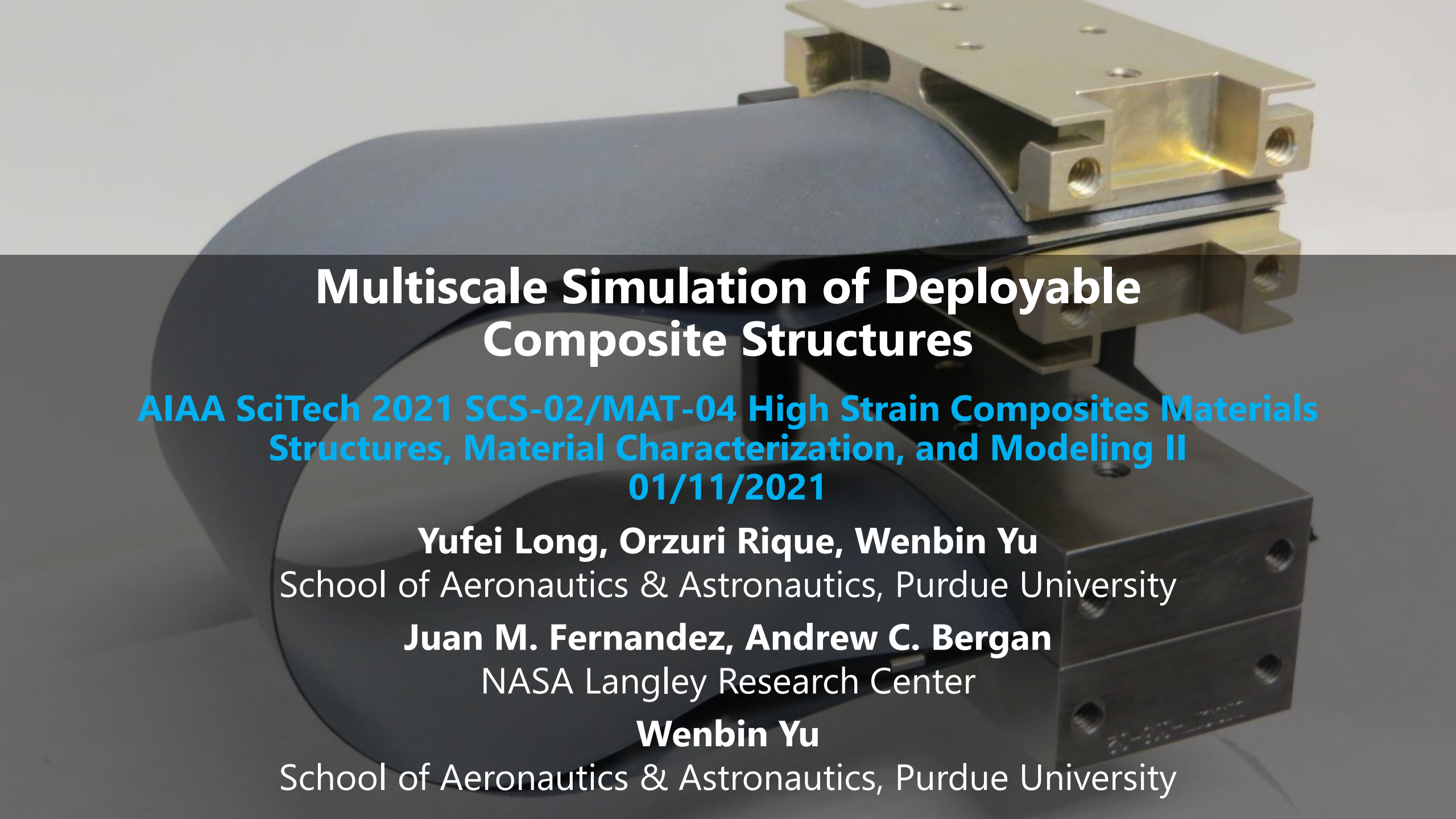

Multiscale Simulation of Deployable Composite Structures

AIAA SciTech 2021 SCS-02/MAT-04 High Strain Composites Materials Structures, Material Characterization, and Modeling II
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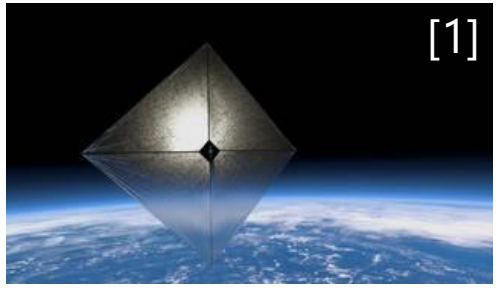
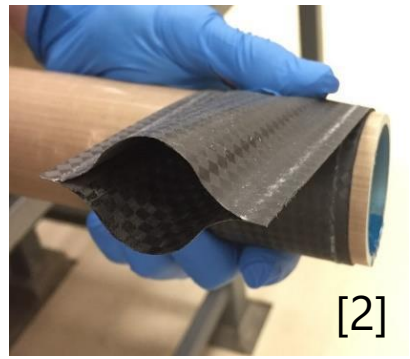
Introduction

Deployable composite structures:

TP-HSC: ply thickness 0.02 to 0.1 mm.

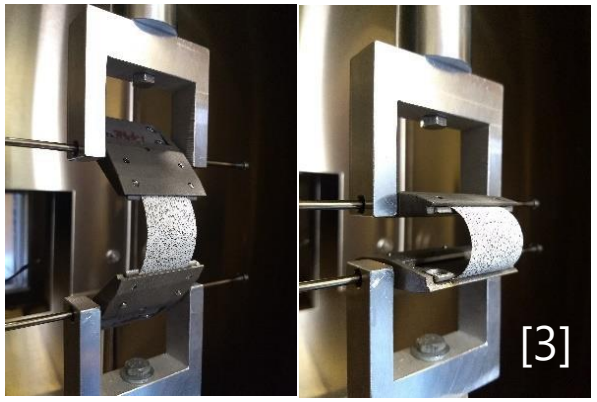
Small satellite: small in stowed volumn, large after deployment; large deformation, long stowage time.

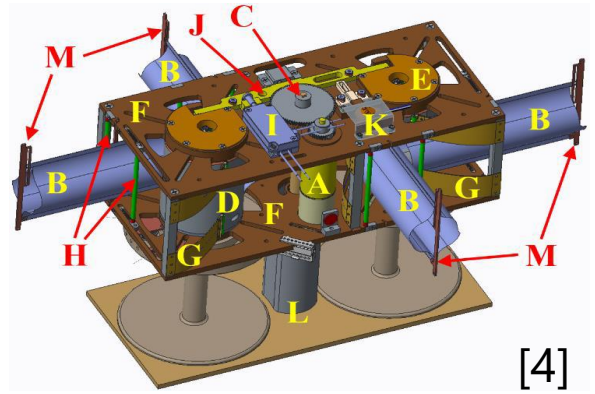




Simulation:

