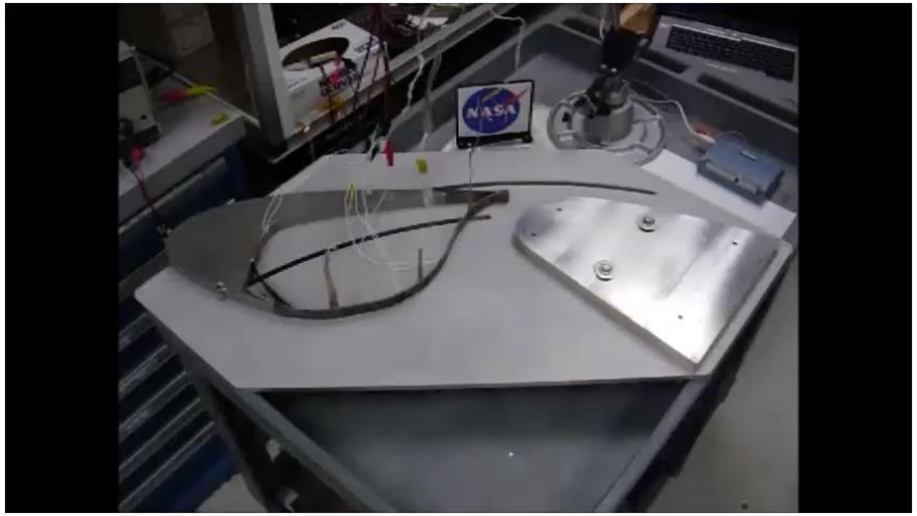



Fabrication of SCF using SMP composite. (a) sample mold in breathing fabric after curing in autoclave, (b) SMP SCF in aluminum mold, (c-d) retrieving SMP SCF sample from the aluminum mold.

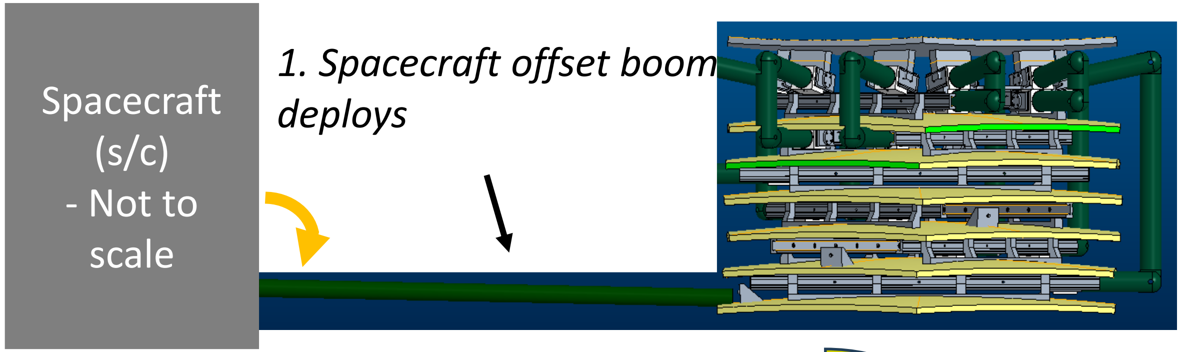
# Bench-Top Demonstration of SCF Fabricated with SMPC-1



