

Simulation of deployable composite structures based on Mechanics of Structure Genome

Emerging Spacecraft Structures Workshop and TC Summer Meeting

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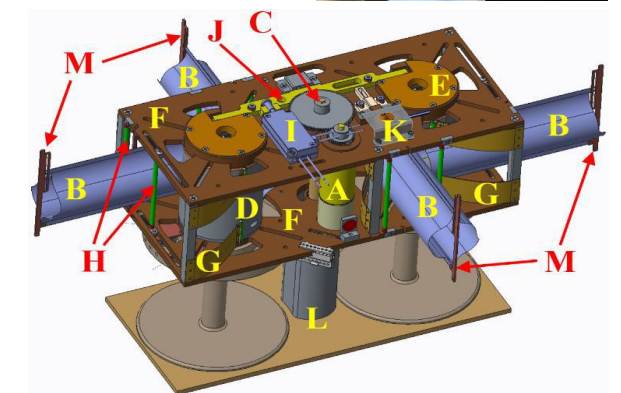
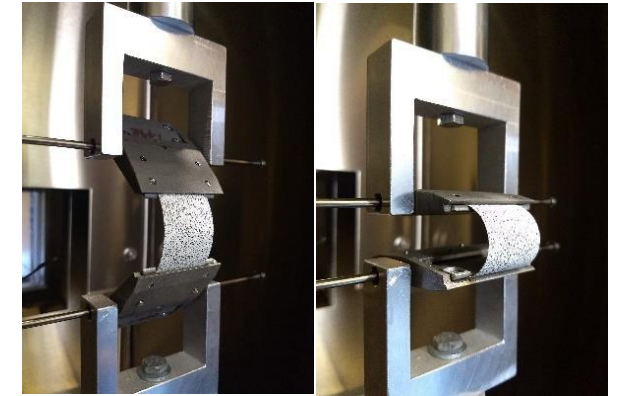
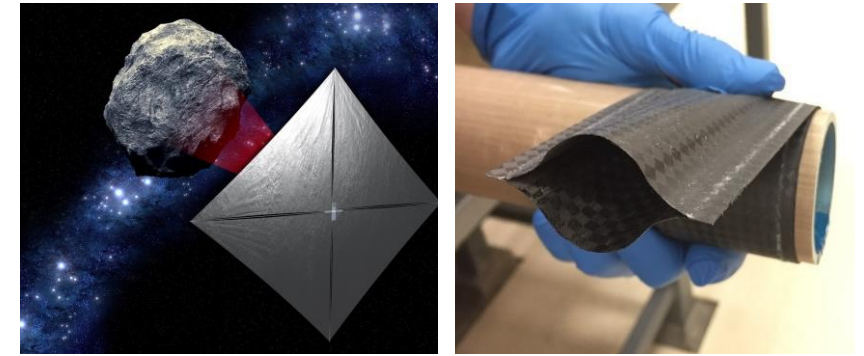
Introduction

Deployable composite structures:

TP-HSC, small in stowage, large after deployment;
large deformation, long stowage time, viscoelasticity.

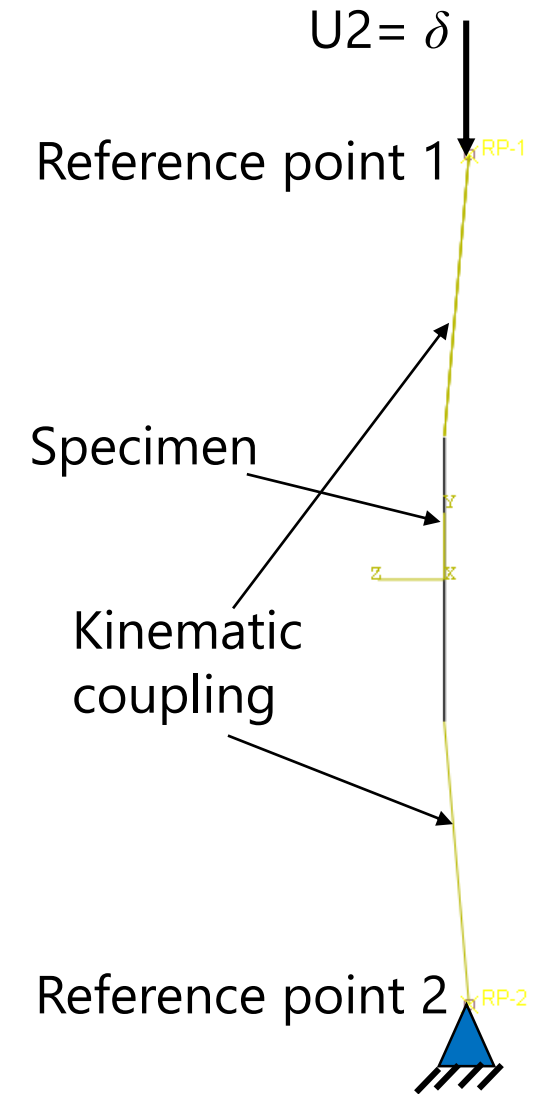
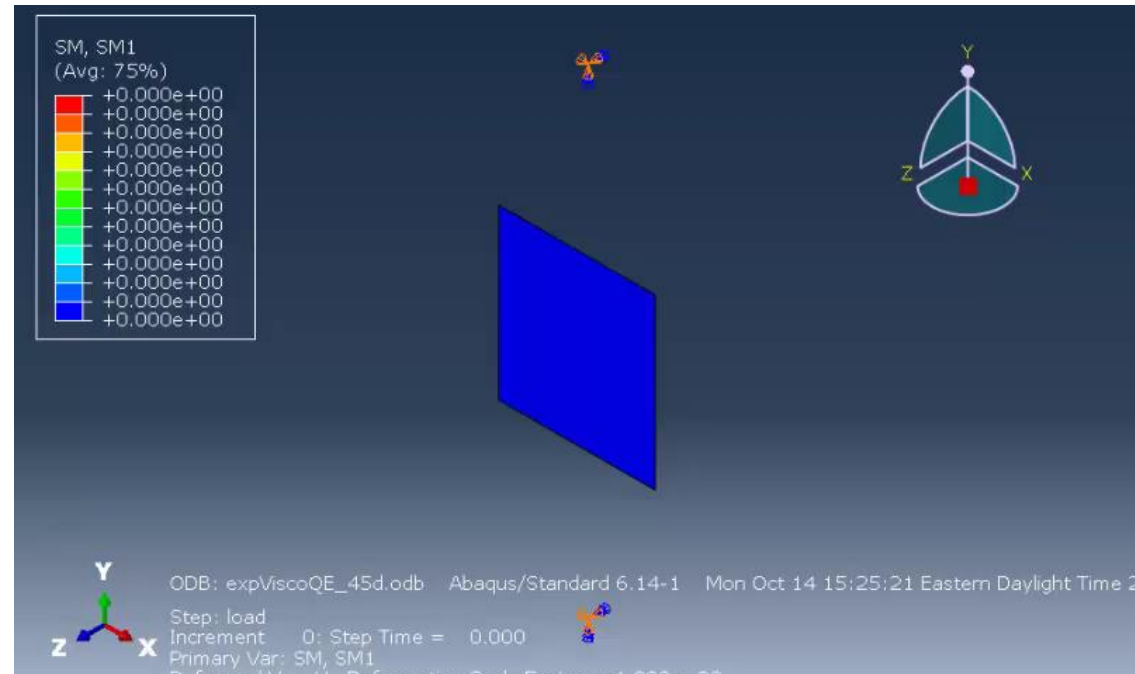
Simulation:

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



Column Bending Test

- Finite element simulation of the CBT
- Abaqus Standard solver
- General purpose shell element S4
- Viscoelastic material properties
- 4-step analysis
 1. Folding
 2. Relaxation
 3. Unfolding
 4. Recovery



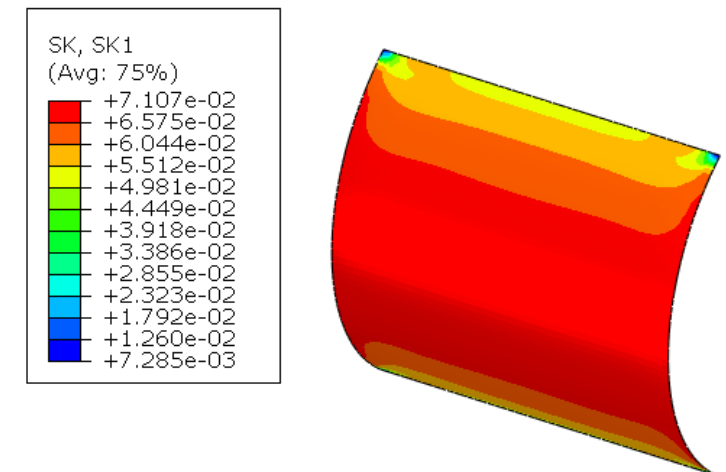
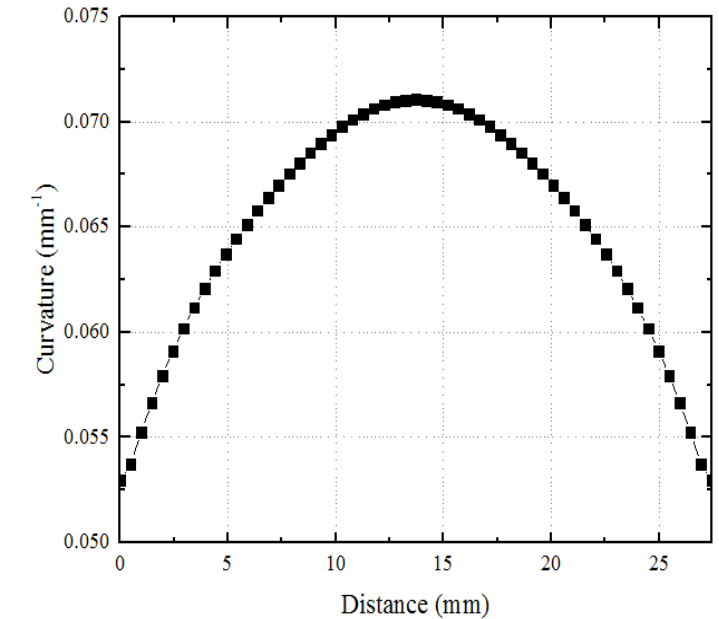
Column Bending Test (cont.)