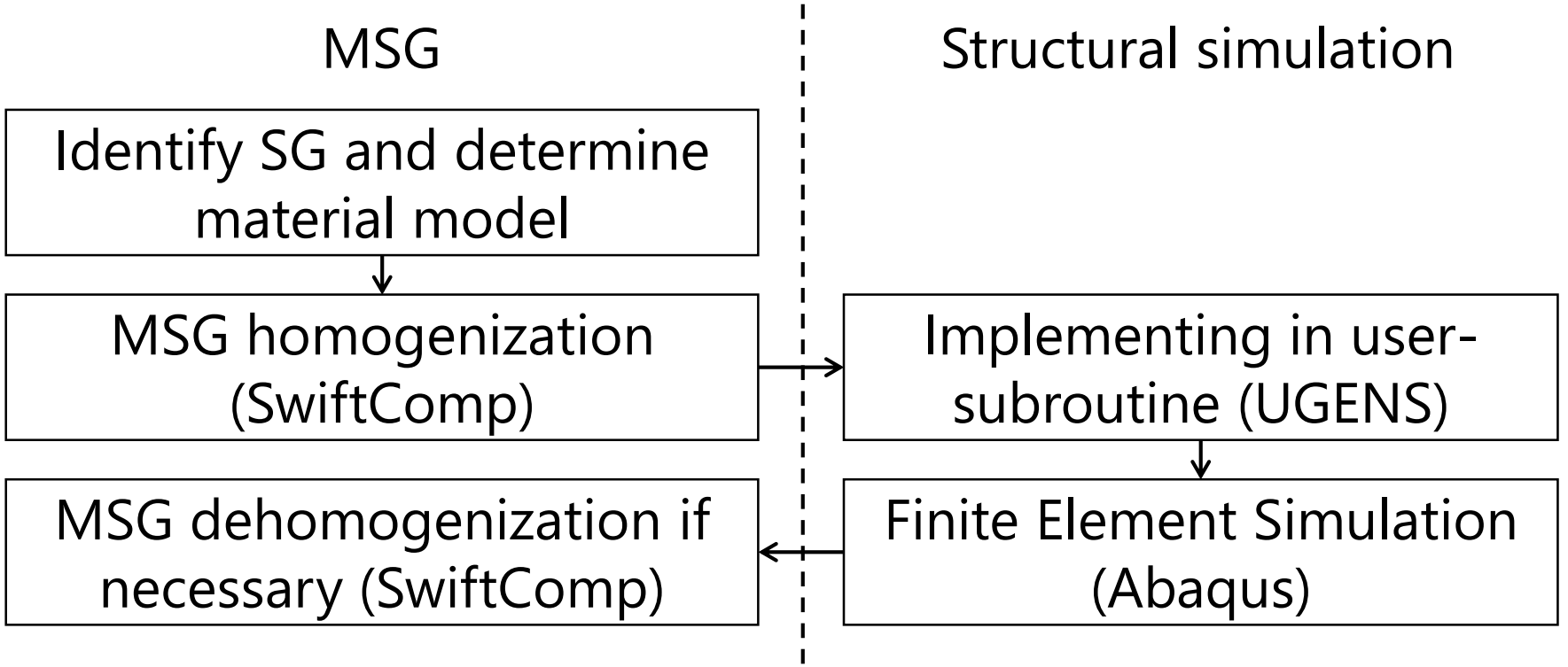
- Experiment: column bending test (CBT), close to pure bending, less stress concentration;
  verification of material constitutive model.
- Deployable boom structures: coiling and deployment of a lenticular boom;
  influence of large deformation and long stowage time on the geometry of the boom after deployment





[1] NASA, https://gameon.nasa.gov/projects/deployable-composite-booms-dcb/. [2] A. Lee, J. Fernandez, Composite Structures 225 (2019).
[3] J. Fernandez et al., ICCM22 (2019). [4] J. Fernandez et al., AIAA SciTech (2018).

MSG-Based Multiscale Simulation Framework



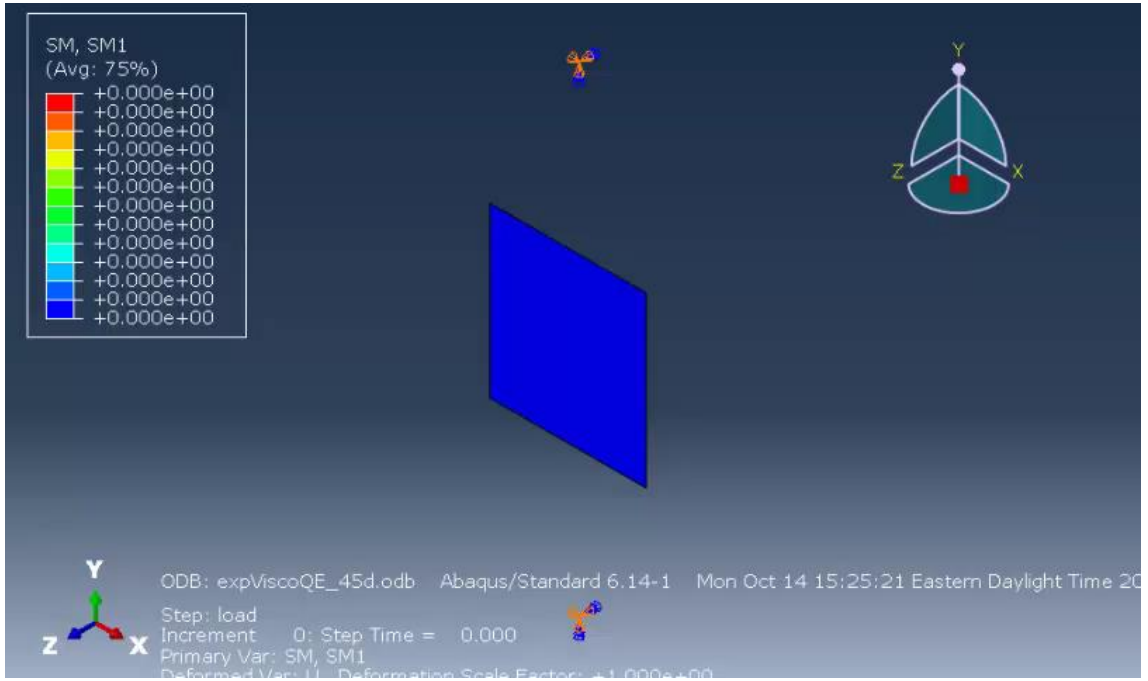
$$\Delta N\left(t_{n+1}\right) = A_{eq}\Delta\epsilon\left(t_{n+1}\right) + B_{eq}\Delta\kappa\left(t_{n+1}\right) + \Omega_N$$

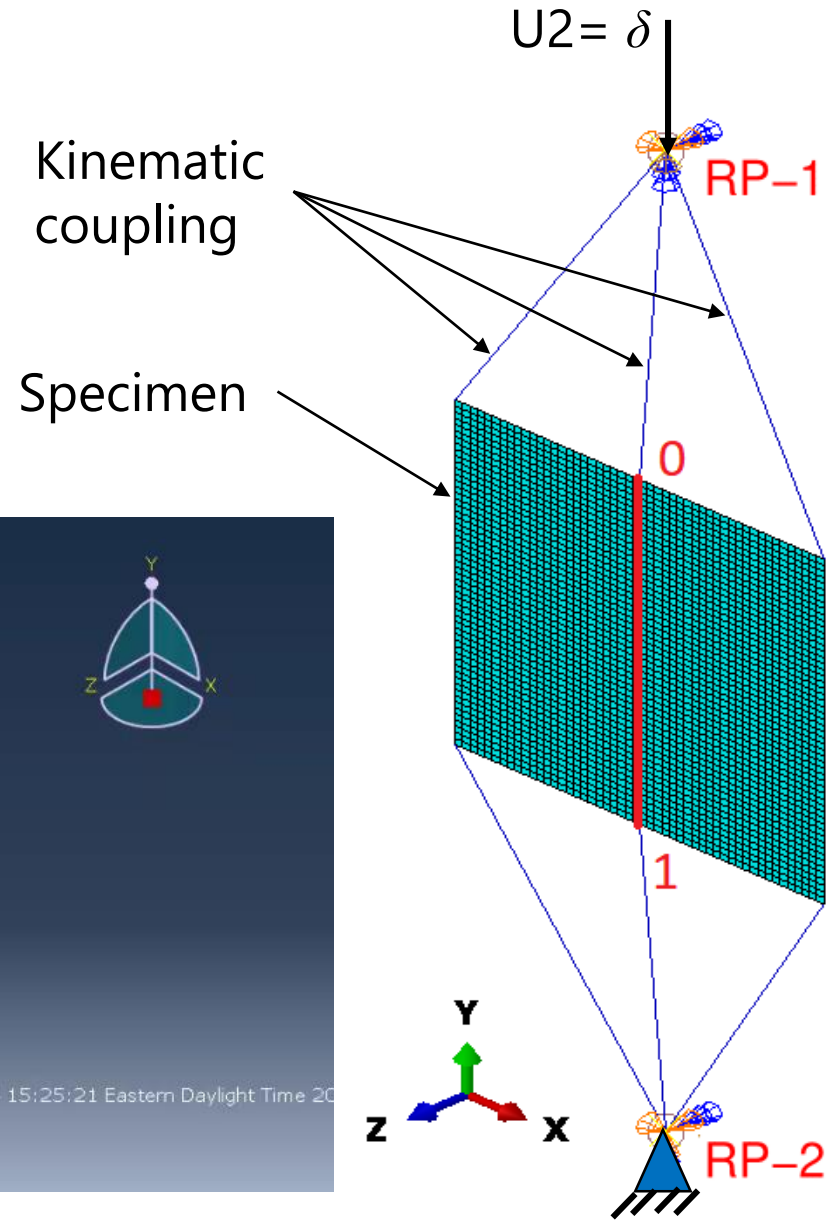
$$\Delta M\left(t_{n+1}\right) = B_{eq}\Delta\epsilon\left(t_{n+1}\right) + D_{eq}\Delta\kappa\left(t_{n+1}\right) + \Omega_M$$

