space structures laboratory

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Folding and Deployment of Stored-Energy Composite Structures

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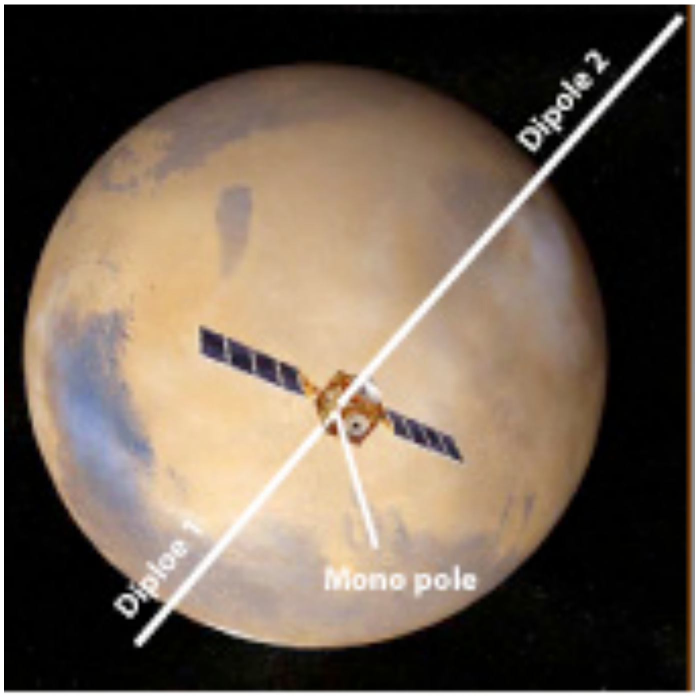
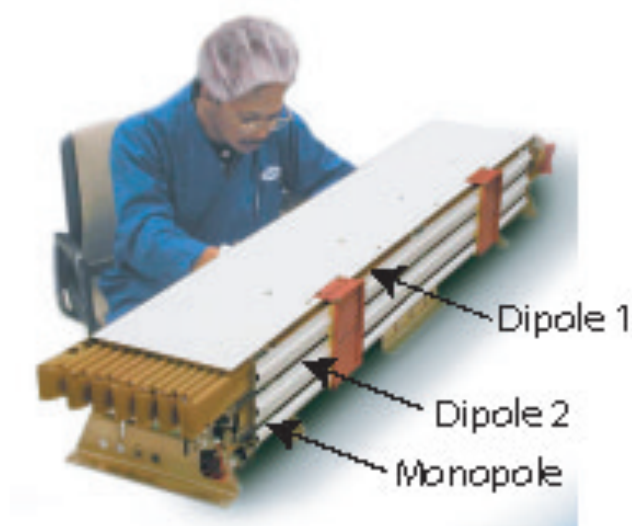
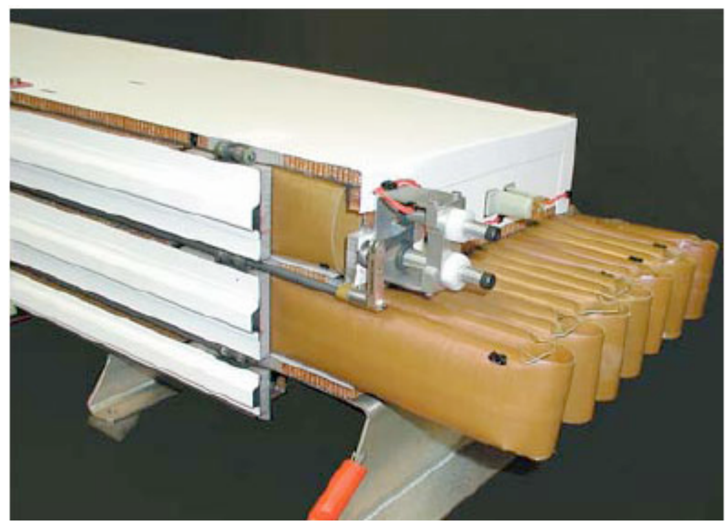
1. Stored-Energy Deployables

Mars Express Booms

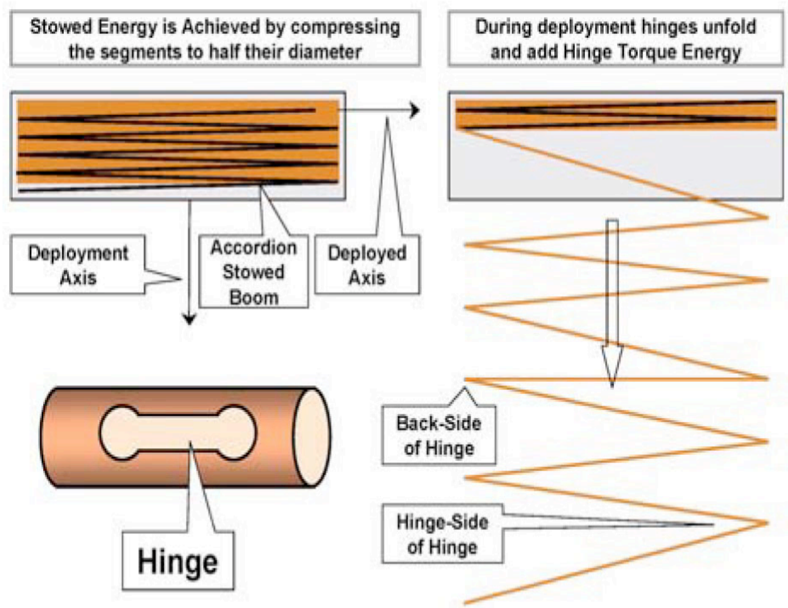


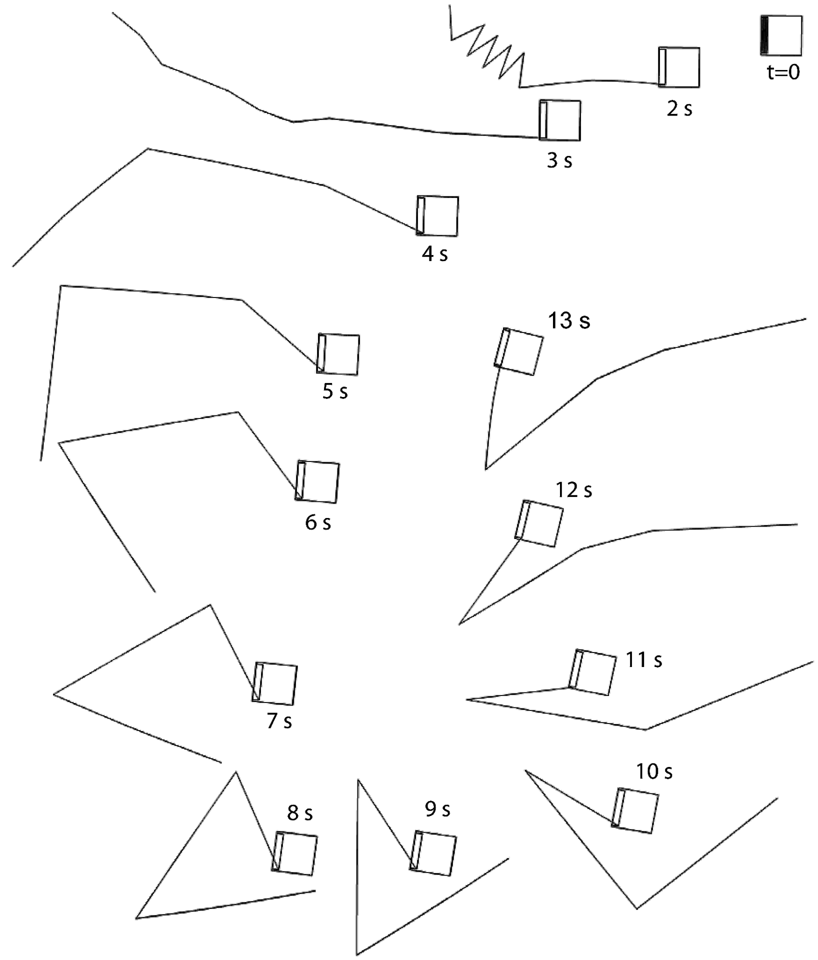


NGST Astro Aerospace Foldable Flattenable Tubes (FFT) for MARSIS antenna



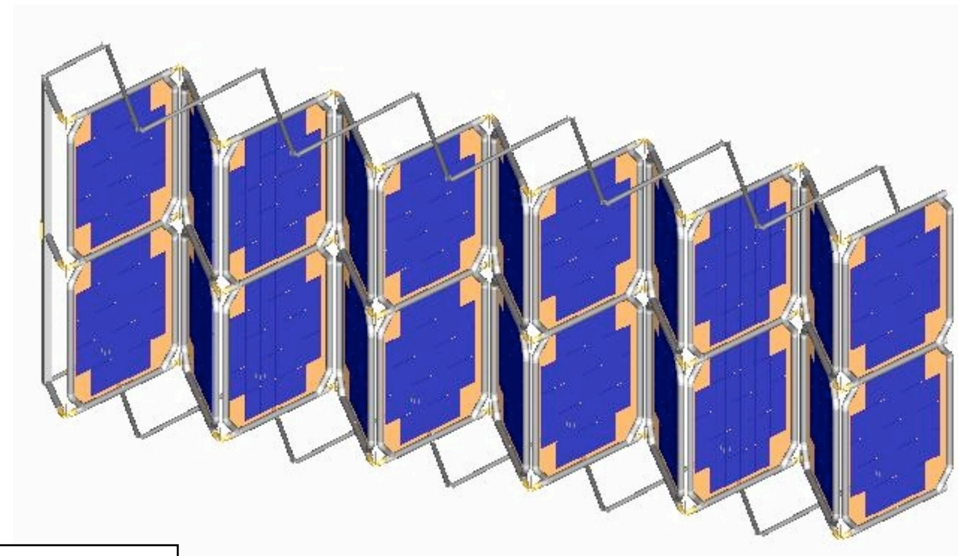
Deployment:
Concept vs Actual Behaviour





(Mobrem and Adams, Analysis of the lenticular jointed MARSIS antenna deployment, AIAA-2006-1683)

QinetiQ high-power solar array



SIMONE Near-Earth Orbit mission

Pairs of interlaced pantographs: only 1 deployment DOF

Integral hinges made by cutting slots in CFRP tubes

Collapsible Large Antenna Structure (CLAS) Reflector

1/10th scale model

Folding movie

Deployment movie

Soykasap, Watt and Pellegrino (2005) New concept for ultra-thin deployable structures, Journal of IASS, 46(147): 3-8.