Process of the CBT:

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

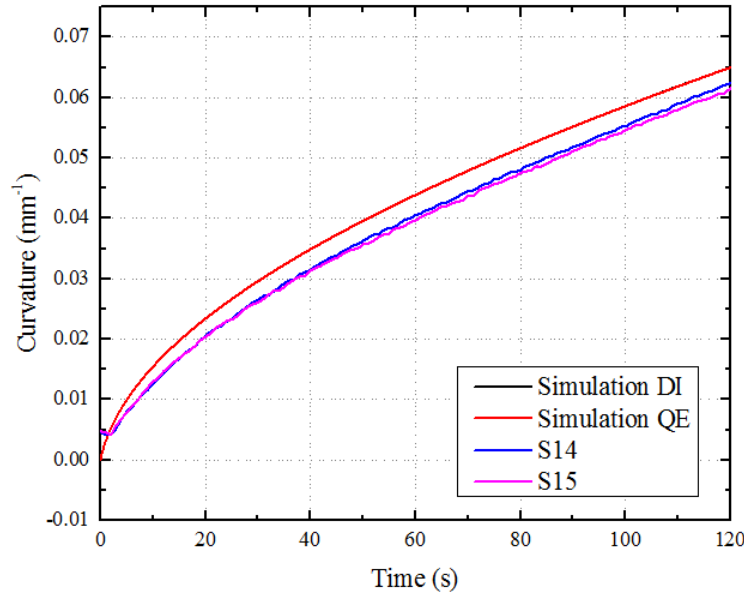
Kinematics modeling assumes uniform deformation while nonuniform distribution of curvature observed in simulation

Simulation results can be post-processed for comparison with experiments

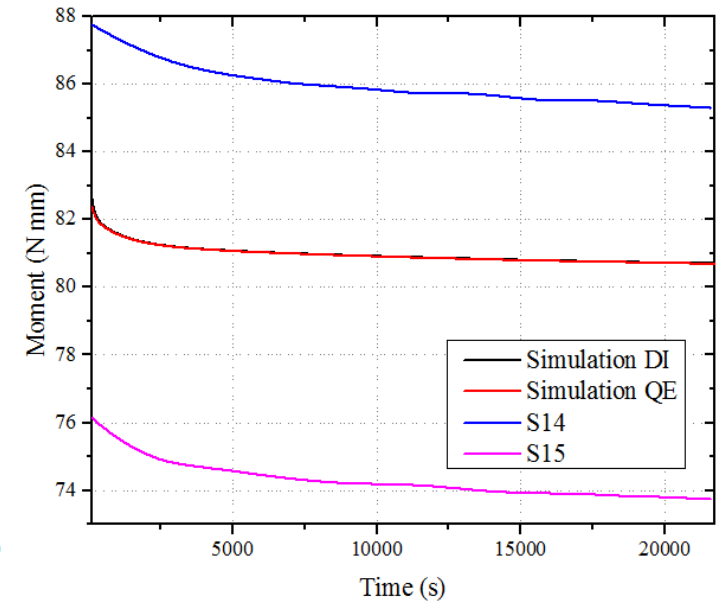


Column Bending Test (cont.)

- Viscoelasticity implemented in UGENS
 1. Quasi-elastic method: easy to implement, accurate prediction of relaxation, unable to capture residual deformation
 2. Direct integration: complex formula and implementation, capture both relaxation and residual deformation



History of curvature κ during folding
 κ calculated with $\phi = 2 \times \text{UR1}$ and $\kappa = \frac{\phi}{s}$

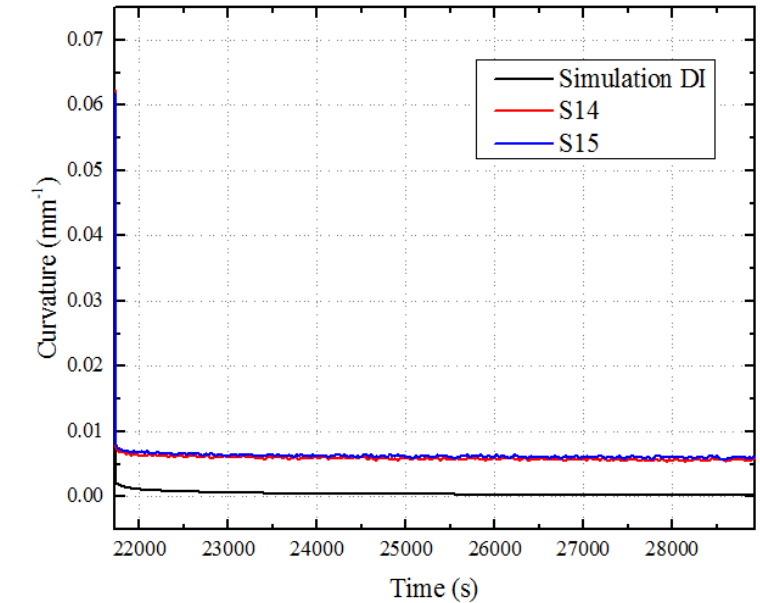


History of moment $M_{\max}$ during relaxation
 $M_{\max}$ calculated with $r = \text{U3} + r_0$ and $M_{\max} = Pr$

Column Bending Test (cont.)

Curvature (mm ⁻¹)	Relaxation	After unfolding (Approx.)	After recovery
QE	0.06400	0	0
DI	0.06400	0.002325	0.0003408
Exp. 1 (S14)	0.06239	0.007749	0.005936
Exp. 2 (S15)	0.06153	0.008352	0.006154

	Curvature change during recovery (mm ⁻¹)	Simulation error of curvature change
DI	-0.001985	--
Exp. 1 (S14)	-0.001813	9.485%
Exp. 2 (S15)	-0.002198	-9.704%