Direct integration UGENS: force and moment increment calculated from ABD Prony series and loading history

Column Bending Test Simulation

- Abaqus/Standard solver
- General purpose shell element S4
- M30S/PMT-F7 plain weave (PW), $[\pm 45_{PW}]_4$
- Viscoelastic shell properties
- 4-step analysis
  1. Folding
  2. Relaxation
  3. Unfolding
  4. Recovery

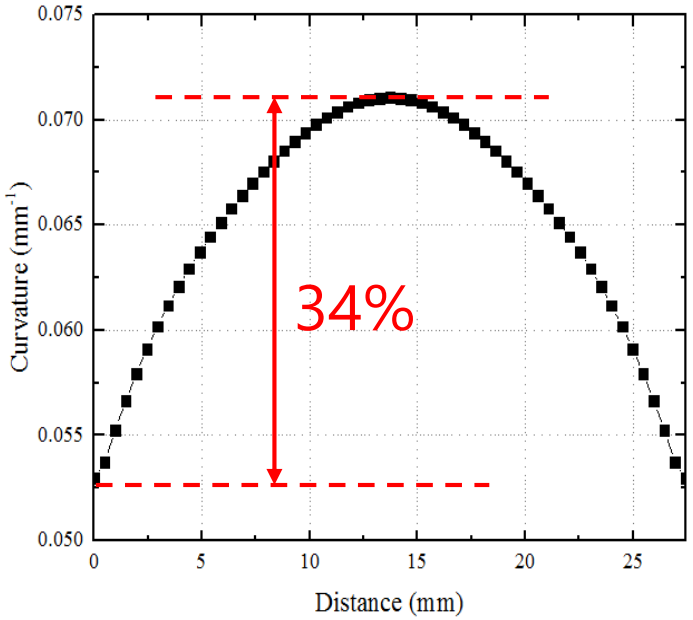




Column Bending Test Simulation

Process of the CBT:

Step	Time (s)
Folding	120
Relaxation	21600 (6 h)
Unfolding	5
Recovery	7200 (2 h)

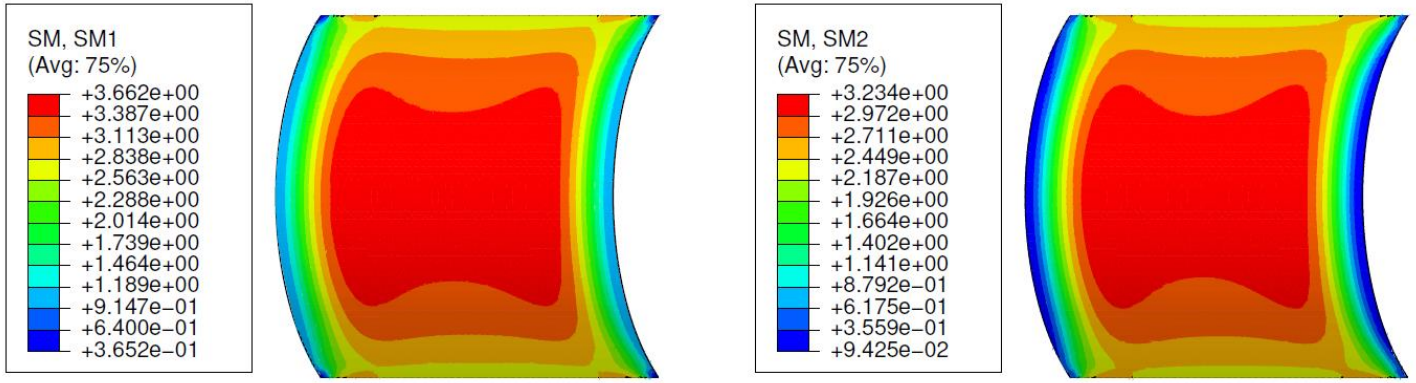


Data reduction:

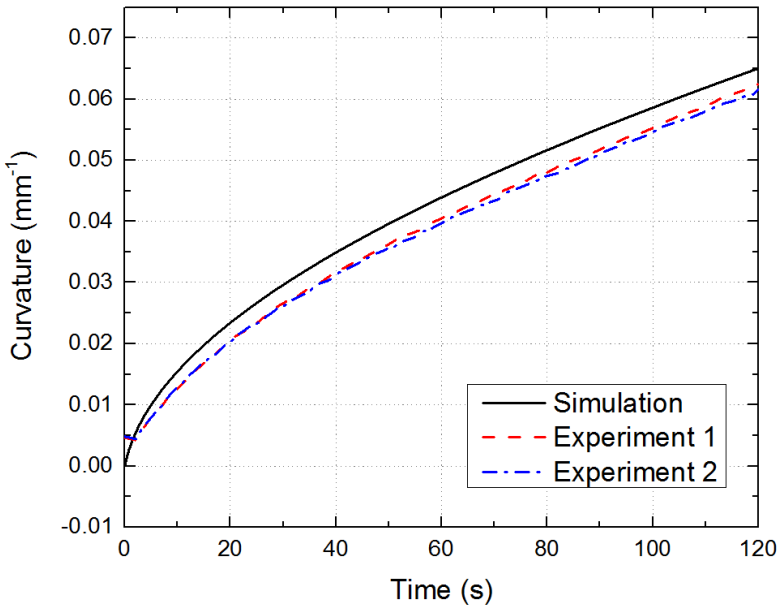
$$\kappa = \frac{\phi}{s} \qquad \phi = 2\phi_{rp}$$

$$M_{max} = Pr \qquad r = u_3 + r_0$$

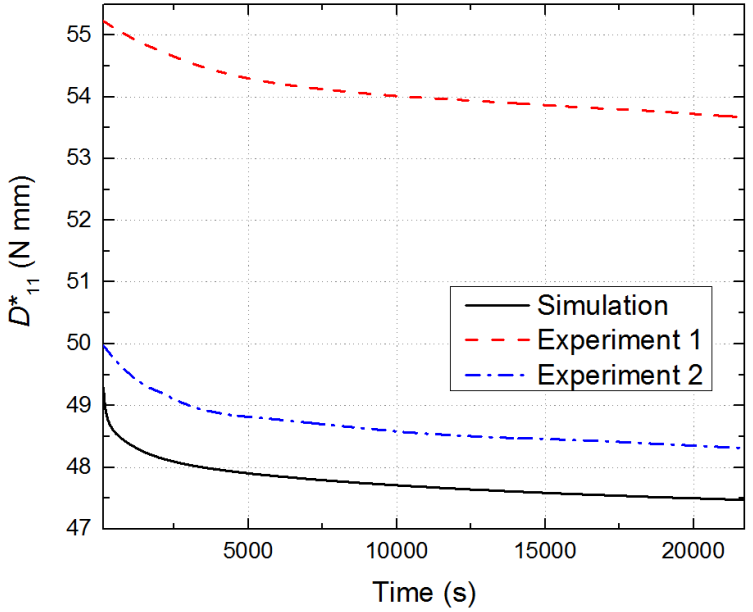
$$D_{11}^{*} = \frac{M_{max}/d}{\kappa}$$