2. The Need for Novel Simulation Techniques

Design Validation and On-orbit Prediction

- Design of these structures begins from overall structural concept
- Their “intuitive” structural behaviour is hard to quantify
- Engineering realization of concept is key challenge
  - Impossible to fully replicate gravity-free conditions for large structures
  - Possible (but expensive) to test deployment behaviour of scaled models in drop-towers or parabolic (zero-g) flights
  - Component level testing of prototypes useful to validate simulation models

High-Fidelity Simulation: Challenges

- Geometric non-linearity (small strains but large curvatures)
- Dynamic events (jumps) and bifurcations
- Extensive contact regions
- Appropriate constitutive models?
- Newton-Raphson solvers struggle to achieve convergence

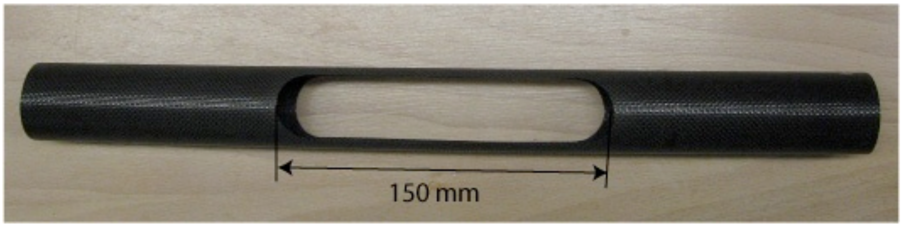
- Folding/deployment is an essentially inextensional (stiff) process, but actual details governed by bending behaviour (soft)

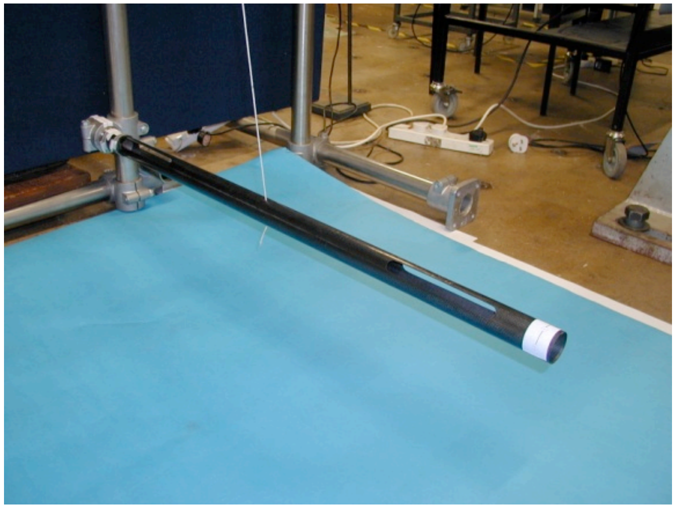
Engineering Questions

- For a given design:
  - What is the folded configuration?
  - Is a particular folding sequence acceptable?
  - Is there a sufficient margin against failure at all stages of folding/deployment?
  - Is the deployment path unique?
  - Is deployment reliable and robust?

3. A Representative Problem: Tube Hinge

Tube Hinge Details

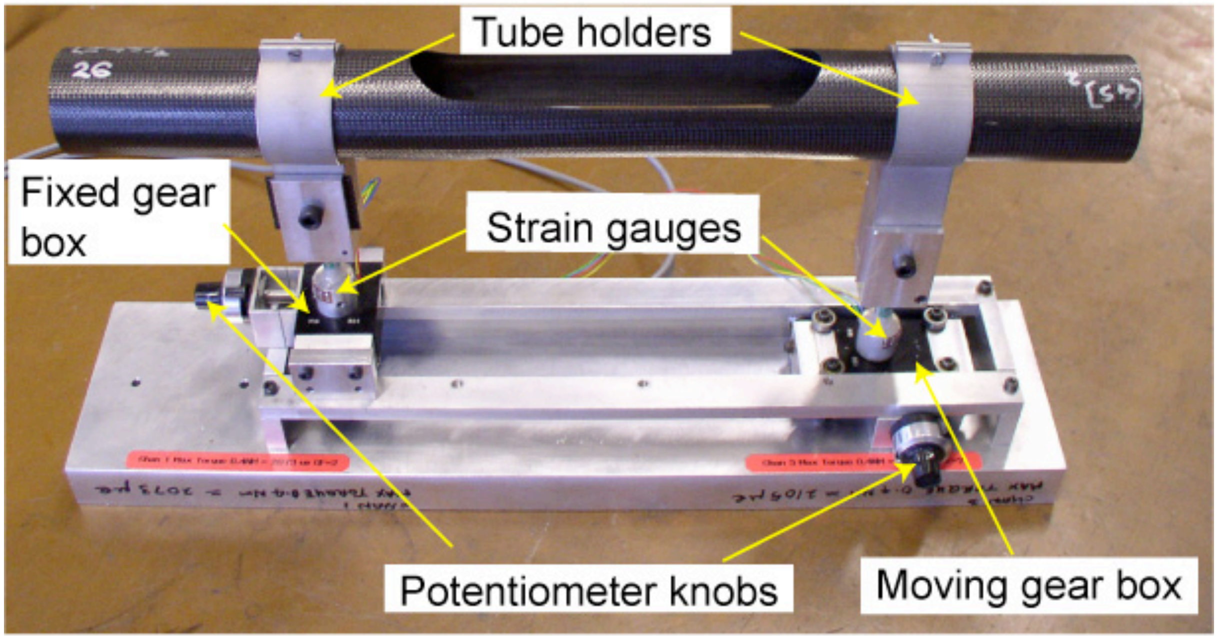




- Two plies $[\pm45]_2$
  - T300-1k plain weave fabric
  - Hexcel 913 epoxy resin
- 38 mm internal diameter, approx. 200 μm thick
- Autoclave cured
- Cut-outs made with pressurized water jet

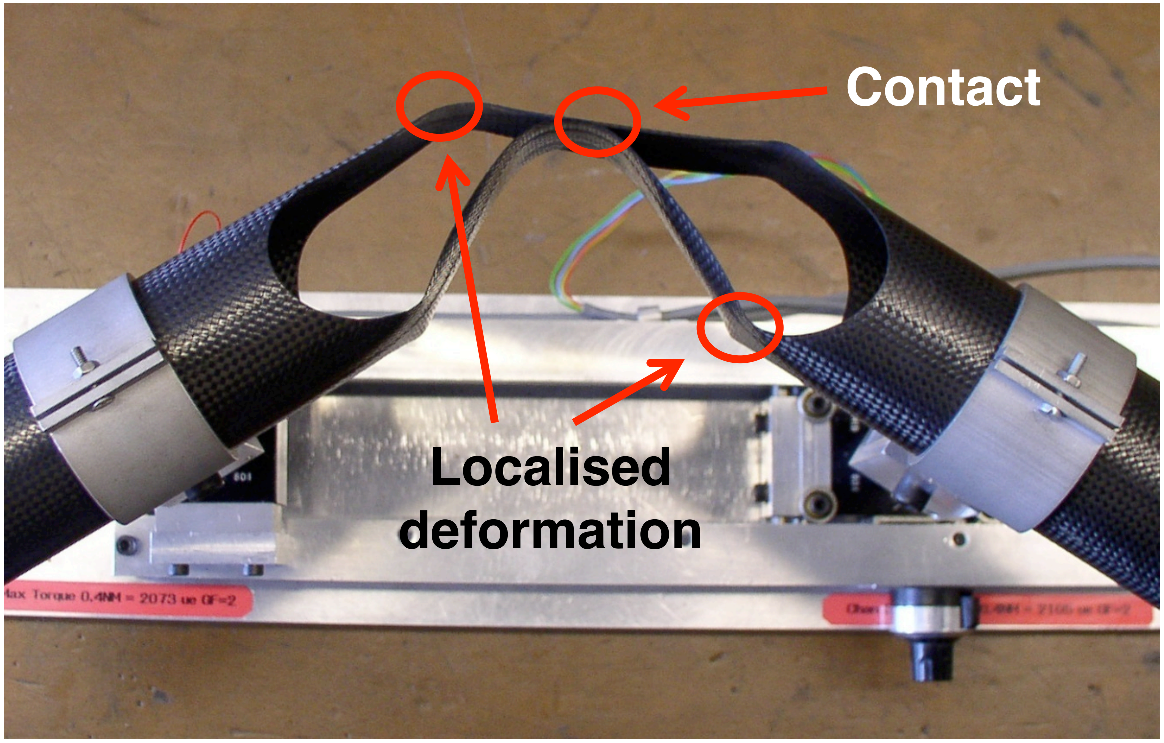
[Deployment movie]

Folding / Deployment Rig (Quasi-Static)



- Unstressed configuration
- Fold by pinching the middle and then rotating the ends by equal and opposite amounts

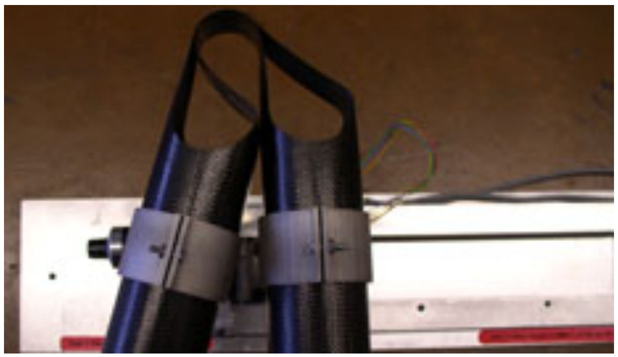
An Intermediate Configuration



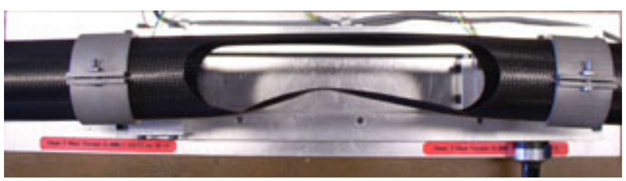
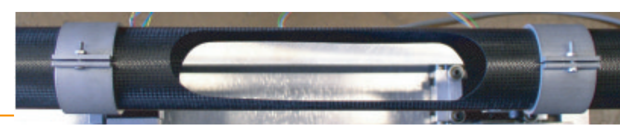
Note asymmetric folding

Quasi-Static Deployment

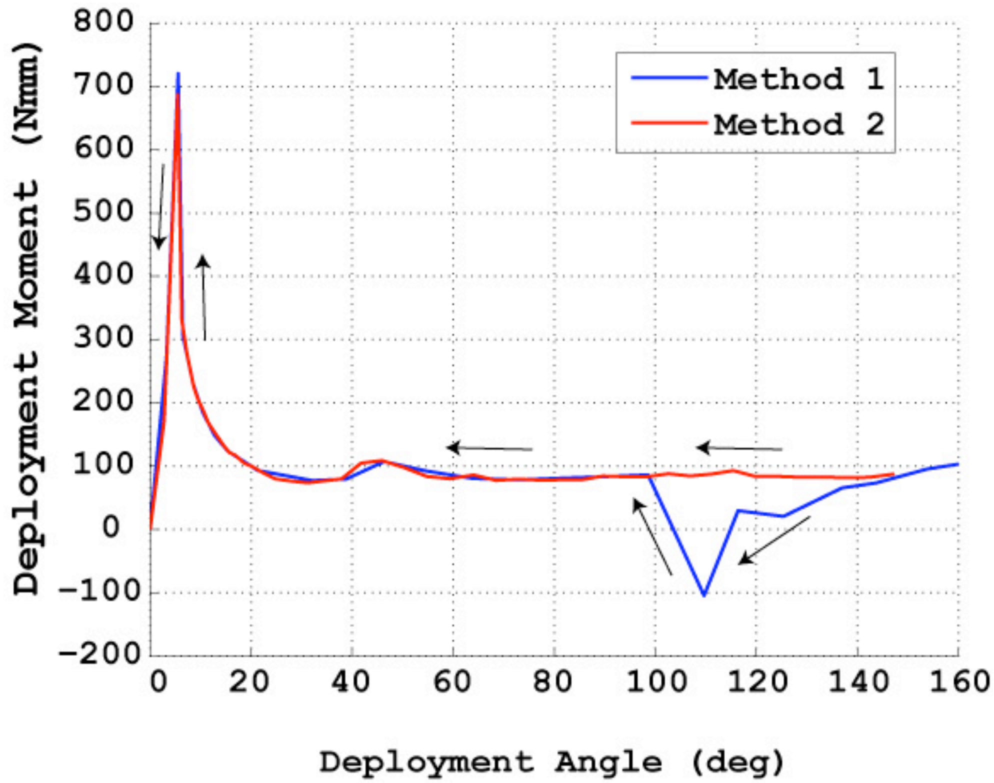
- Rotated back in small steps
- Equal end moments (two methods)





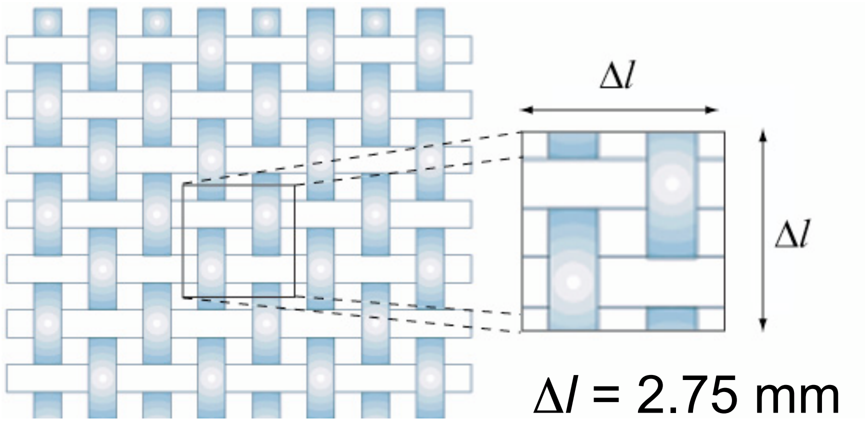
Deployment Experiment: Results



- Method 1: simultaneous end rotations
- Method 2: one end rotated first, then the other until moments are equal