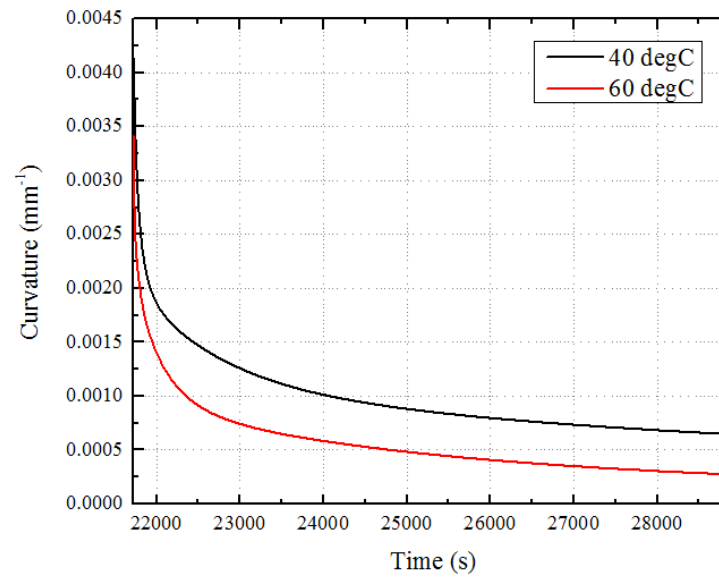
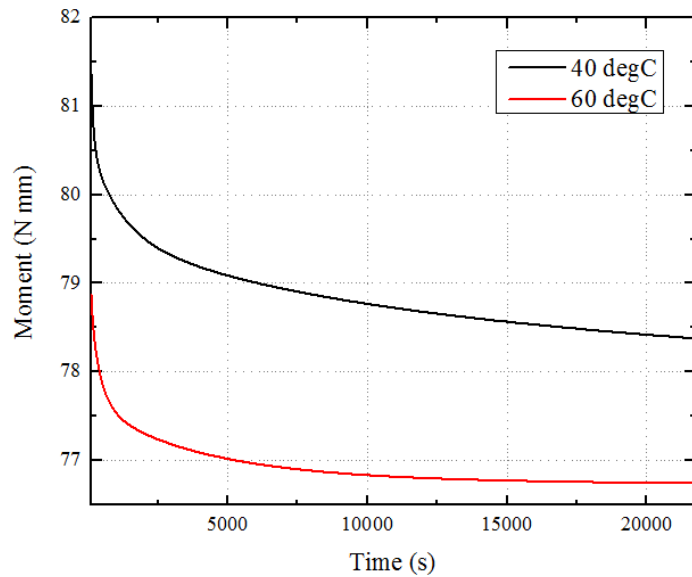


History of curvature κ after unfolding

Column Bending Test (cont.)

Thermoviscoelastic simulation of CBT, enabling simulation with different temperatures using reduced time calculated based on a shift factor

Simulation with temperature shift under 40 °C and 60 °C



Resin as thermorheologically simple material, with a shift factor

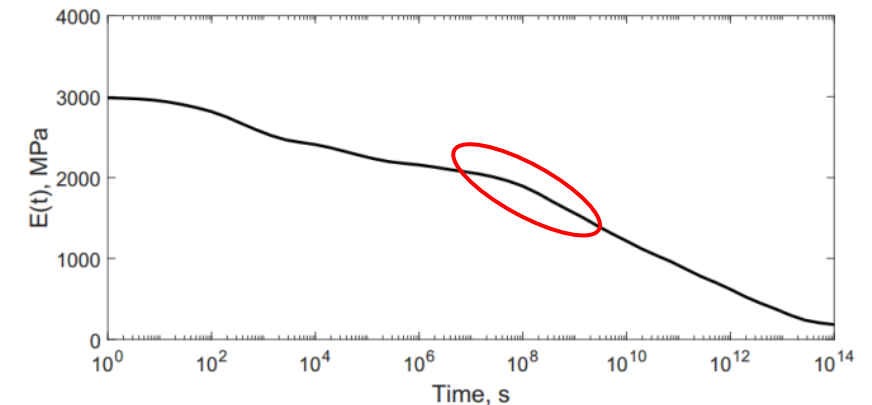
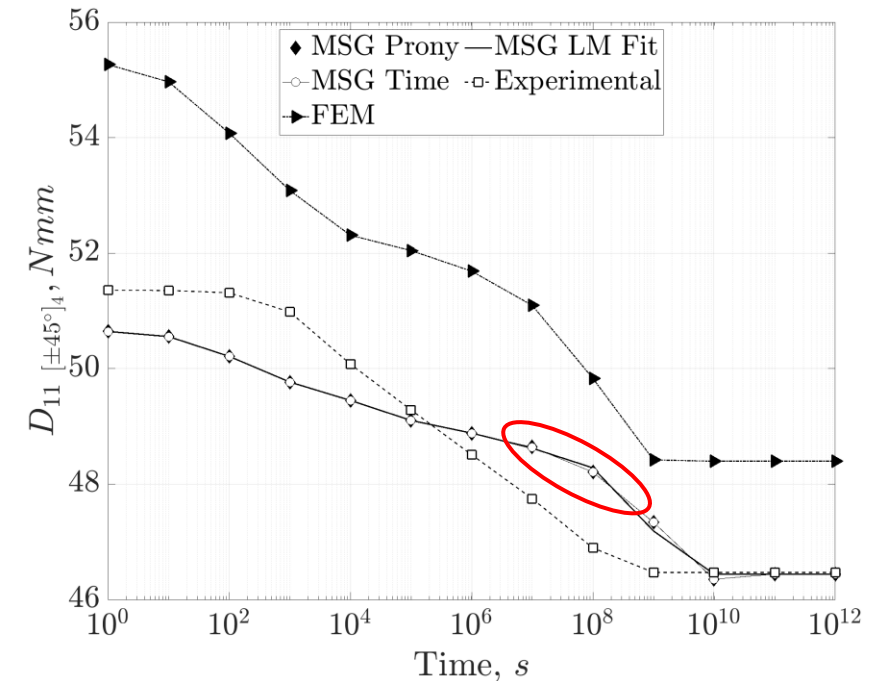
$$\log a_T = -\frac{3.64410(T - T_0)}{13.4582 + (T - T_0)}$$

Calibration Using CBT Simulation

- Non-uniform distribution of curvature and moment leads to

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

- Effective properties obtained from homogenization can be sensitive to material model in the microstructure
- Demonstrative case study: calibration of the shell bending stiffness D_{11}
- Can be used for determination of material parameters based on experiment results



Calibration Using CBT Simulation (cont.)