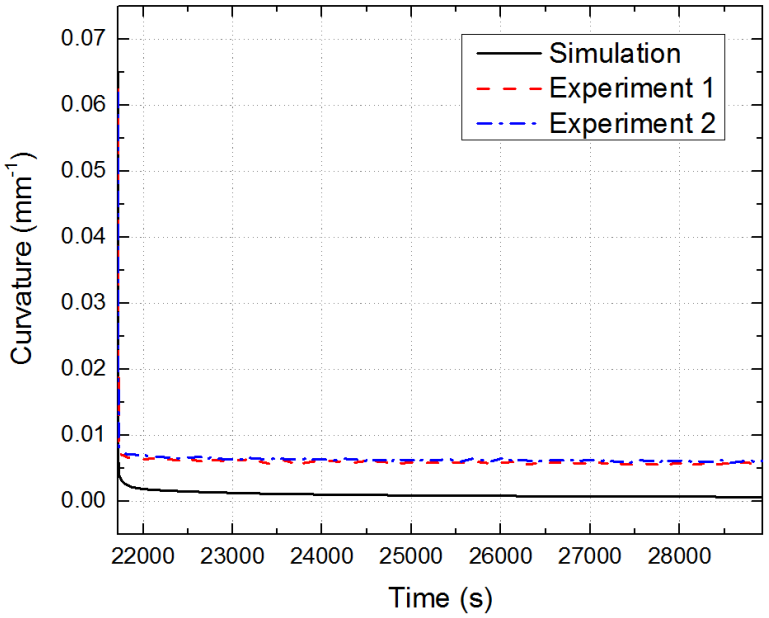
Column Bending Test Simulation



Curvature history κ during folding



Effective bending stiffness D^*_{11} history during relaxation



Curvature history κ after relaxation

Calibration Using CBT Simulation

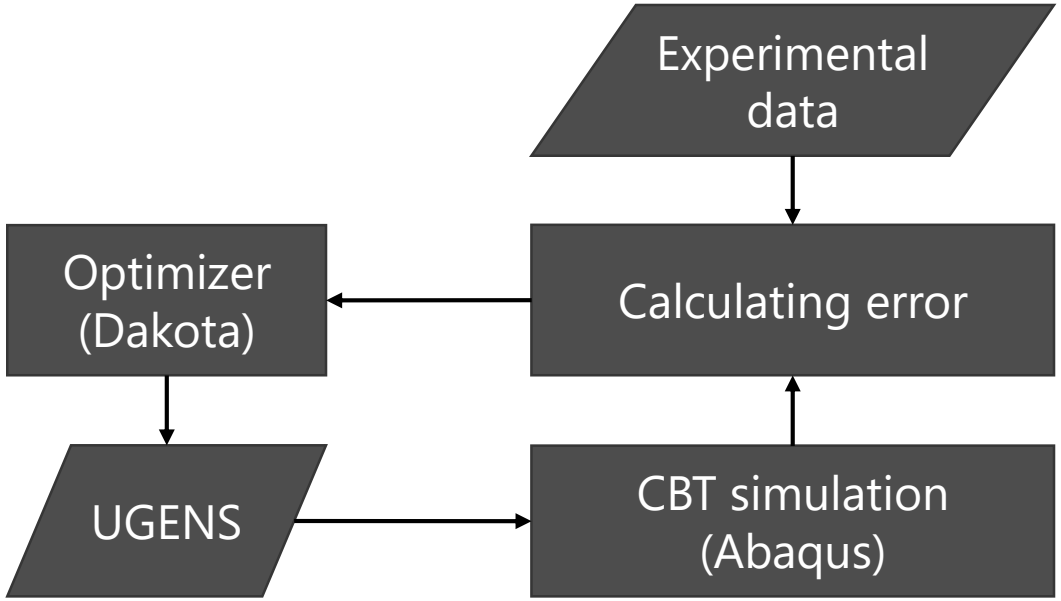
Calibrating coefficients of Prony series

k	ρ_k	$D_{11,k}$ (N·mm)
∞	--	(calculated)
1	1.00E+01	0.0760
2	1.00E+02	0.5130
3	1.00E+03	0.4345
4	1.00E+04	0.2178
5	1.00E+05	0.4873
6	1.00E+08	1.0000
SUM		**50.6562**

D_{12} and D_{33} keep the MSG results

A_{ij} estimated with $A_{ij} = D_{ij}\frac{12}{h^2}$

The SUM is kept unchanged



Comparing $D_{11}^{*} = \frac{M_{max}/d}{\kappa}$

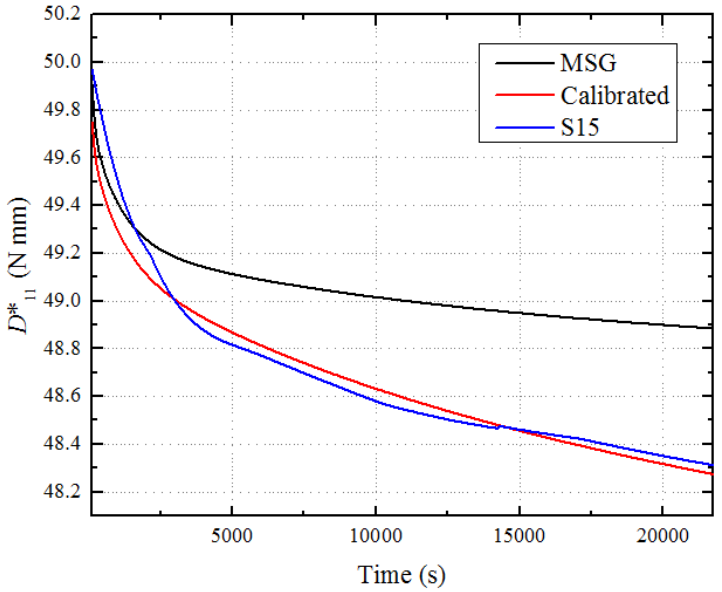
Error evaluated using Error Sum of Squares (SSE)

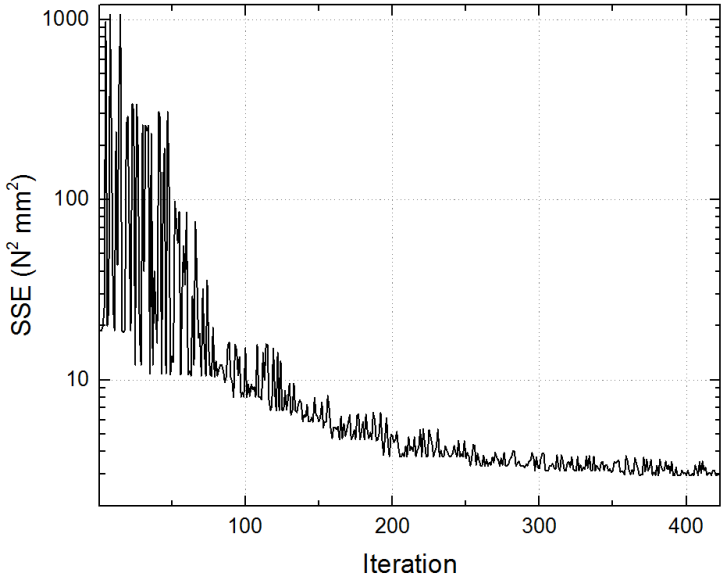
SSE = SUM[(predicted – target)^2]

Calibration Using CBT Simulation

Calibration was judged converged after 423 iterations. Best results at iteration 408

k	ρ_k	$D_{11,k}$ (N·mm)
∞	--	45.246725
1	1.00E+01	0.000000
2	1.00E+02	0.348000
3	1.00E+03	0.403250
4	1.00E+04	0.434050
5	1.00E+05	1.629175
6	1.00E+08	2.595000
SUM		**50.656200**