4. Material Model

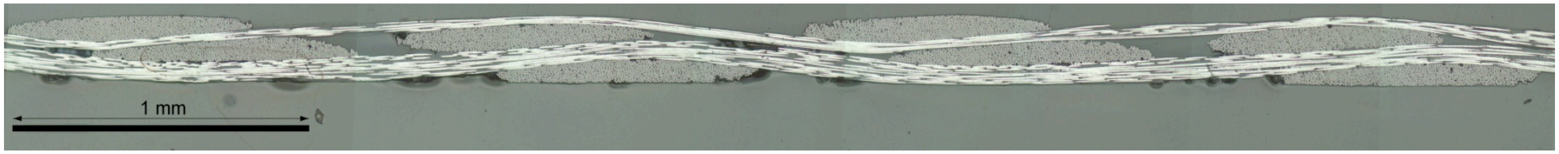
Woven Plain Weave Composite



Δl = 2.75 mm

- Classical lamination theory does not work well for small numbers of plies
- For two plies, bending stiffness off by a factor of 2 (Soykasap, 2006)
- Micromechanics models are needed

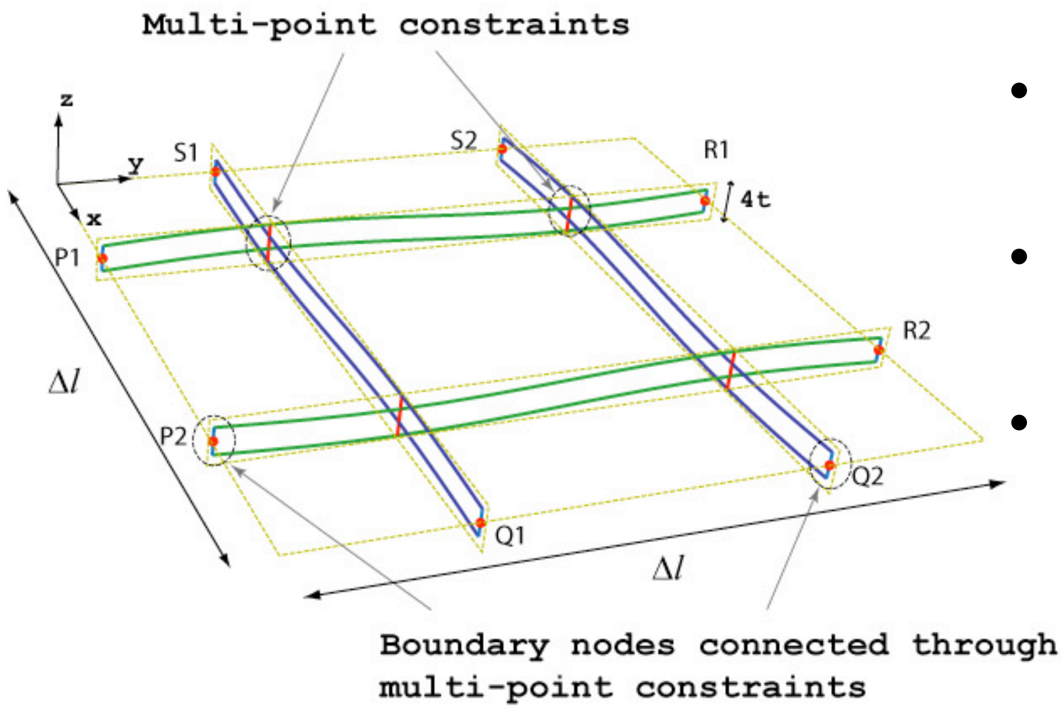
Properties of Cured Tows



- From micrographs: Tow fibre volume fraction 0.68
- Equal area rectangular section:
  Width b = 1.12 mm
  Thickness t = 0.055 mm

T300-1k/913 tow properties	Value
Longitudinal stiffness, E_1 (N/mm^2)	159, 520
Transverse stiffness, $E_2 = E_3$ (N/mm^2)	11,660
Shear stiffness, $G_{12} = G_{12}$ (N/mm^2)	3,813
Shear stiffness, G_{23} (N/mm^2)	3,961
Poisson's ratio, $\nu_{12} = \nu_{13}$	0.27
Poisson's ratio, ν_{23}	0.47

Unit Cell for Homogenization



- Wavy beams with uniform rectangular cross section
- Rigid beam multi-point constraints
- Eight boundary nodes on mid-plane
- Periodic boundary conditions:

  Translation terms

  $\boldsymbol{\Delta u_i = \overline{\varepsilon}_{ij}\, \Delta x_j}$

  Rotation terms

  $\boldsymbol{\Delta \theta_i = \overline{\kappa}_{ij}\, \Delta x_j}$

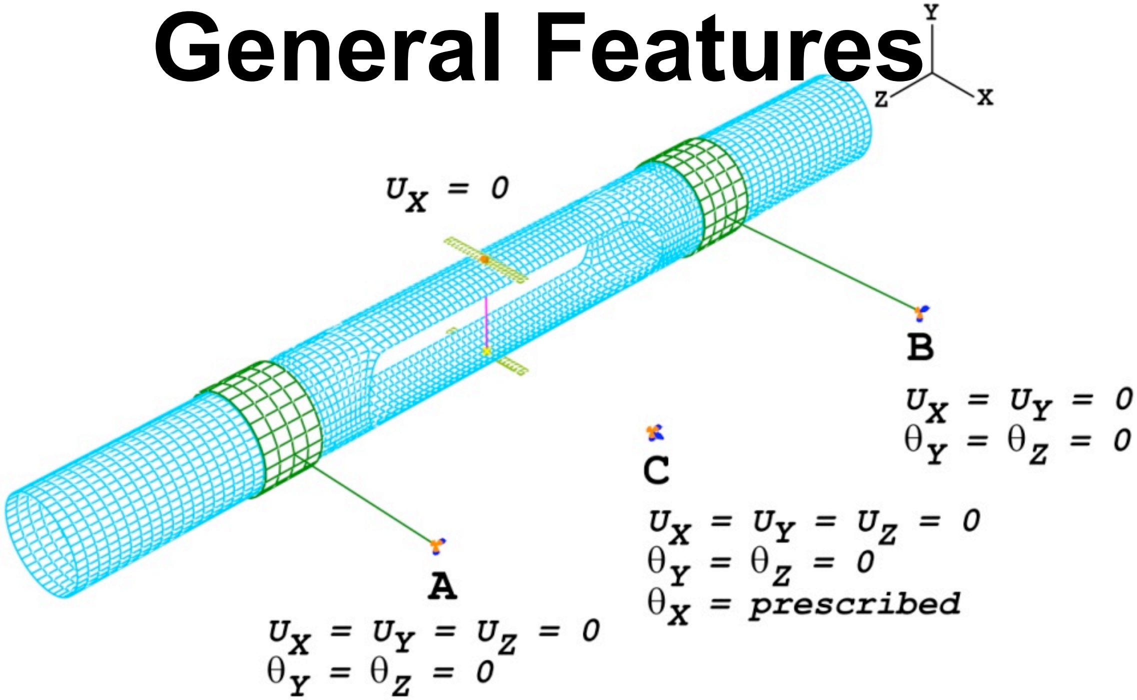
Kirchhoff Plate Model: ABD Matrix

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ \hline M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \left[\begin{array}{c|c} A & B \\ \hline B^T & D \end{array} \right] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \\ \hline \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix}$$

- Entries of ABD matrix for **$[0/90]_2$** computed by virtual work, after analysing 6 load cases with ABAQUS/Implicit (Kueh and Pellegrino, 2007)
- Rotated 45 degrees to obtain ABD matrix for **$[\pm 45]_2$**

5. ABAQUS/Explicit Model

General Features



- Four node, fully integrated shell elements (S4)
- $\theta_x^A - \theta_x^B = \theta_x^C$; equal moments M_x
- "Smooth step": time variation of applied actions is 5th order polynomial
- "Shell general section" assigns stiffness through ABD matrix
- "General contact" for entire model, frictionless

Stable Time Increment

- Newmark β-method (β= 0, γ= ½)
- Central difference time integration
- Diagonal mass matrix
- Conditionally stable if

$$\Delta t \le \frac{2}{\omega_{\max}}\left(\sqrt{1+\xi^2}-\xi\right)$$

$\omega_{\max}$ is highest frequency in structure and ξ is fraction of critical damping in corresponding mode

- ABAQUS/Explicit uses the approximation

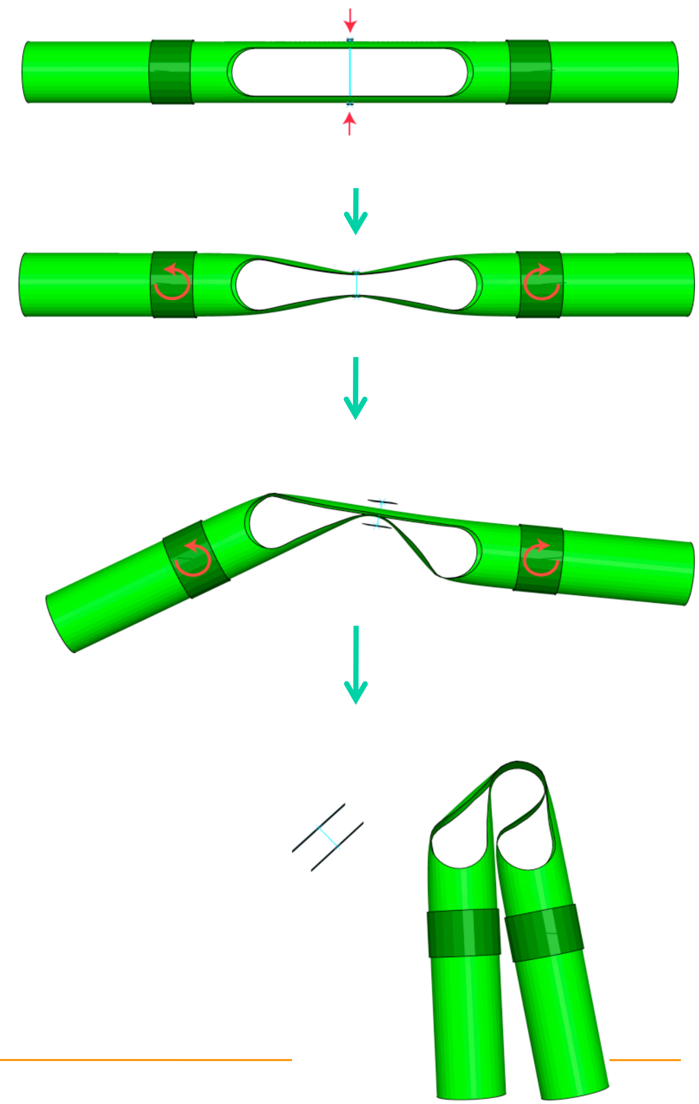
$$\Delta t \le \frac{\ell_{\min}}{\sqrt{E/\rho}}\left(\sqrt{1+\xi^2}-\xi\right)$$

Overall Simulation Time

- Aim to complete simulations in shortest possible time
  - Simulation time proportional to computation time and storage requirements
  - Occasional use of mass scaling (by factor of 10 for pinching simulation)
- Select loading rate such that KE << 10% of IE for deployment simulation (unnecessary for folding simulation)
  - First mode of vibration in deployed configuration is 0.02 s
  - Hence start from 10 × fundamental period of vibration (0.2 s)
  - Increase simulation time until KE is sufficiently small