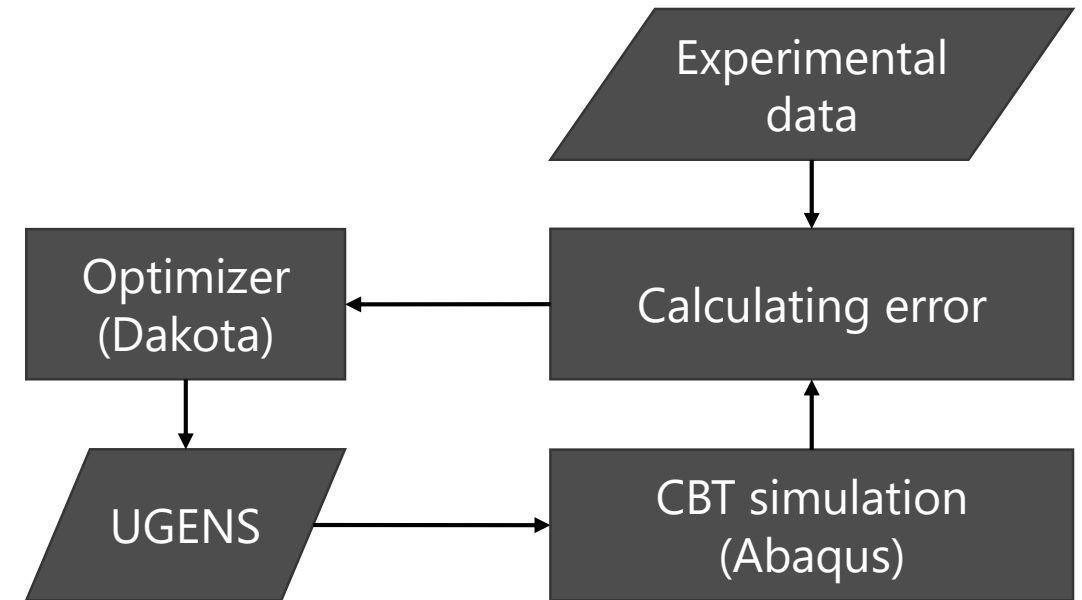
Calibrating coefficients of Prony series

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

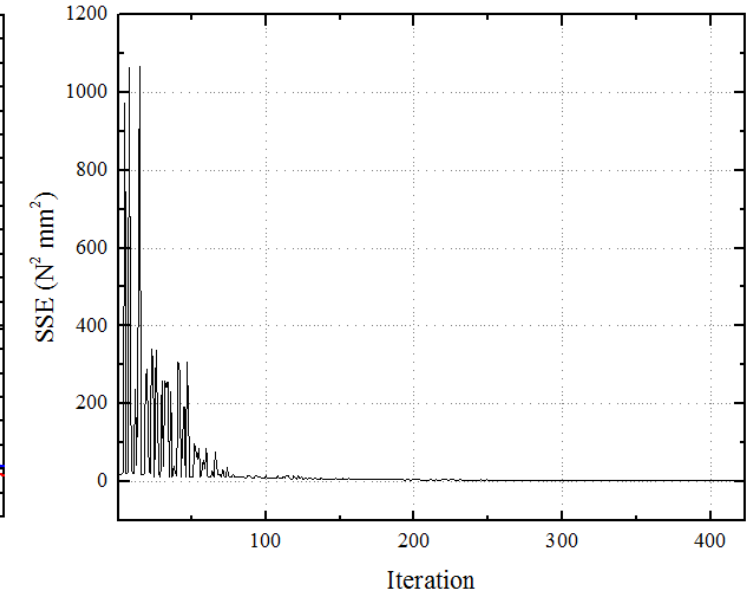
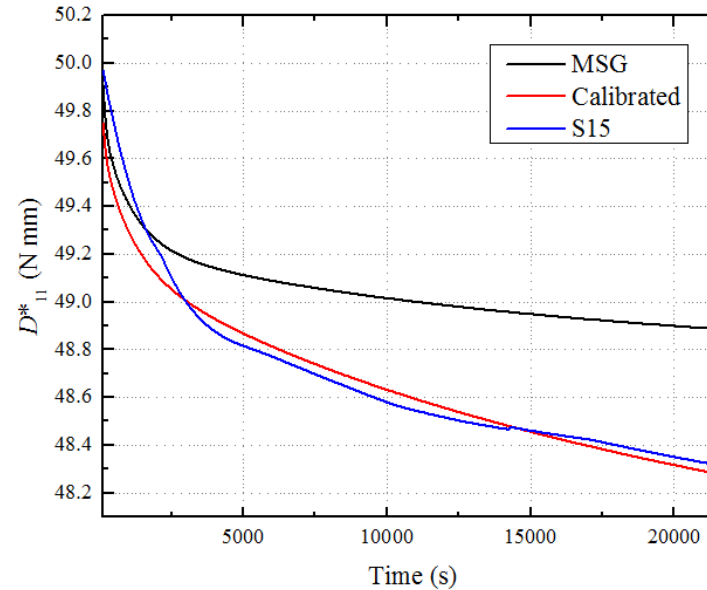
Error evaluated using Error Sum of Squares (SSE)

$SSE = \text{SUM}[(\text{predicted} - \text{target})^2]$

Calibration Using CBT Simulation (cont.)