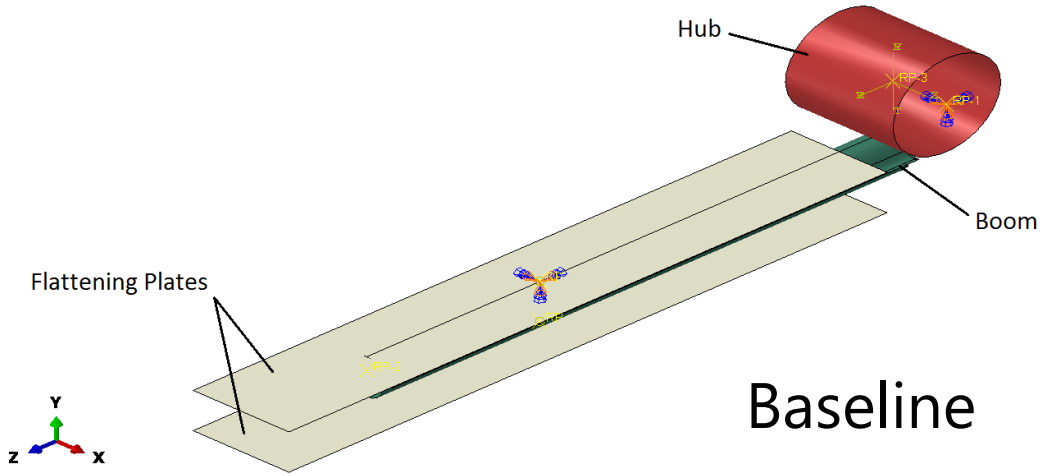


Initial SSE: 18.78167923
Minimized SSE: 2.9520415814

Deployable Lenticular Boom and Hub Simulation

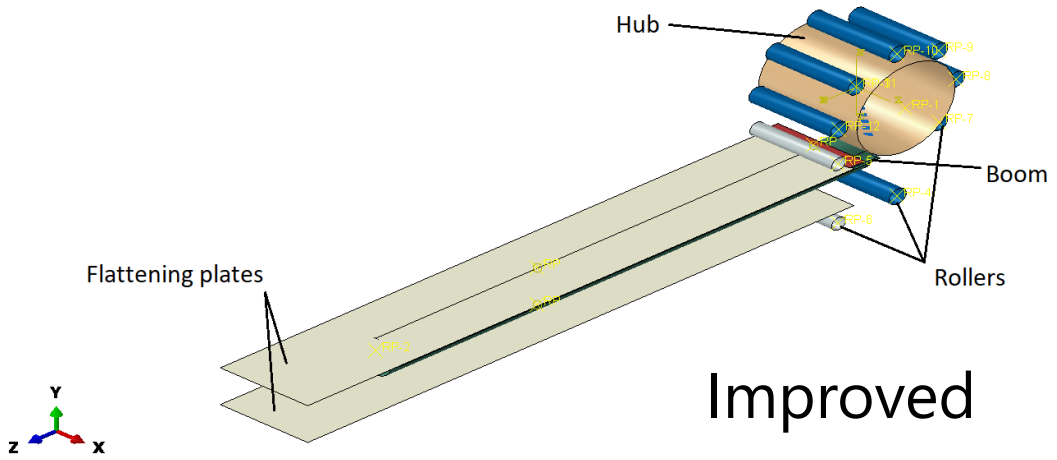
Abaqus/Standard, implicit dynamics, quasi-static analysis
Boom length: 880 mm; Hub radius: 90 mm; Boom coiled approx. 1.5 rev.
Tension force of 0.4 N/mm, the whole boom flatten with plates before coiling

Tension force and plates kept through coiling, stowage and deployment. Released after deployment



Baseline

Rollers with forces applied: 2 nip & 7 radial rollers. Tension force and plates removed after coiling



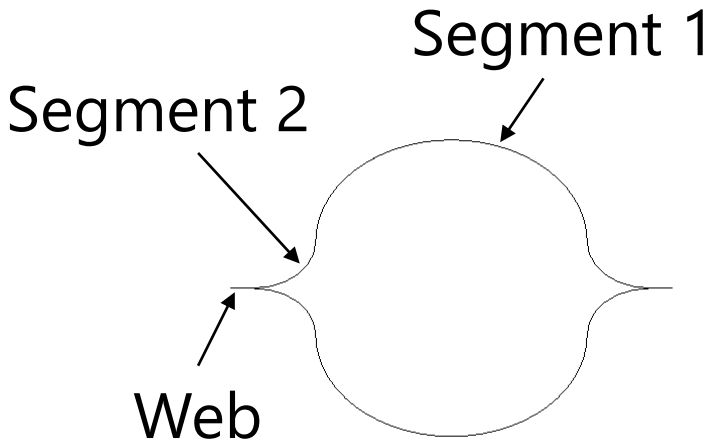
Improved

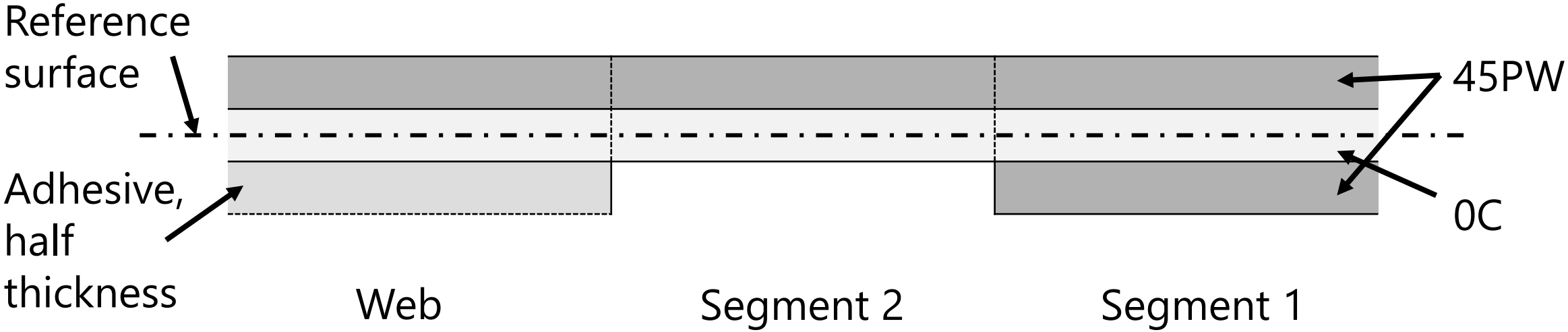
Deployable Lenticular Boom and Hub Simulation

Unidirectional carbon fiber/epoxy (C): MR60H/PMT-F7

Plain weave carbon fiber/epoxy (PW): M30S/PMT-F7

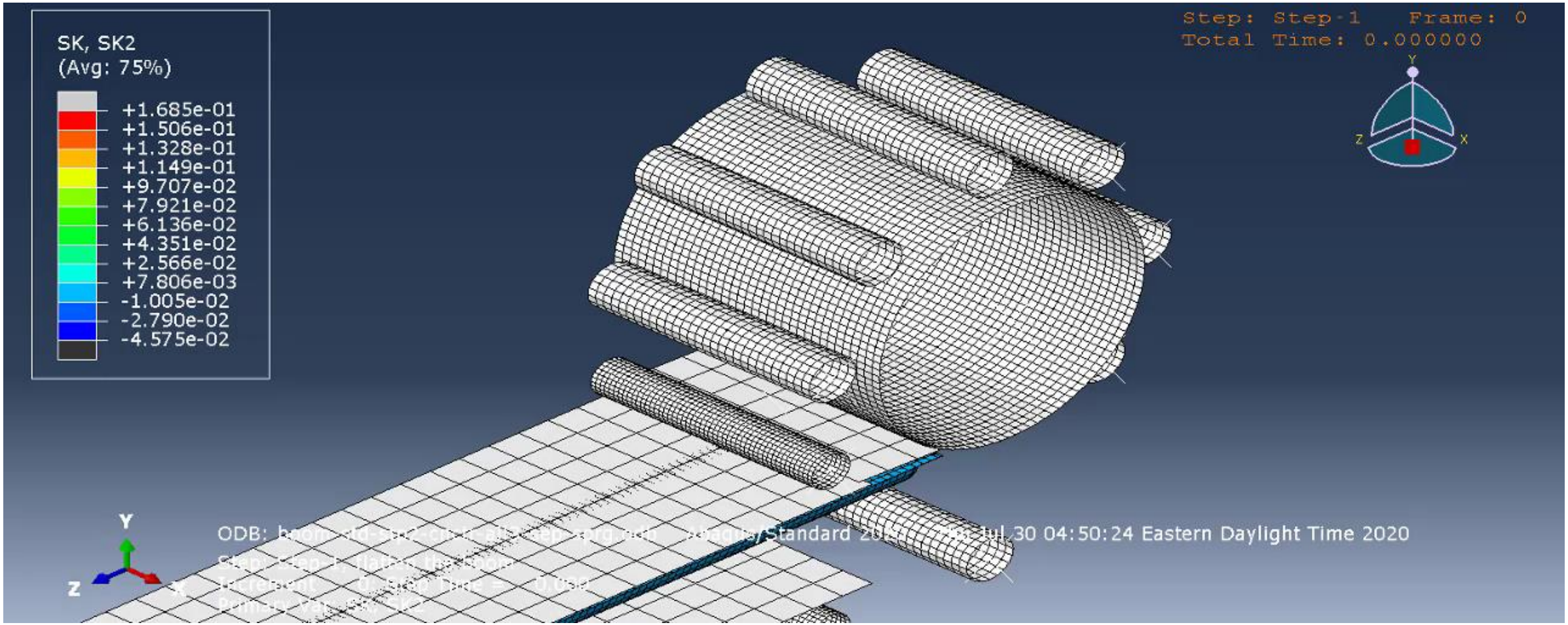
Different layups in segment 1, 2 and the web