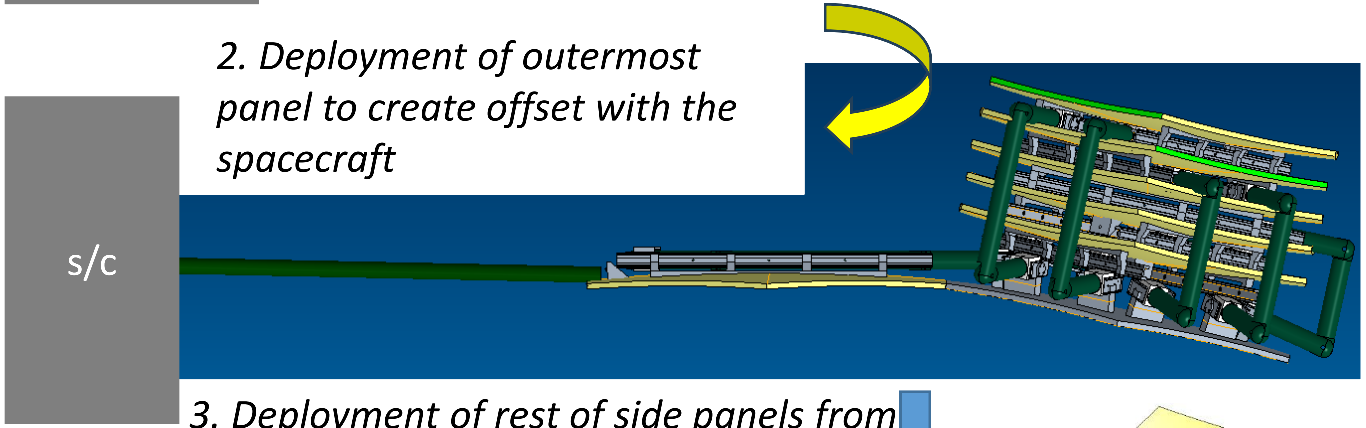

Bench-top demonstration of SCF fabricated with **<u>Kevlar® fiber/SMPC</u>**. (a) before retraction, (b) heating tapes in top and bottom sections, Nitinol spring, (c-h) full process of stowage and deployment, and (i) yielding a **<u>permanent damage</u>** after runs



# Scalable Architecture Using Robotic In-Space Assembly

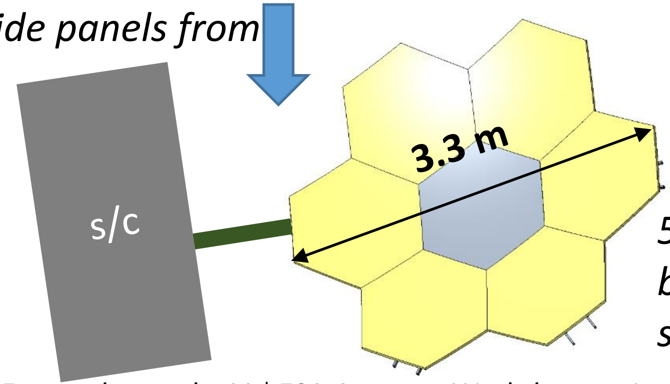



*1. Spacecraft offset boom deploys*



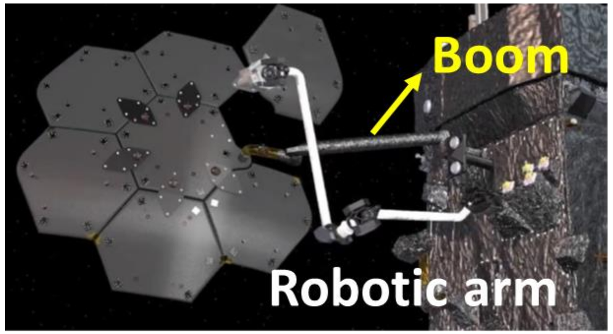

*2. Deployment of outermost panel to create offset with the spacecraft*

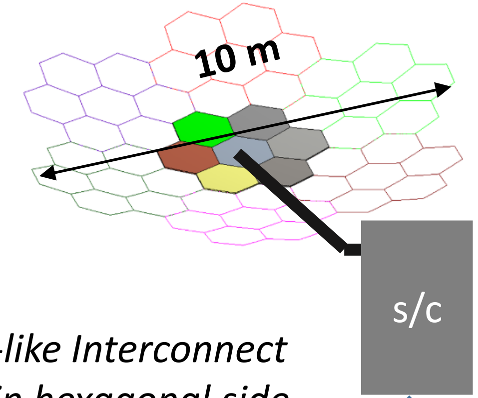
*3. Deployment of rest of side panels from central one*