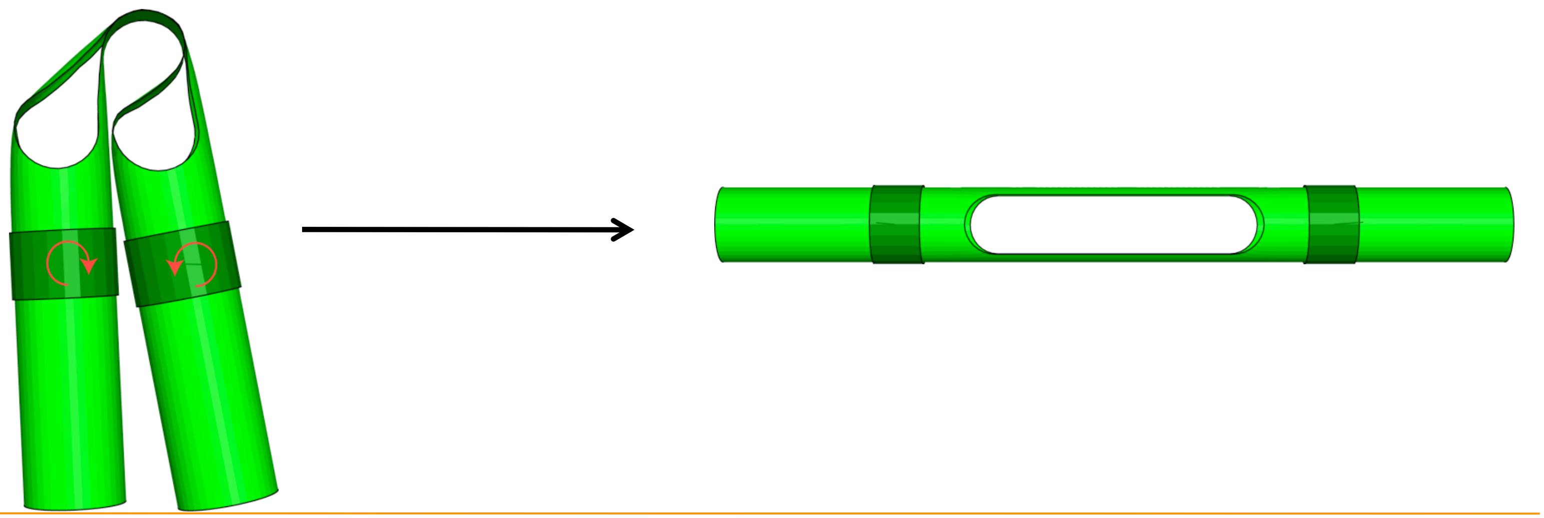
Folding

- Pinching (0.2 s)
  - Two rigid plates connected through a string
  - Thermal contraction
- Rotation step 1 (0.25 s)
  - Rotate both ends while rigid plates are in contact with folded region
- Rotation step 2 (0.55 s)
  - Deactivate contact and continue rotating



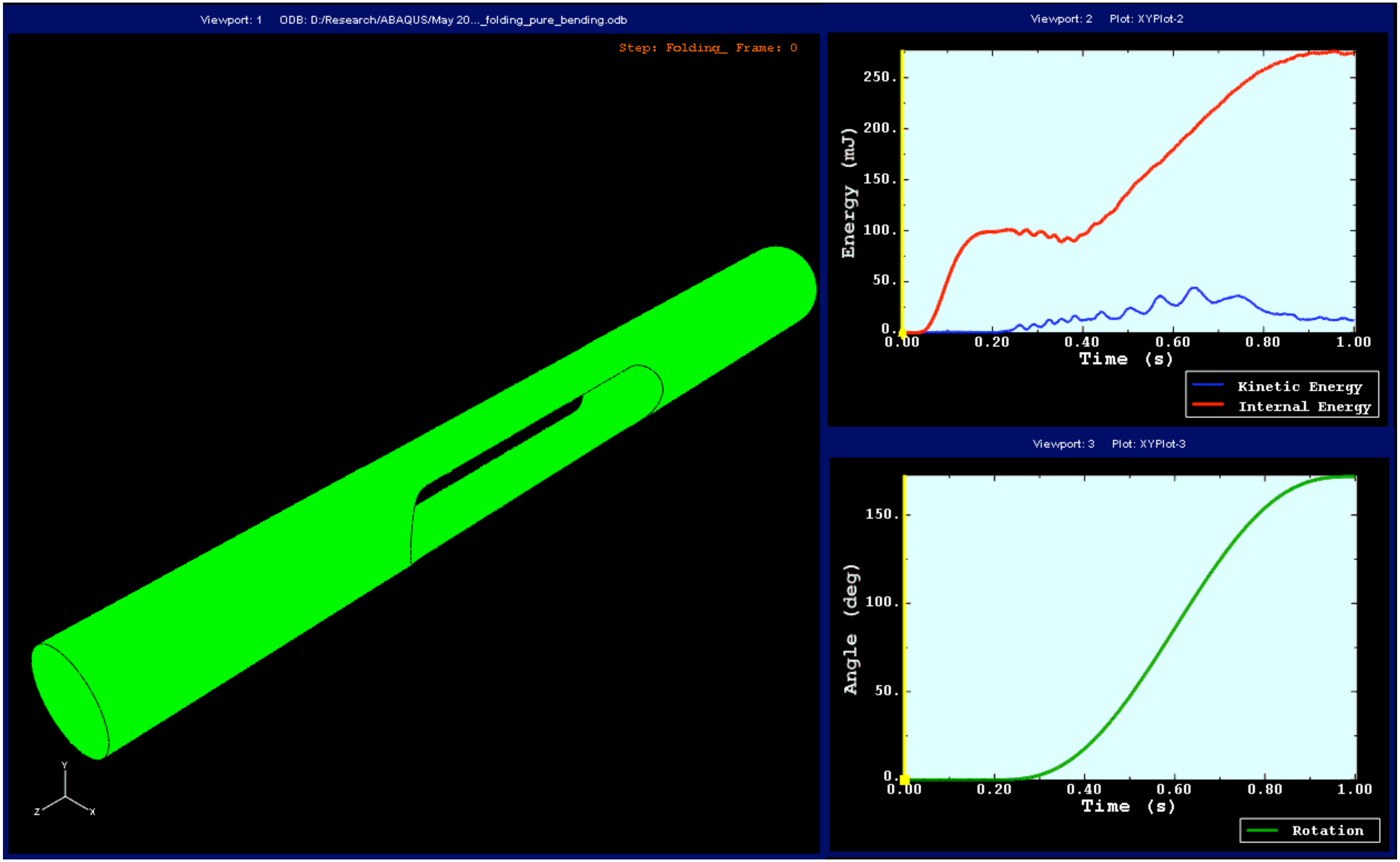
Quasi-Static Deployment

- End rotations in opposite sense, starting from folded config.
- Single smooth step. Longer simulation time (2.4 s)
- Mass scaling did not work well
- Growth in energy balance term: arrested instability (Belytschko et al. 2000). Added damping to force decrease in time step.
- Filtering of high frequency response and strain averaging

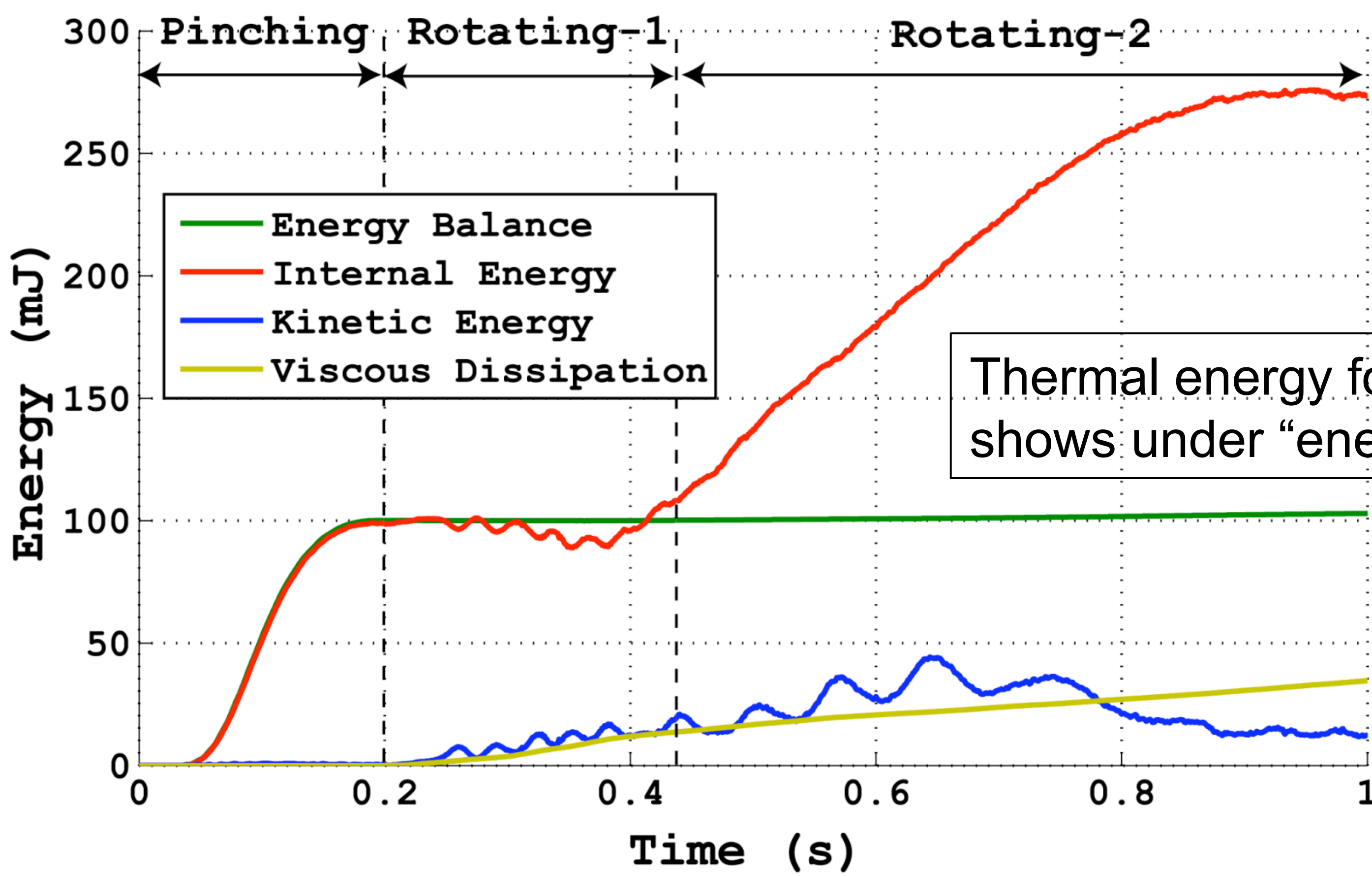


6. Results

Folding Simulation (Longitudinal Curvatures)