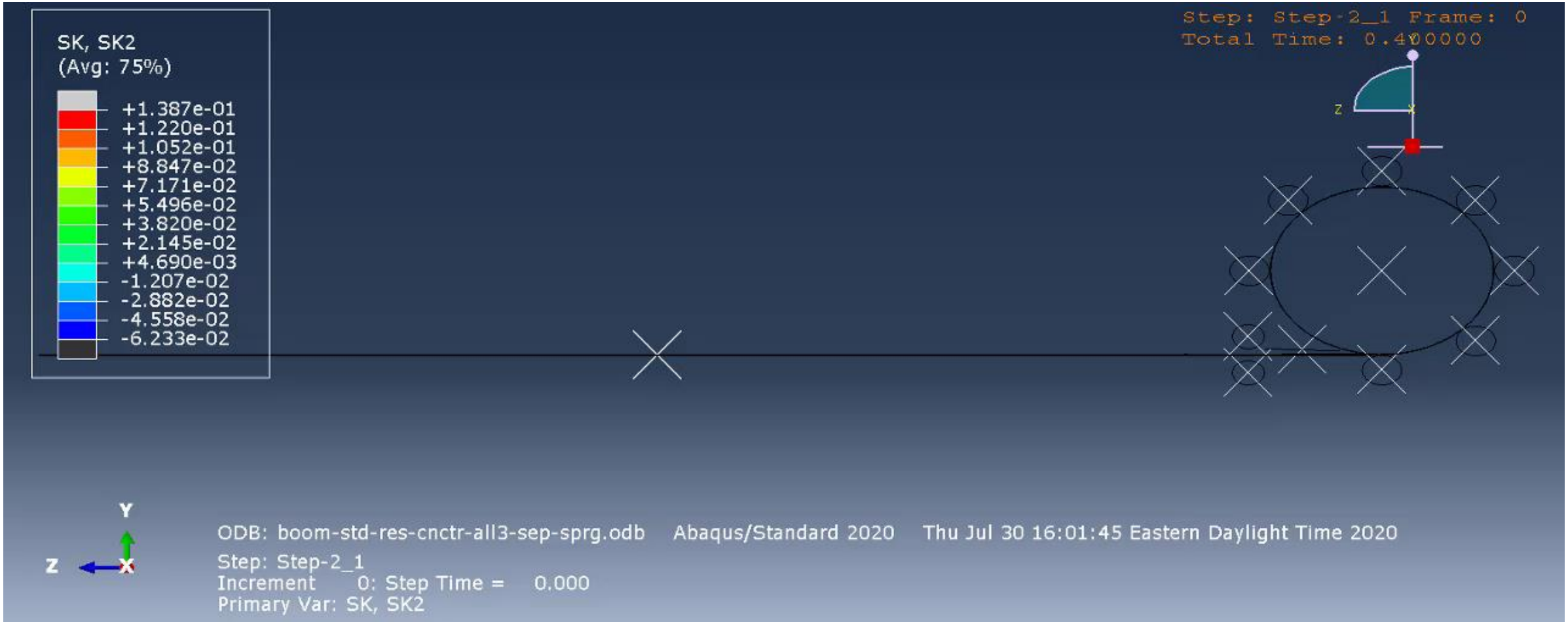
Deployable Lenticular Boom and Hub Simulation