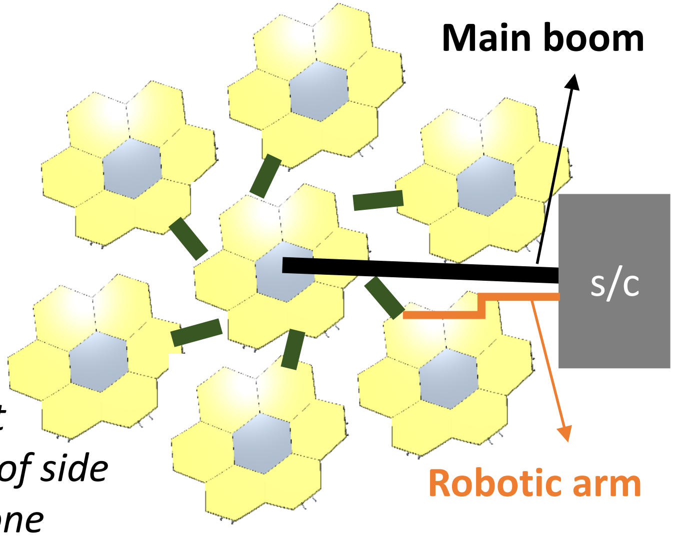

*4. Deployed 3.3 m sub-reflector with offset boom ready to be robotically assembled to the rest*

*5. Robotic arm uses offset booms to initiate mating of side sub-reflectors to central one*