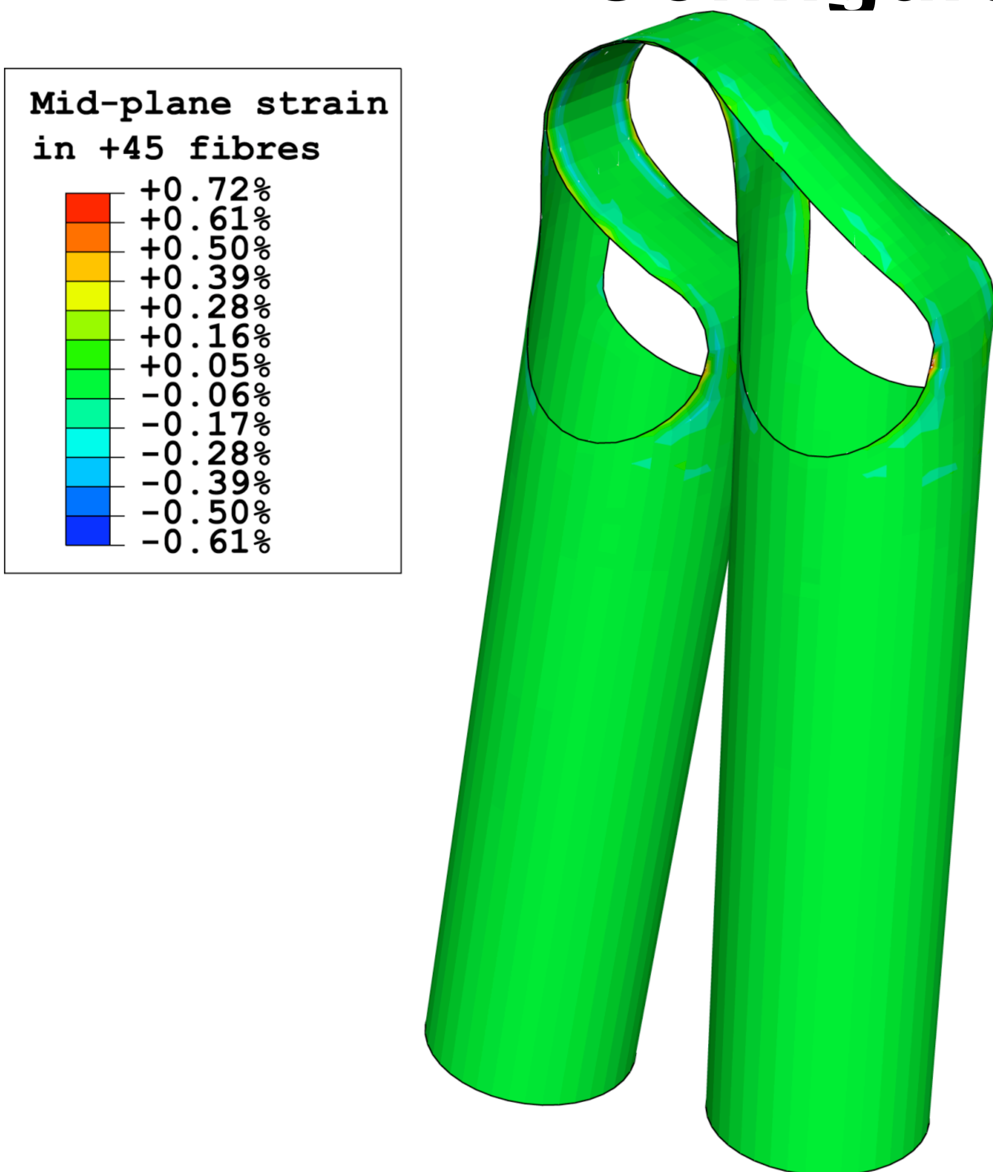
Energy Variation - Folding



Thermal energy for pinching shows under "energy balance"