Improved model, flattening and coiling

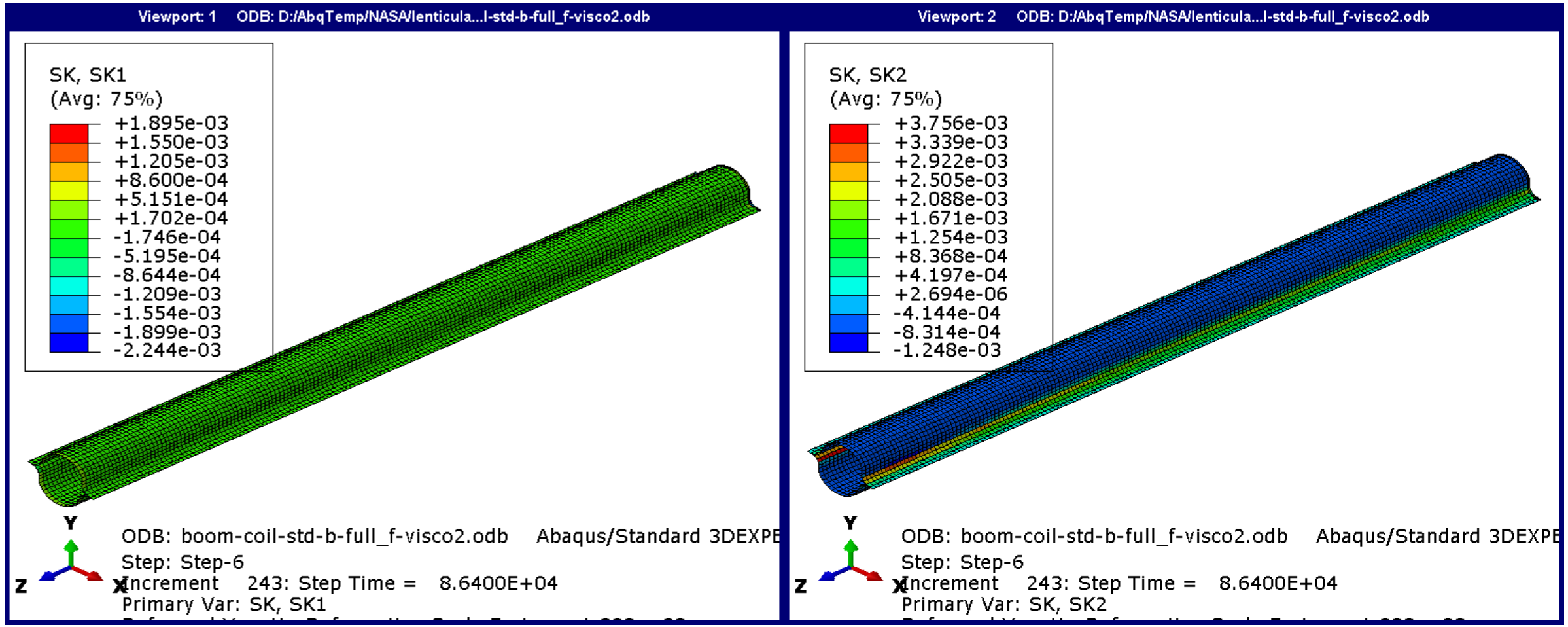


Deployable Lenticular Boom and Hub Simulation

Improved model, relaxation and deployment

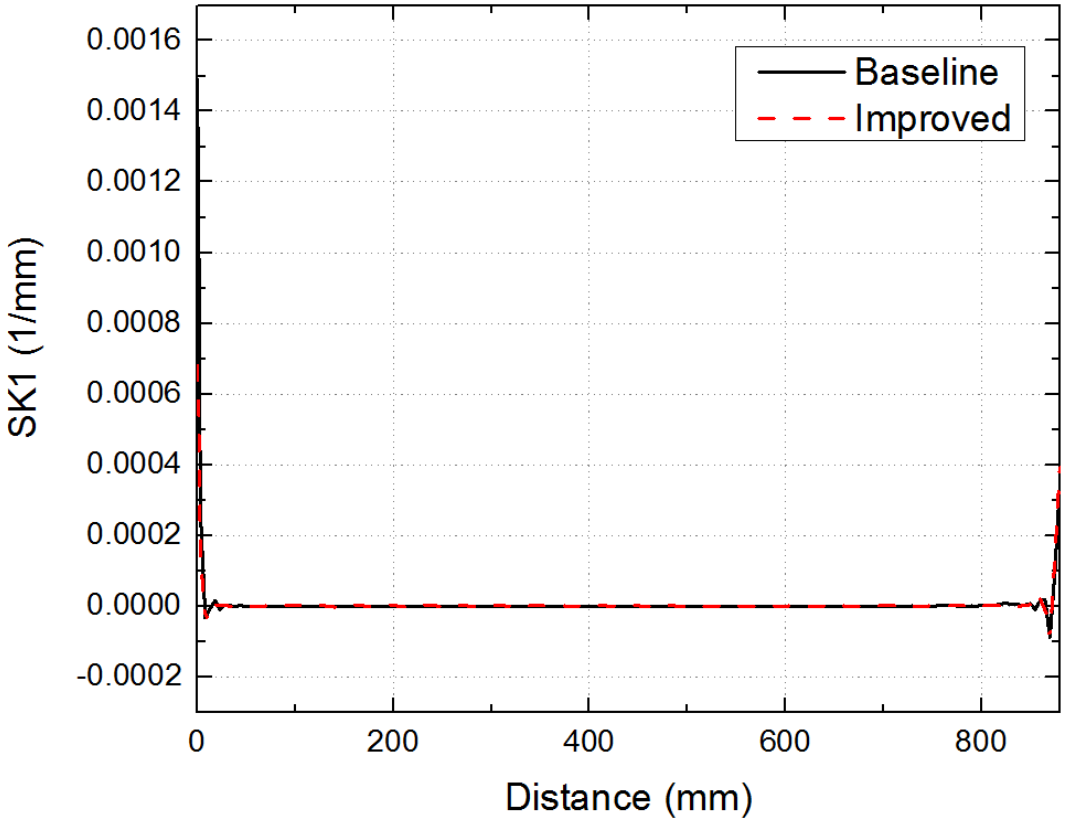


Deployable Lenticular Boom and Hub Simulation

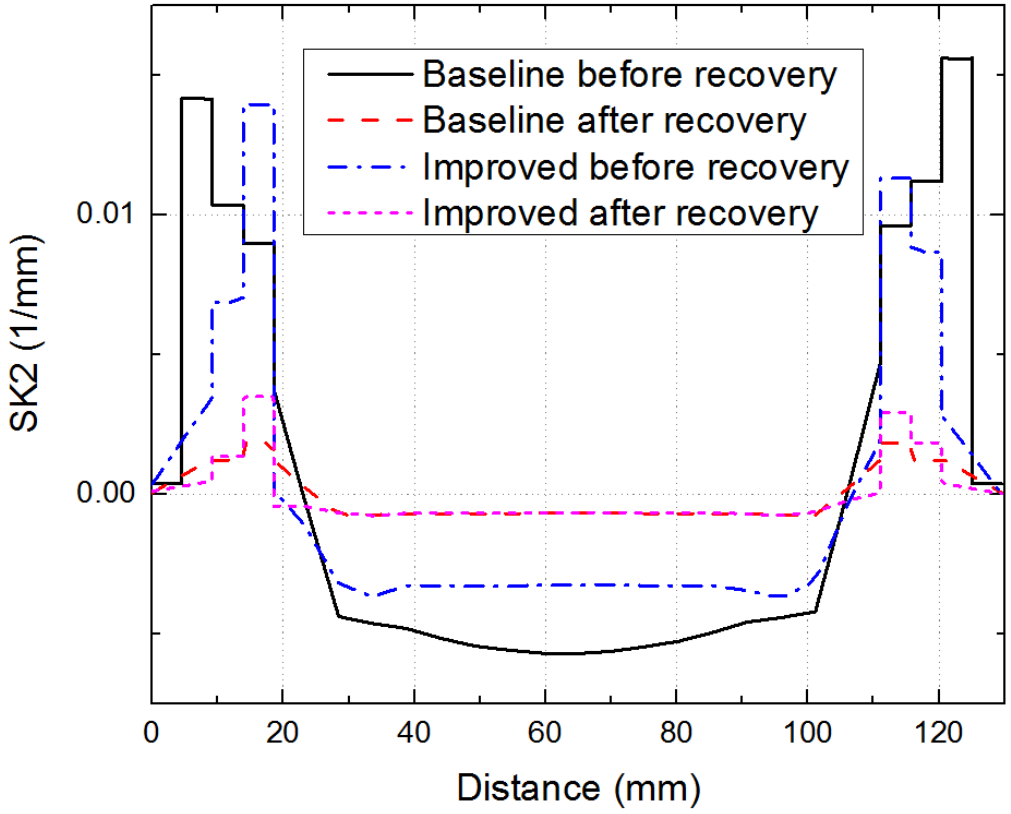


Residual curvature after recovery of 24 h

Deployable Lenticular Boom and Hub Simulation



Curvature in the longitudinal direction
Negligible, only boundary effect



Curvature in the hoop direction
Major, reduced after 24 h recovery

Summary

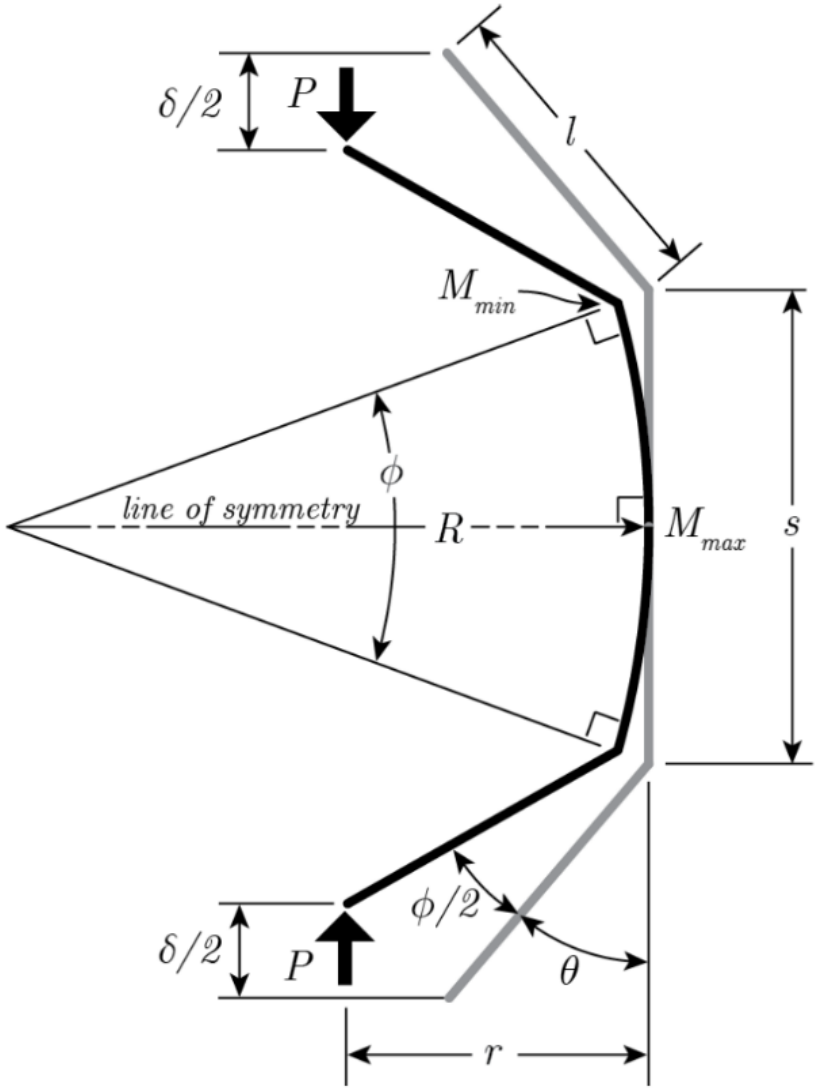
- Simulation framework: MSG homogenization, finite element structural simulation
- CBT simulation: nonuniform deformation captured, consistent data reduction with experiments
  - Accurate prediction of curvature and stiffness during folding and relaxation
  - Underpredict curvature after unfolding, possibly plasticity
- Potential application of CBT simulation for the calibration of material properties
- Deployable boom structure: baseline and improved models
  - Flattening, coiling, stowage and deployment simulated
  - Negligible residual curvature in the longitudinal direction, major in the hoop direction, greatly reduced after recovery

Future work: Nonlinear material constitutive models

Thank You!