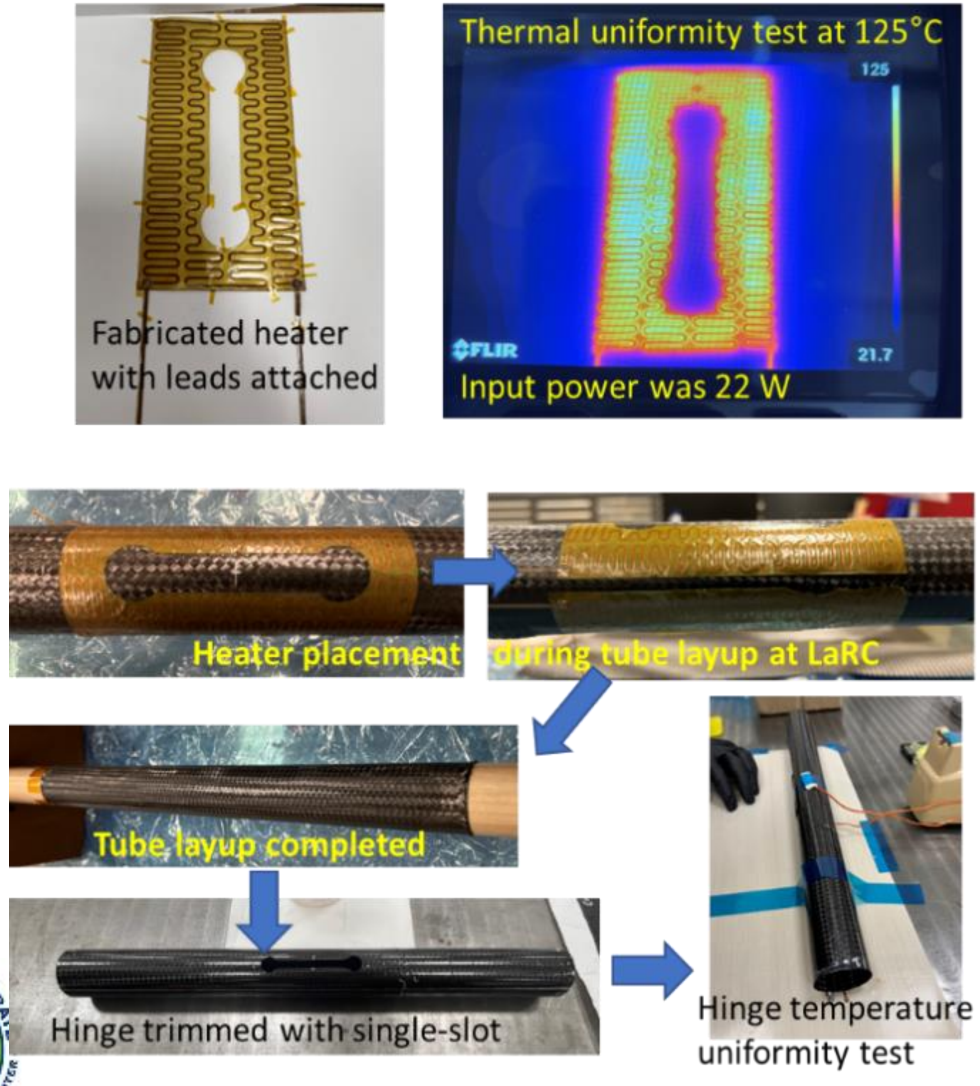



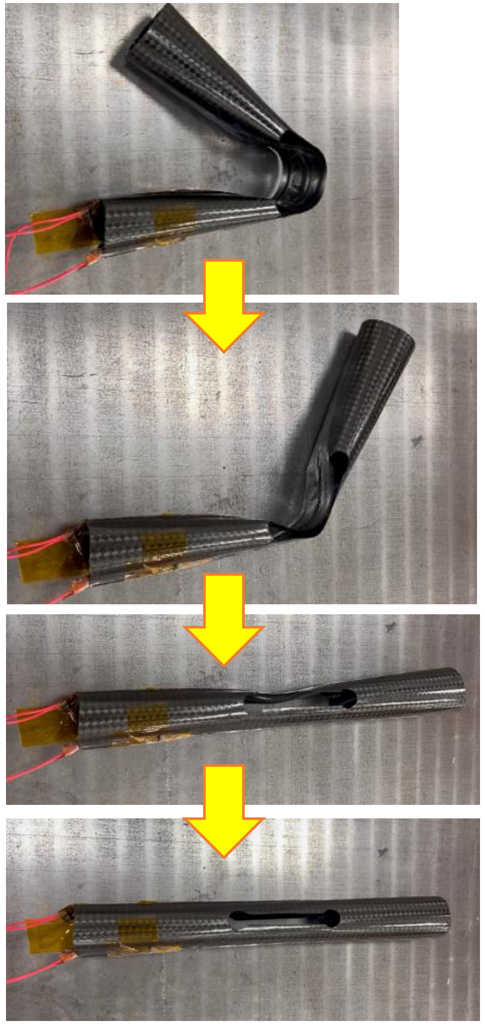

*6. Robotic arm uses SPIDER-like Interconnect Assembly plates to fix certain hexagonal side panels for additional global stiffness of the 10 m reflector*




*Ref.* J. M. Fernandez et al., 41st ESA Antenna Workshop on Large Deployable Antennas, Sept. 2023, ESA-ESTEC in Noordwijk, The Netherlands