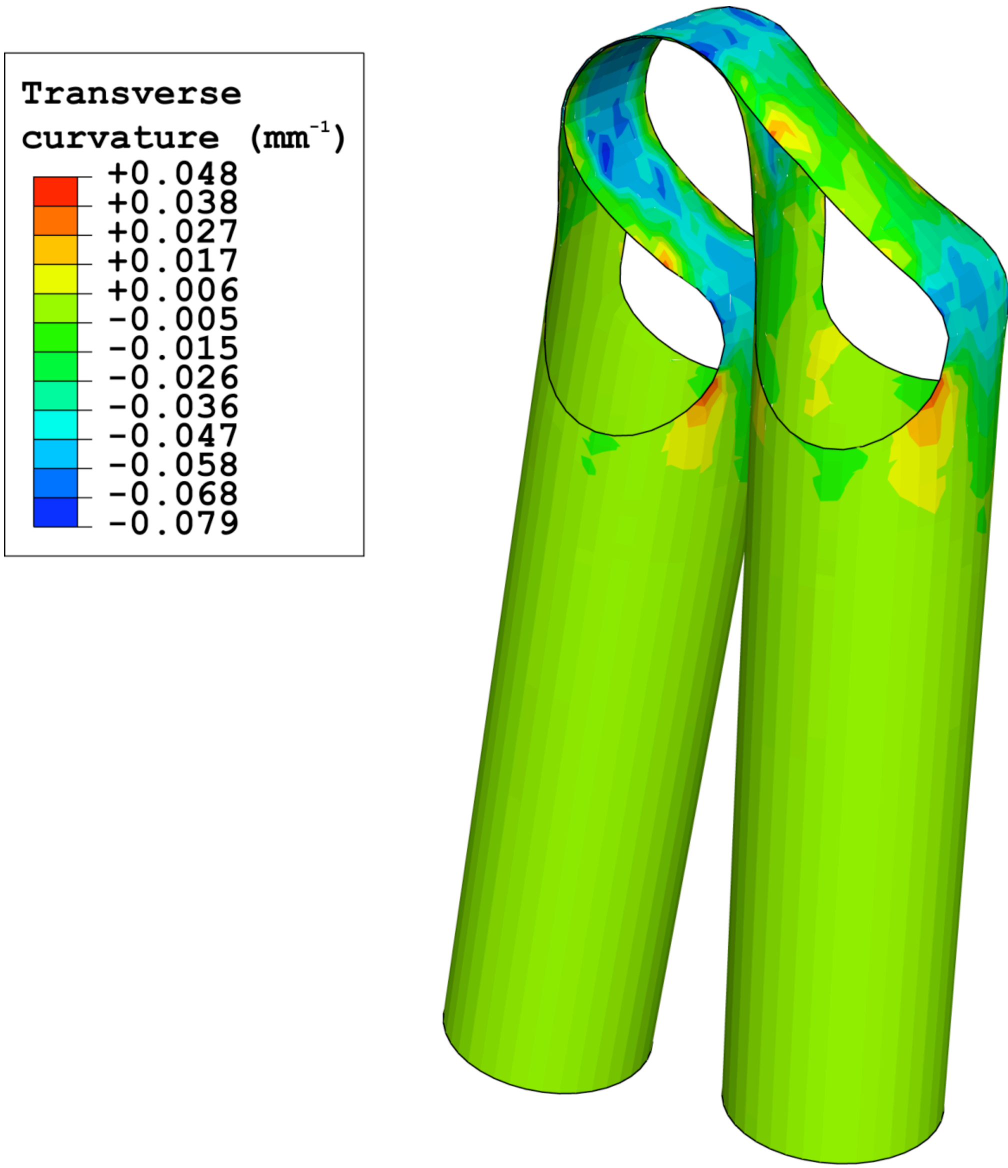
Energy Balance = IE + KE + VD - WK

Mid-Plane Strains in Folded Configuration



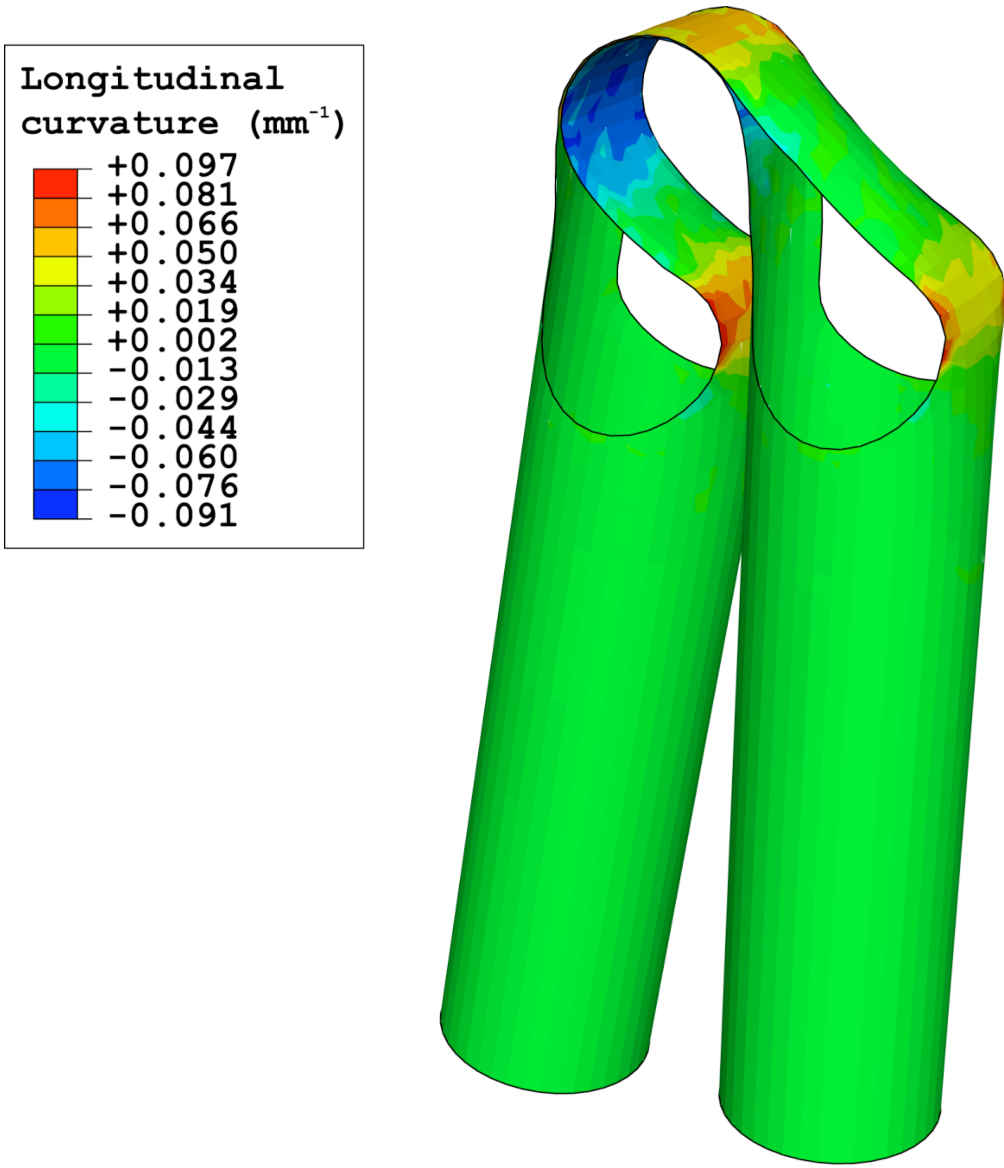
Maximum fibre strain 0.72%

Transverse Curvature Changes



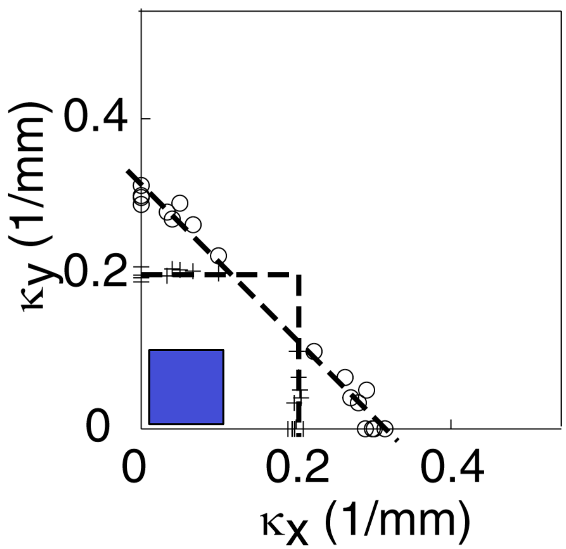
Maximum curvature
0.079 mm^{-1}

Longitudinal Curvature Changes



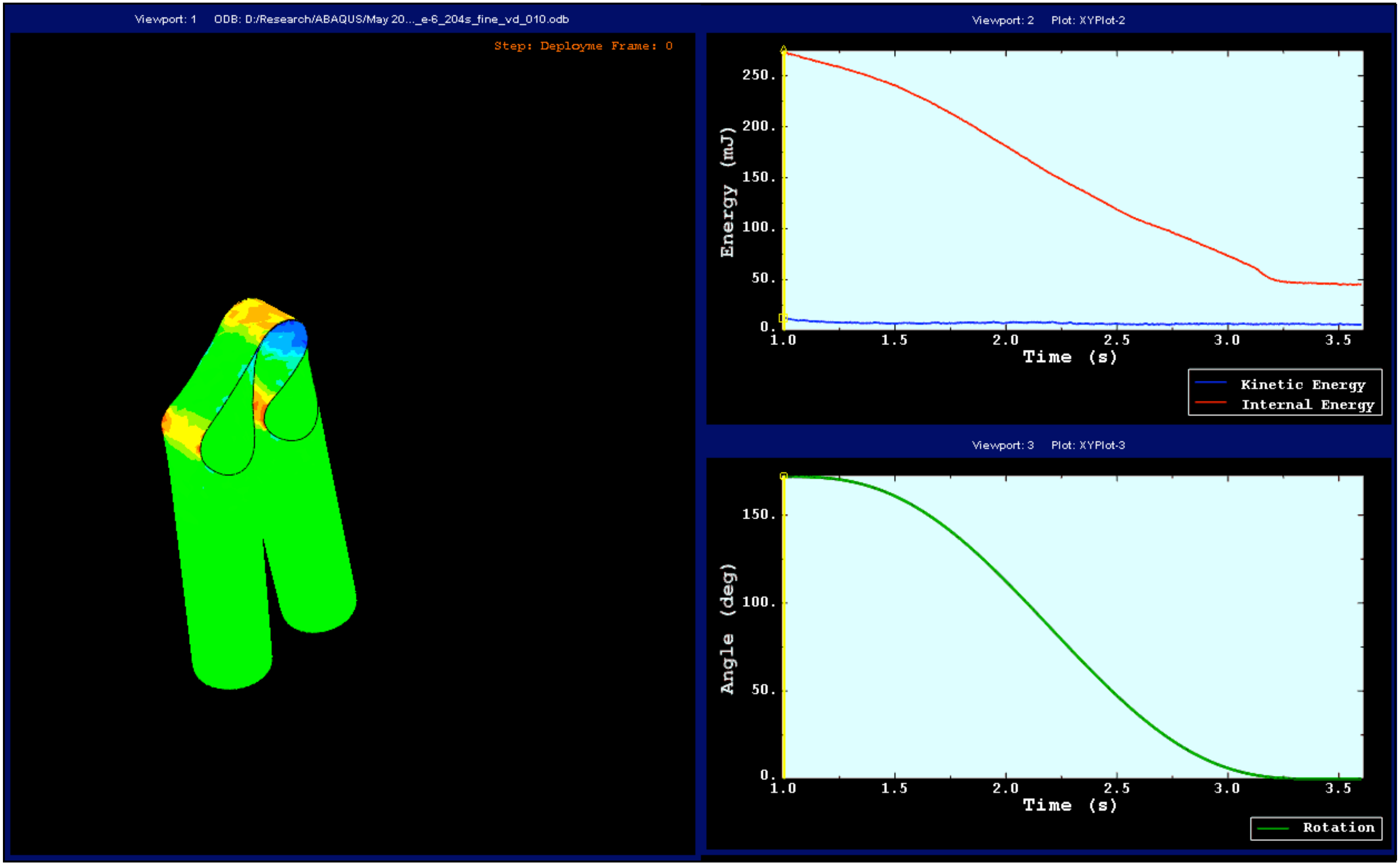
Maximum curvature
0.097 mm^{-1}

Failure Analysis in Folded Configuration

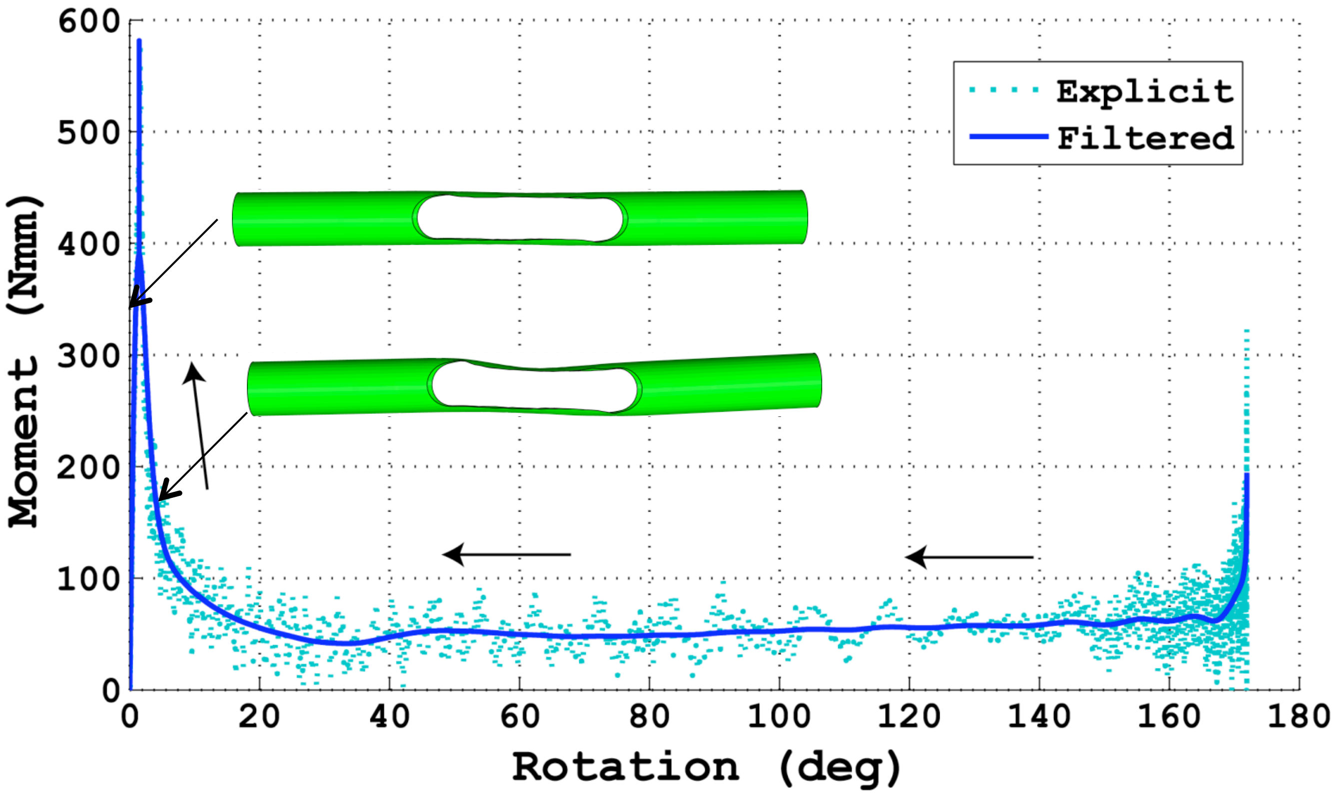


- Maximum curvature = 0.097 mm^{-1}
- Failure locus for biaxial bending of two-ply T300-1k/913 plain weave (Yee and Pellegrino, 2005)
- Maximum mid-plane strain (0.72%) not accounted for

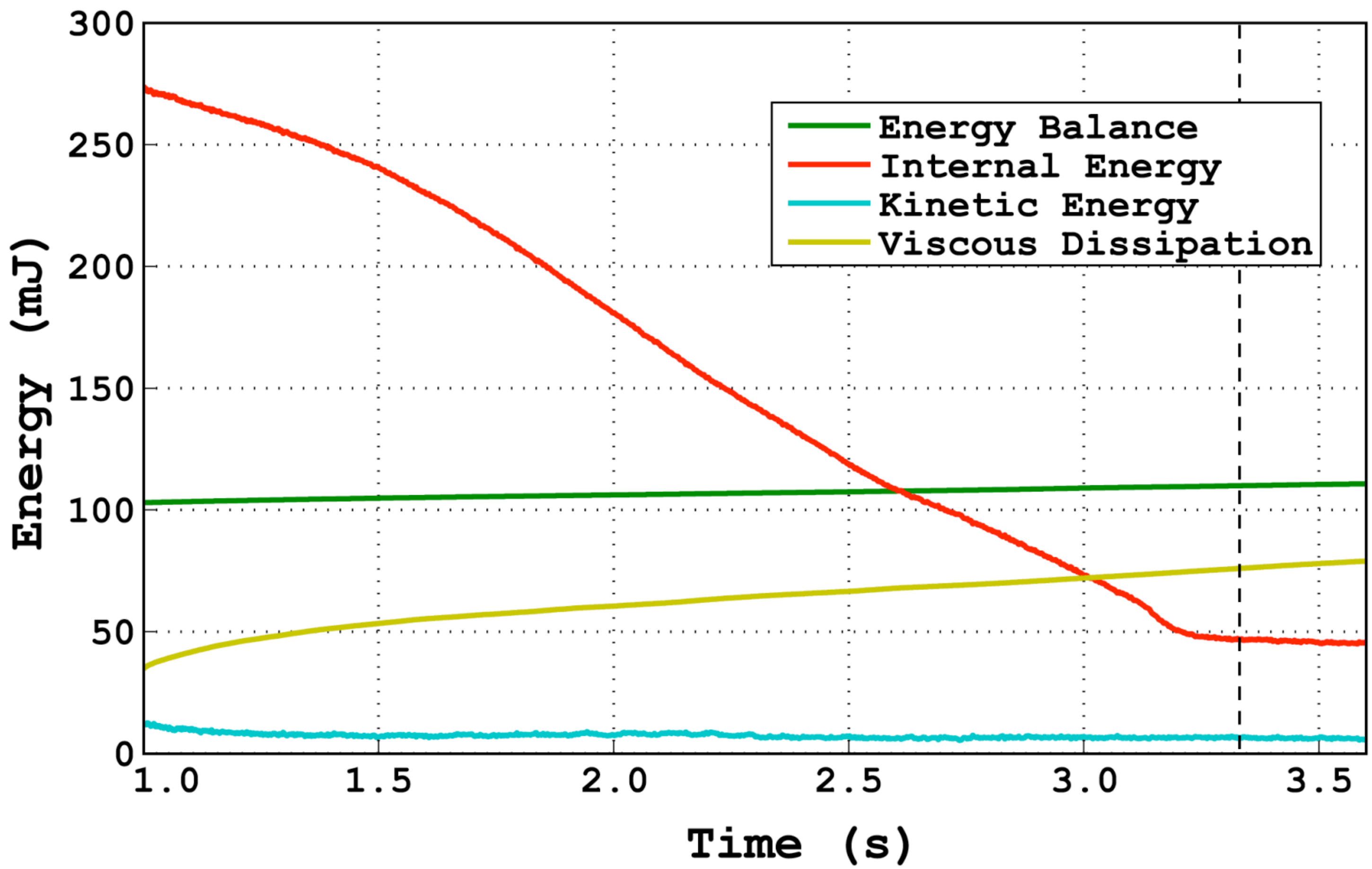
Deployment Simulation (Longitudinal Curvatures)