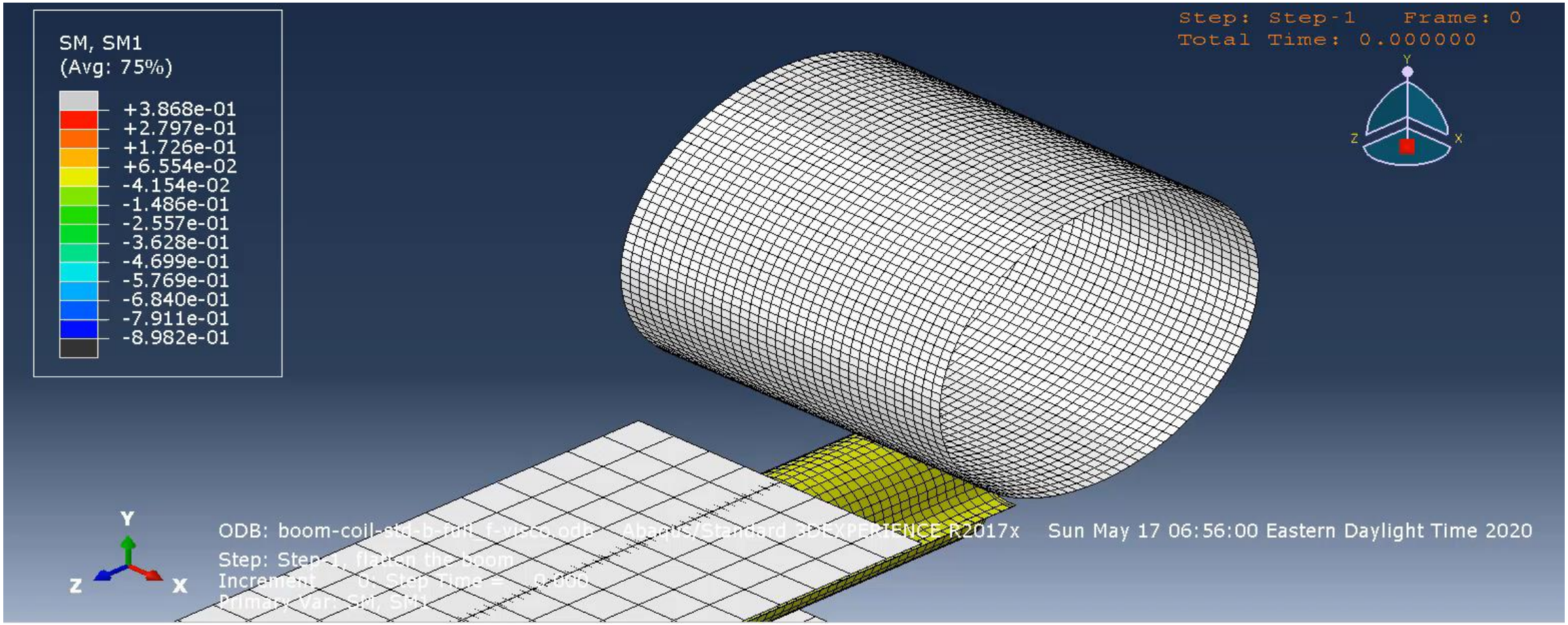
Backup

CBT fixture arm length l (mm)	25.4
Specimen width d (mm)	25.4
Specimen gage length s (mm)	27.432
Fixture arm initial angle θ (rad)	0.0712
Fixture total displacement δ (mm)	25.4
Specimen thickness h (mm)	0.276

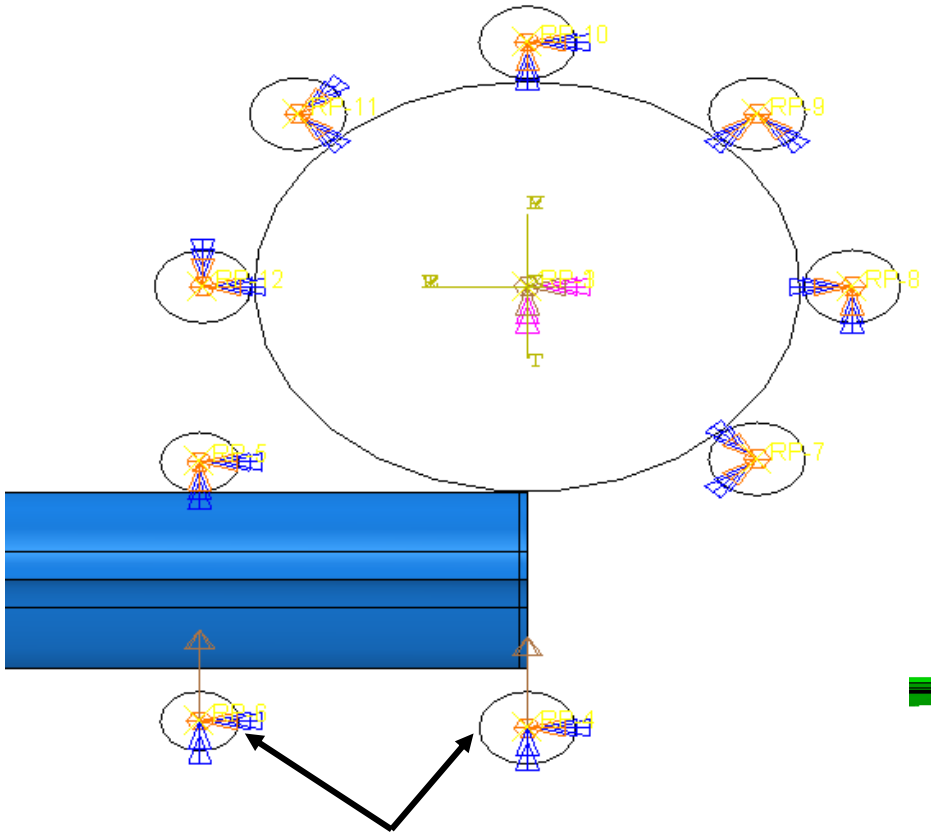


Deployable Lenticular Boom and Hub Simulation

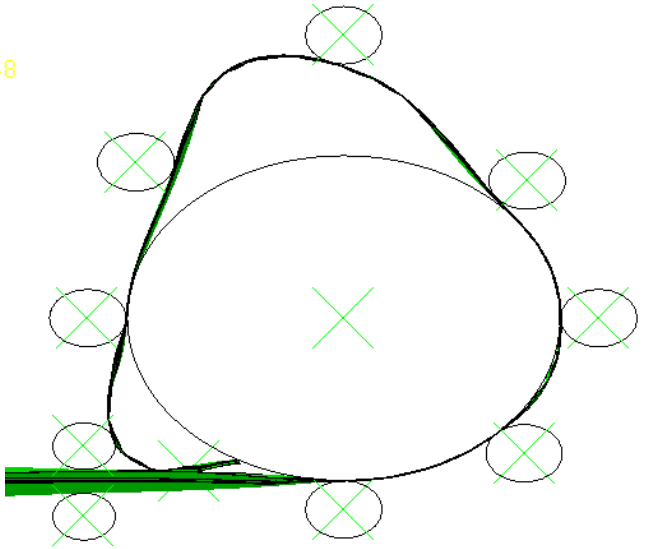
Baseline model



Backup



Moving up during flattening



Roller	Force (N)
1	20
2	21
3	11
4	11
5	6
6	6
7	21

Springs with stiffness of 1 N/mm in addition to the applied force