Calibration judged converged after 423 iterations, best results at iteration 408

k	ρ_k	$D_{11,k}$ (N·mm)
∞	--	45.246725
1	1.00E+01	0.0
2	1.00E+02	0.348
3	1.00E+03	0.40325
4	1.00E+04	0.43405
5	1.00E+05	1.629175
6	1.00E+08	2.595
SUM		50.6562



Initial SSE: 18.78167923

Minimized SSE: 2.9520415814

Lenticular Boom Coiling and Deploying

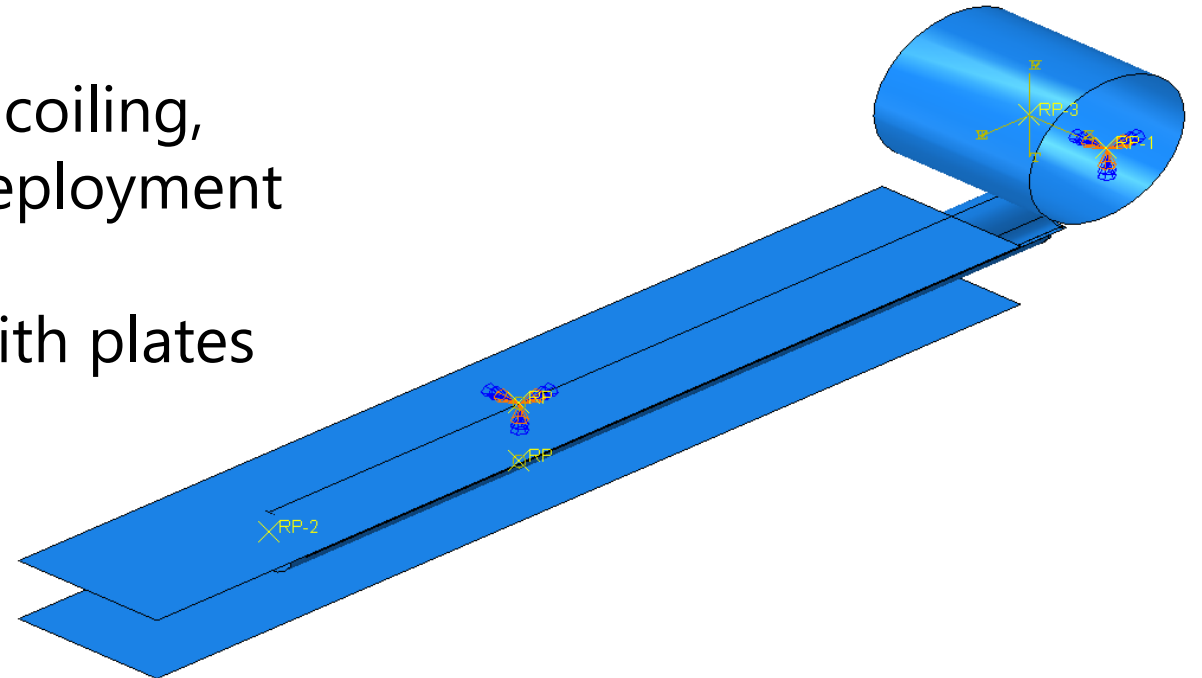
Direct integration viscoelasticity implemented in UGENS

Abaqus Standard, implicit dynamics, quasi-static analysis

Tension force of 0.4 N/mm kept through coiling, stowage and deploying, released after deployment

The whole boom flatten before coiling with plates

Total length: 880 mm
Hub radius: 90 mm
Approx. 1.5 cycles



Lenticular Boom Coiling and Deploying (cont.)