# SMPC Tubular Hinge Fabrication and Test



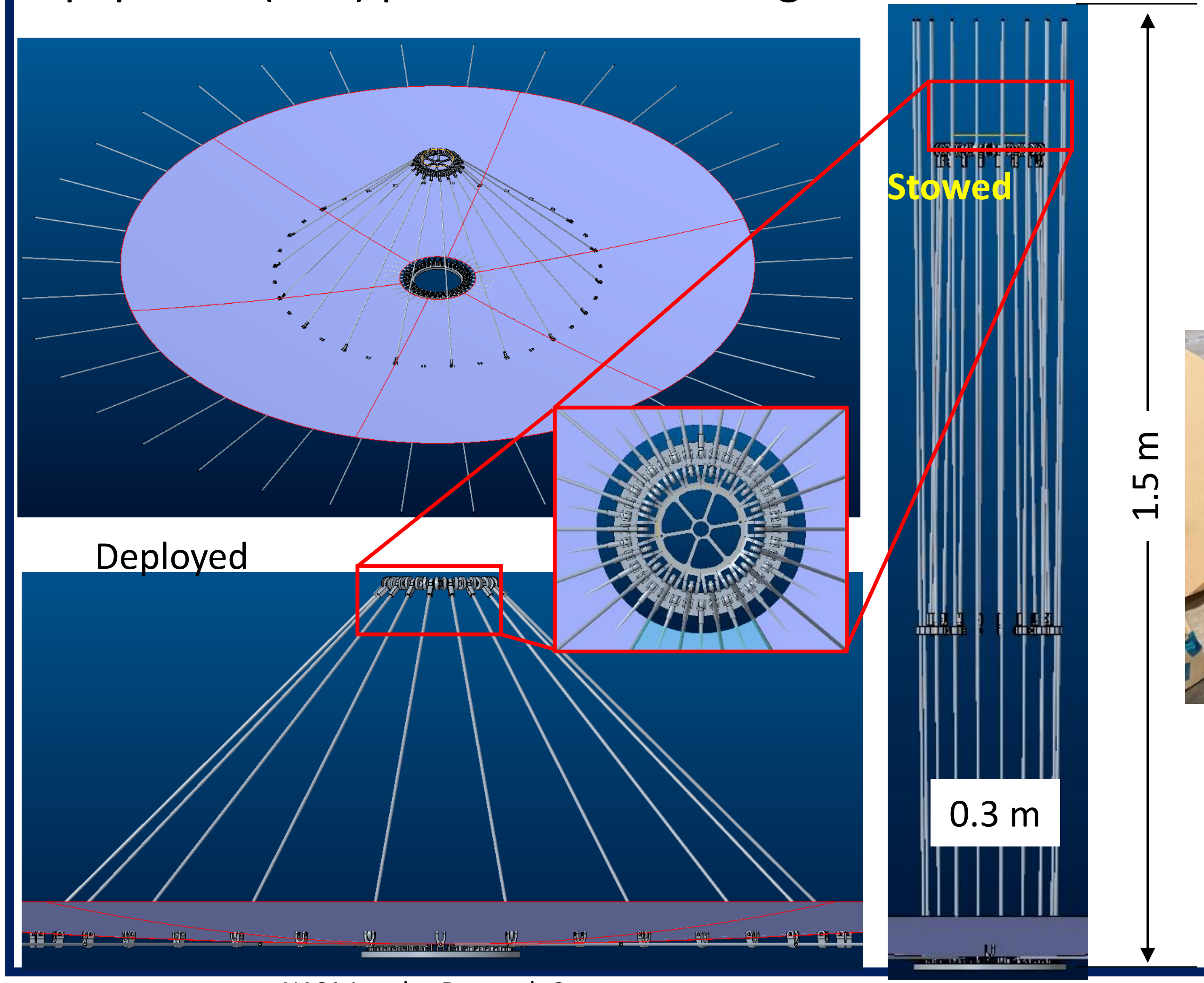



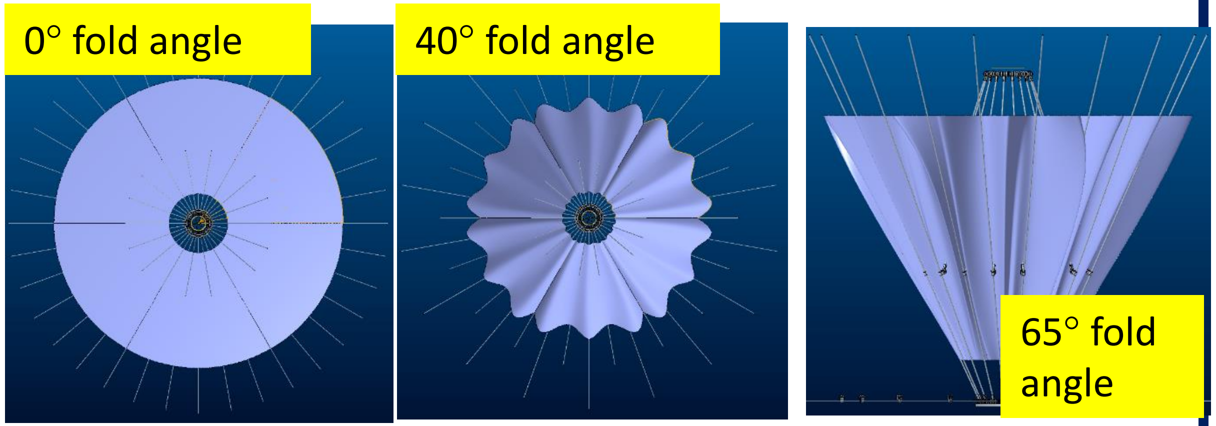
- 26-µm thick heaters have a serpentine shape to increase flexibility without yielding the conductive Copper layer.
- New shape memory composite material developed at NASA produces self-actuation of hinge under thermal input of heaters and sensor control.
- Low power actuation of < 100 W per SMC hinge or < 200 W per panel.
- Controlled self-deployment of hinge over 10 – 15 seconds without final shock.

• Thin film heaters were fabricated by Pennsylvania State University under a Collaboration Research Agreement.

# Design 2: Umbrella-Folded Reflector Packaging Scheme

3 meter-diameter thin-shell reflector with ground support equipment (GSE) push rods for folding like an umbrella




1/6 Gore of 3 meter-paraboloid dish was fabricated for folding test