End-of-Deployment Snap

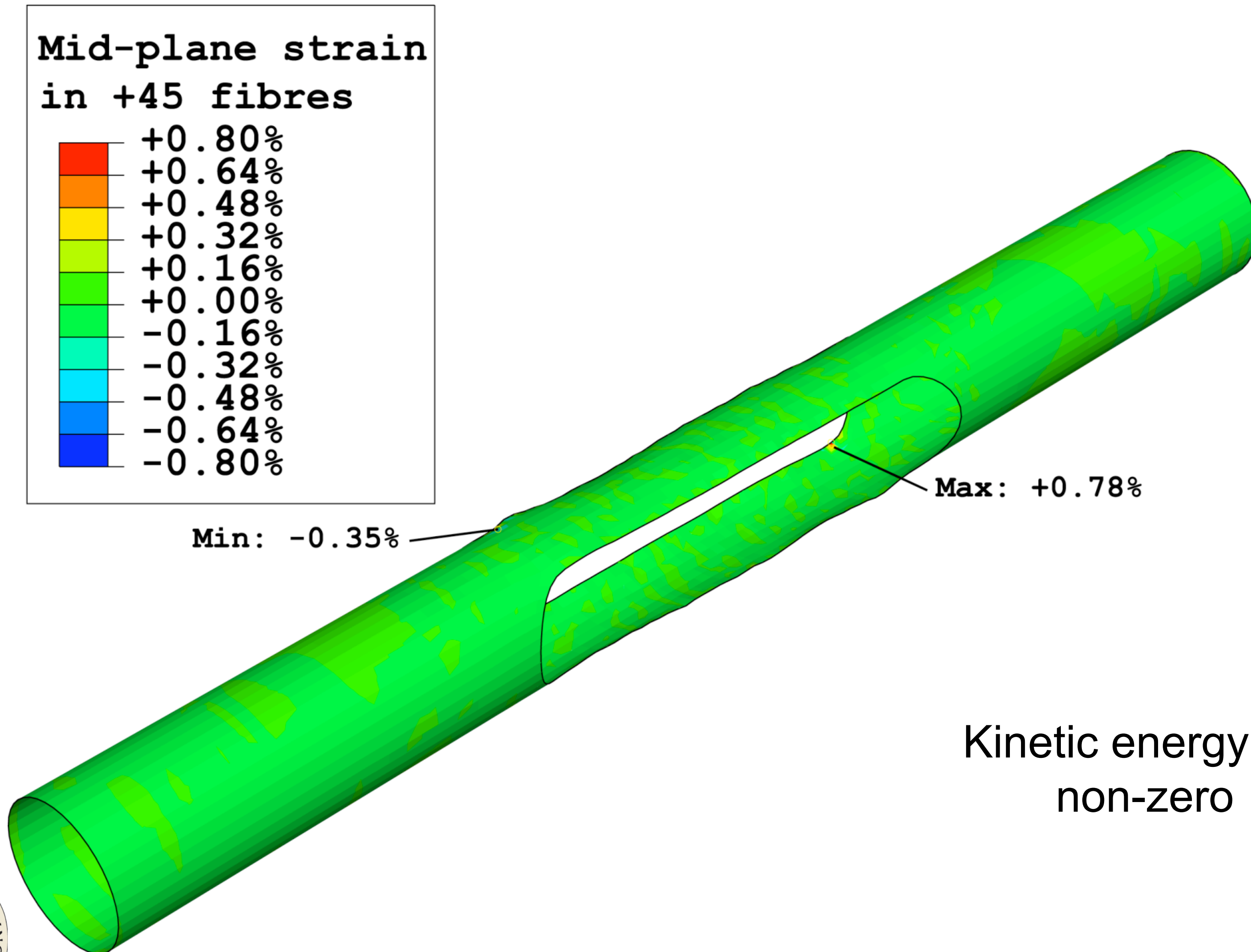


Energy Variation During Deployment



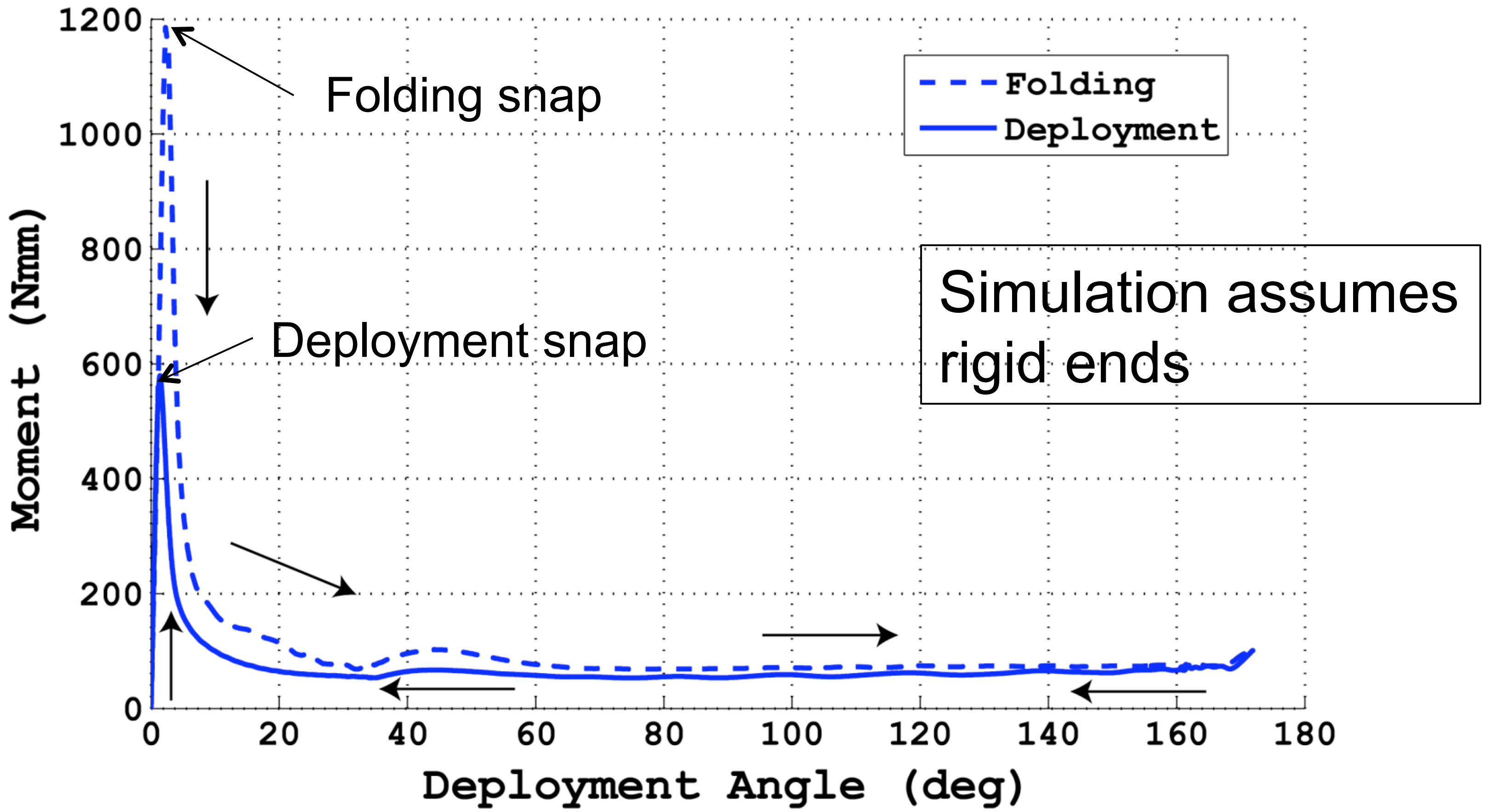
- Small increase in energy balance
- Viscous dissipation continues to increase

“Final” Deployed Configuration



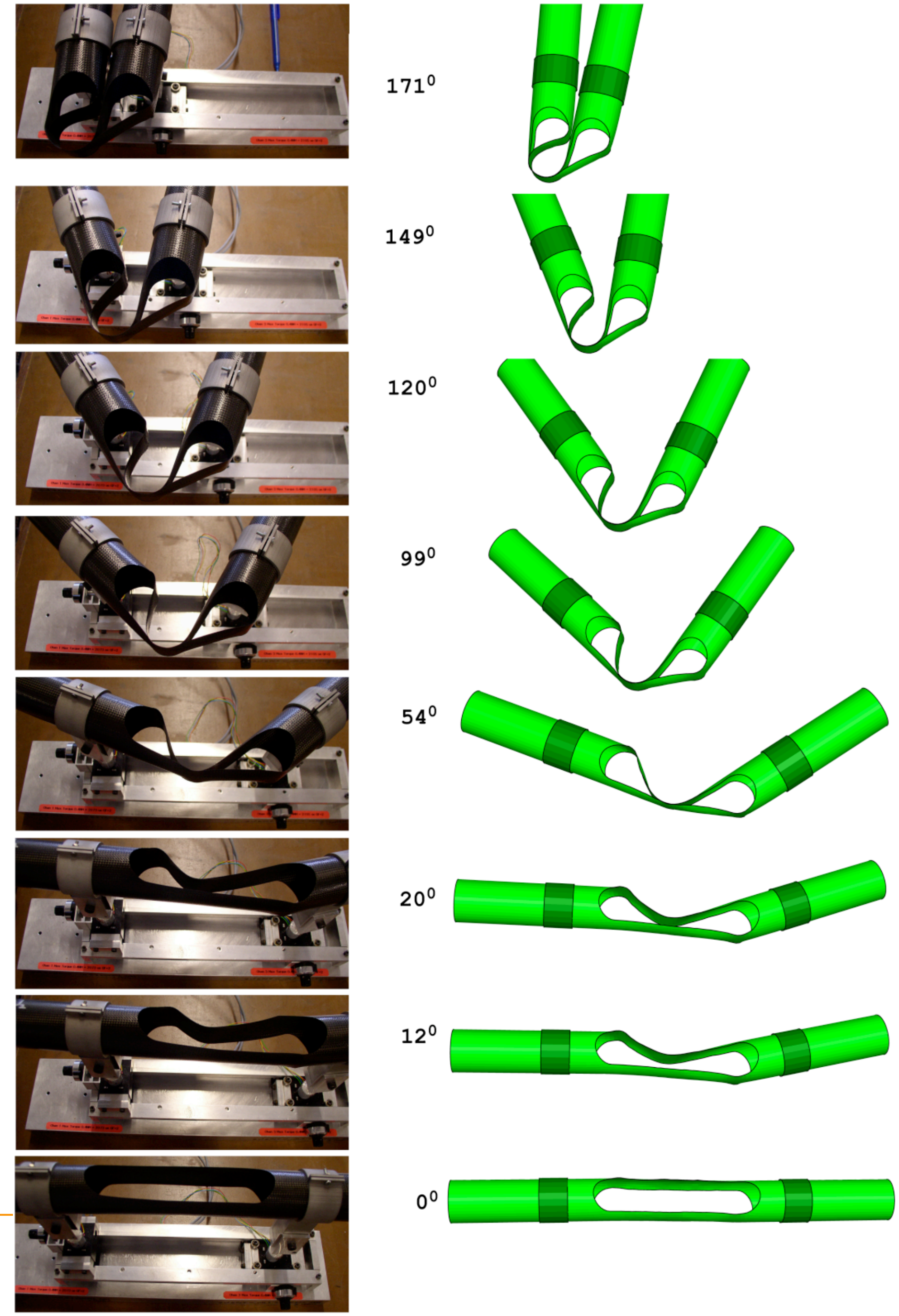
Kinetic energy still non-zero

Folding and Deployment through End Rotations

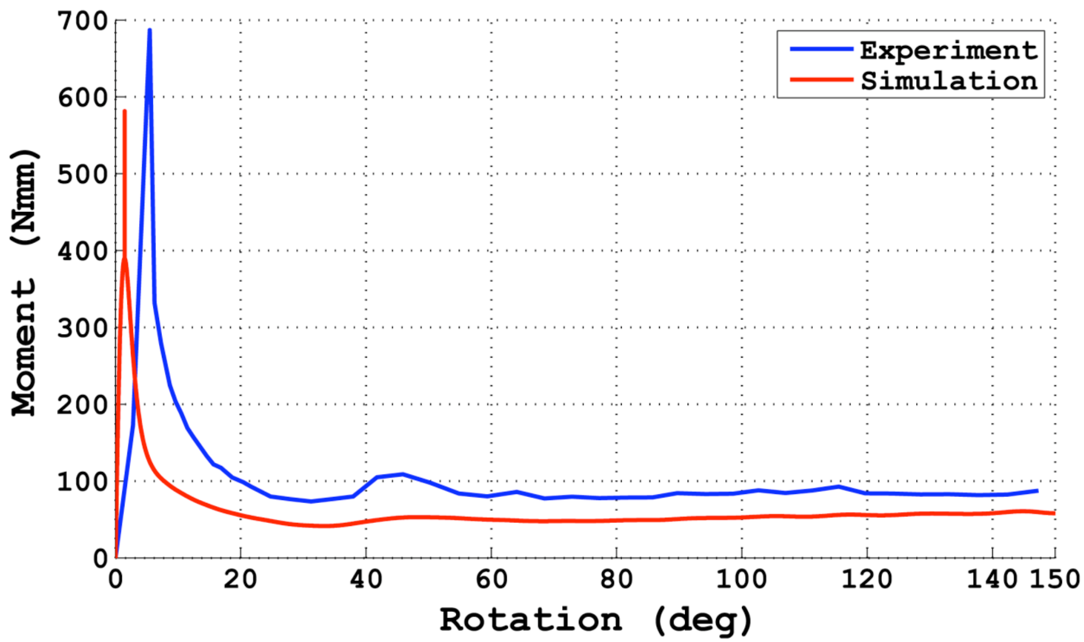


Comparison

- Comparison of quasi-static deployment experiments and snapshots from the simulation
- Good agreement between regions of localized deformation
- However, did not fully recover the original configuration