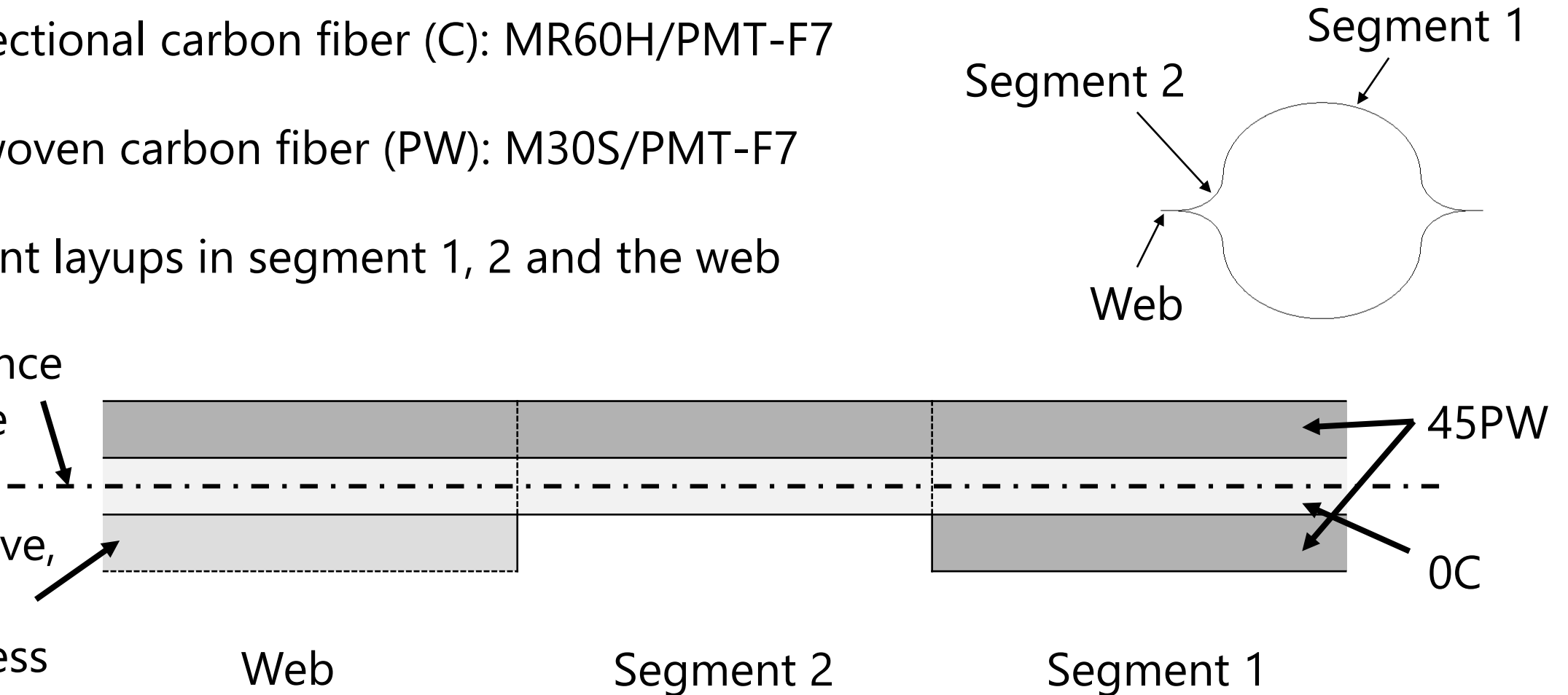
Unidirectional carbon fiber (C): MR60H/PMT-F7