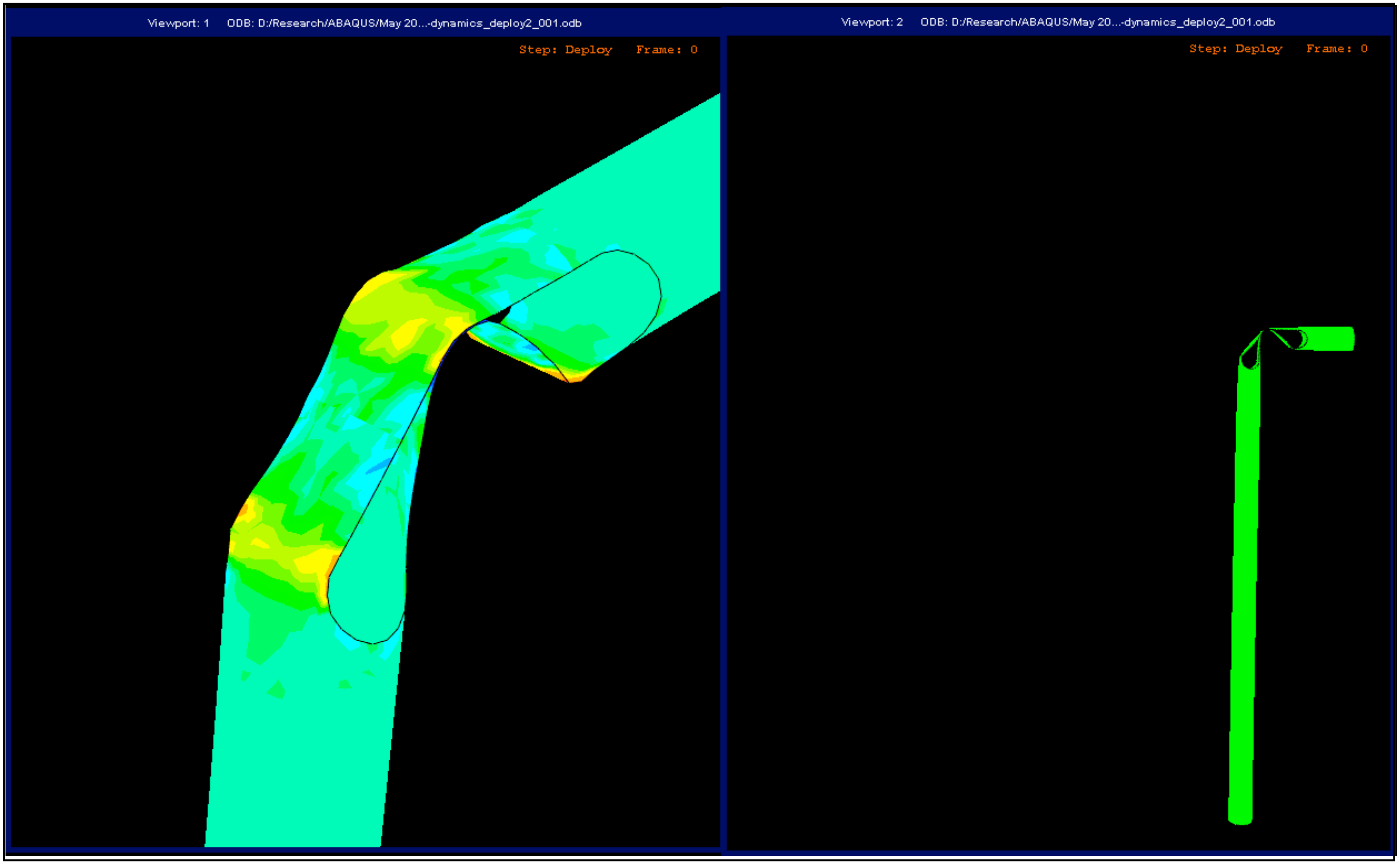
Comparison of Deployment Moment



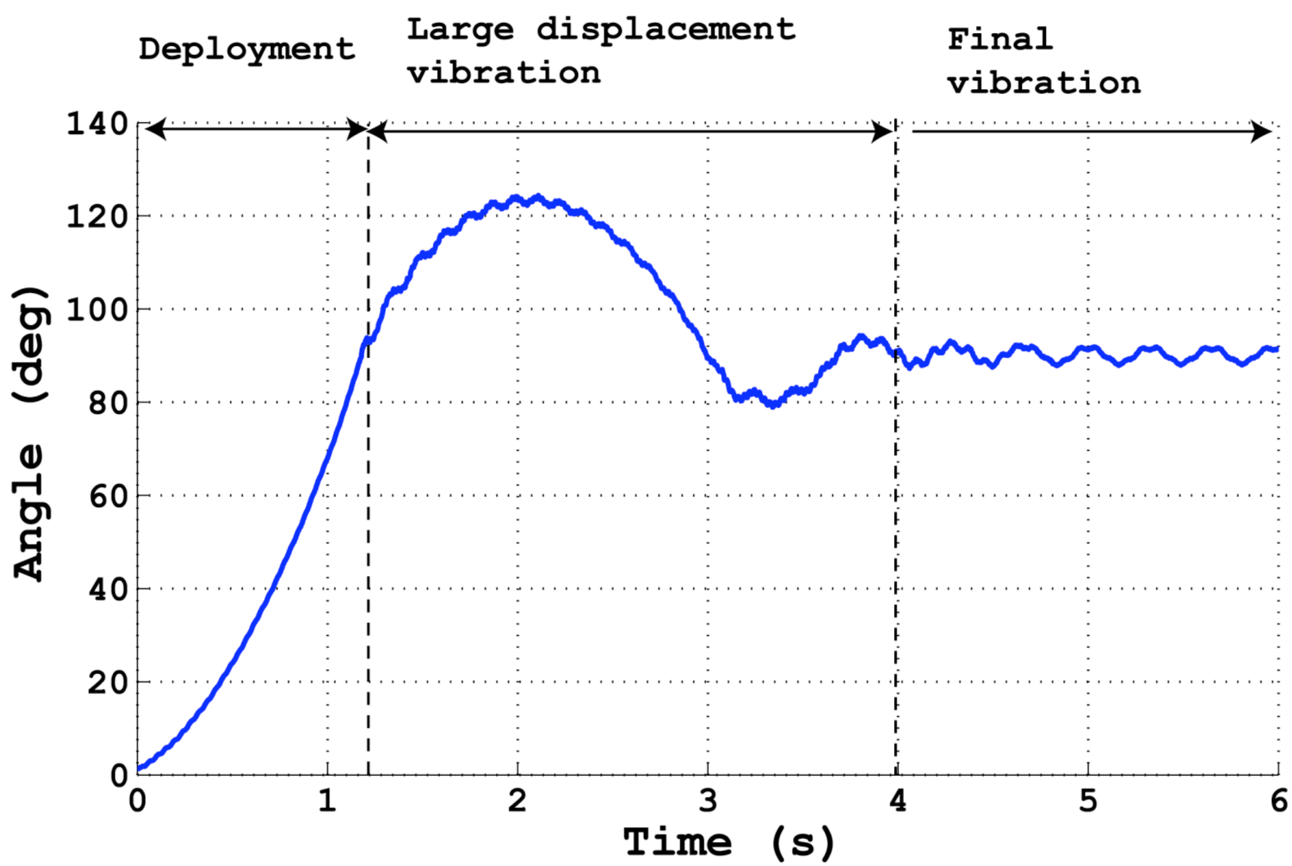
- Simulation has captured the overall behaviour
- Experiment
  - Peak : 5.5°, 690 Nmm
  - Steady state : 85 Nmm
- Simulation
  - Peak : 1.5°, 581 Nmm
  - Steady state : 55 Nmm

7. Deployment Dynamics

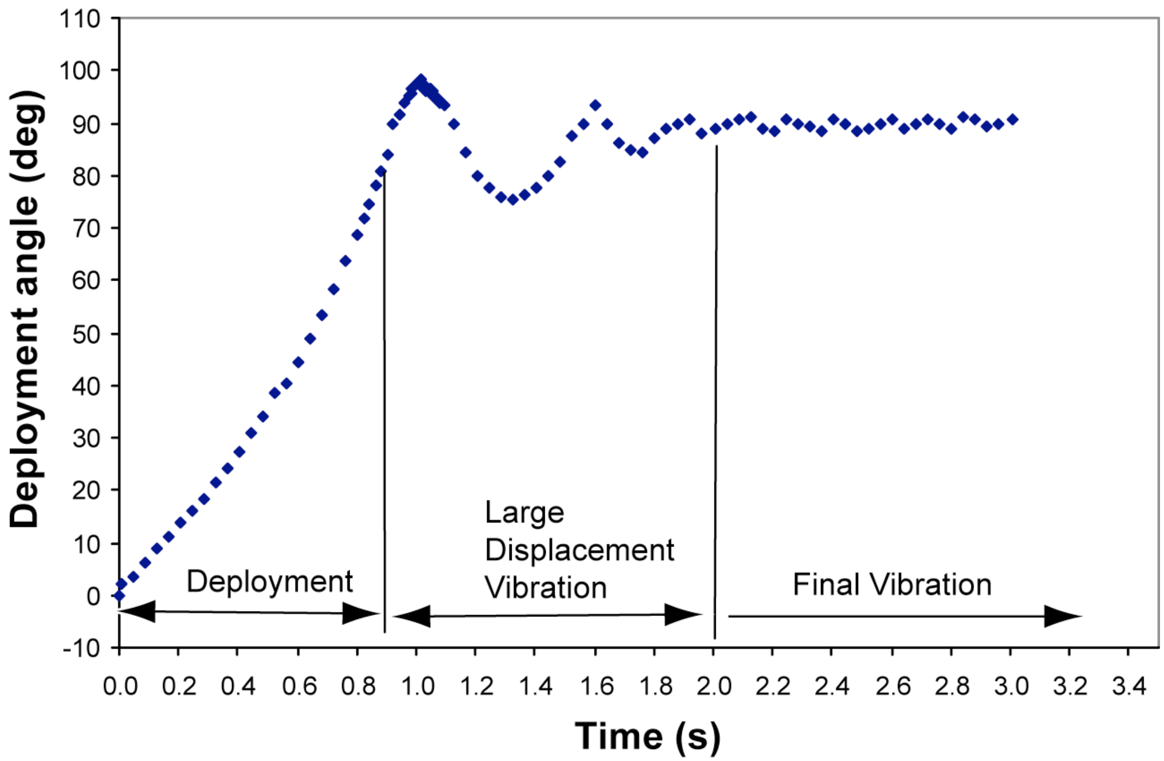
Simulation (Hinge with 2 Slots)



Simulation (Hinge with 2 Slots)



Experimental Results



- Simulation is for 3 ply boom
- Hinge has 3 slots

Concluding Remarks

- General technique for simulation of folding and deployment of thin-composite structures
- Preliminary results for dynamic deployment
- Captures experimental behaviour with reasonable accuracy
- For quasi-static behaviour poor results obtained when kinetic energy is significant proportion of internal energy
- Essential to monitor energy balance to avoid spurious results

- Improvements to quantitative correlation with experiments still needed