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

Different layups in segment 1, 2 and the web

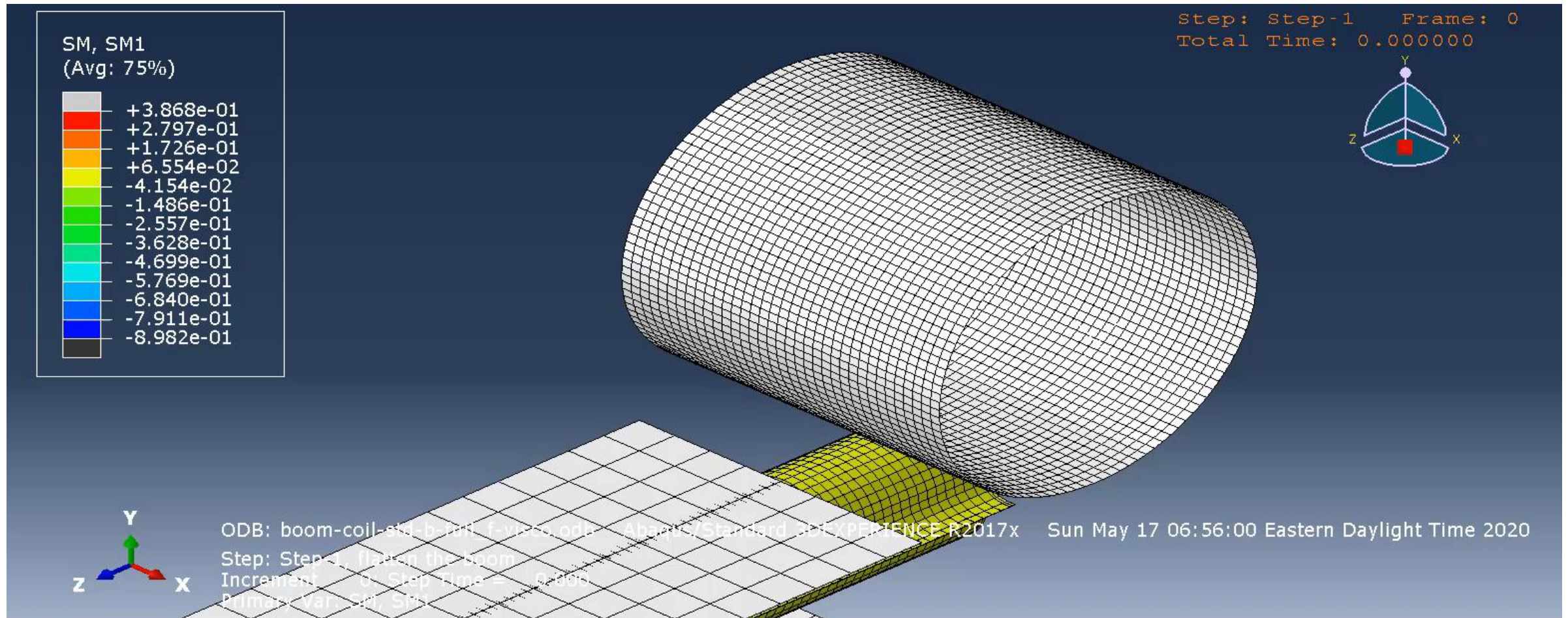
Reference
surface

Adhesive,
half
thickness

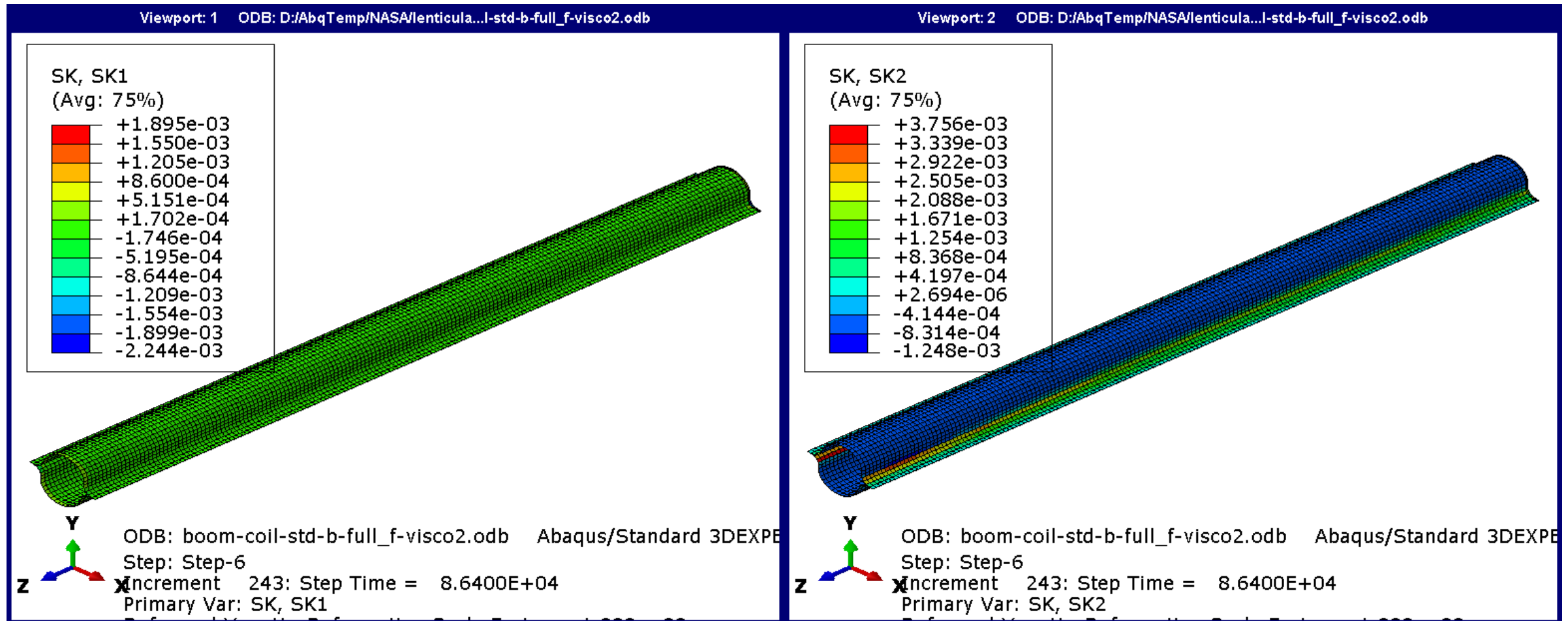


Lenticular Boom Coiling and Deploying (cont.)

Stowage of 30 days

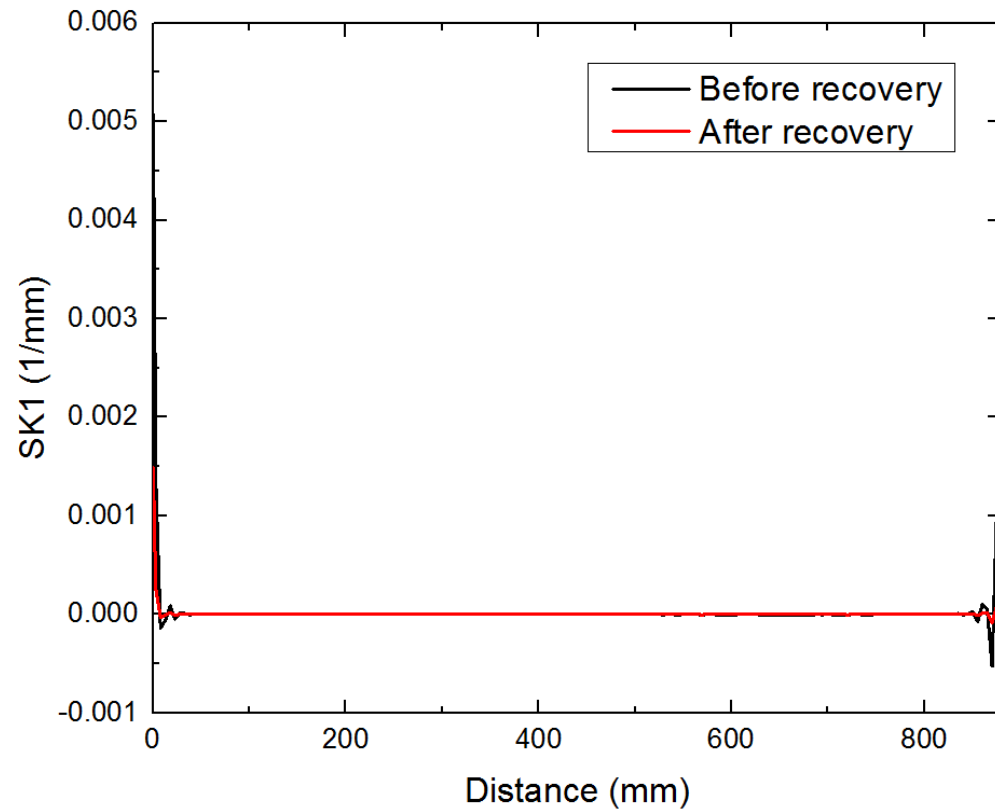


Lenticular Boom Coiling and Deploying (cont.)

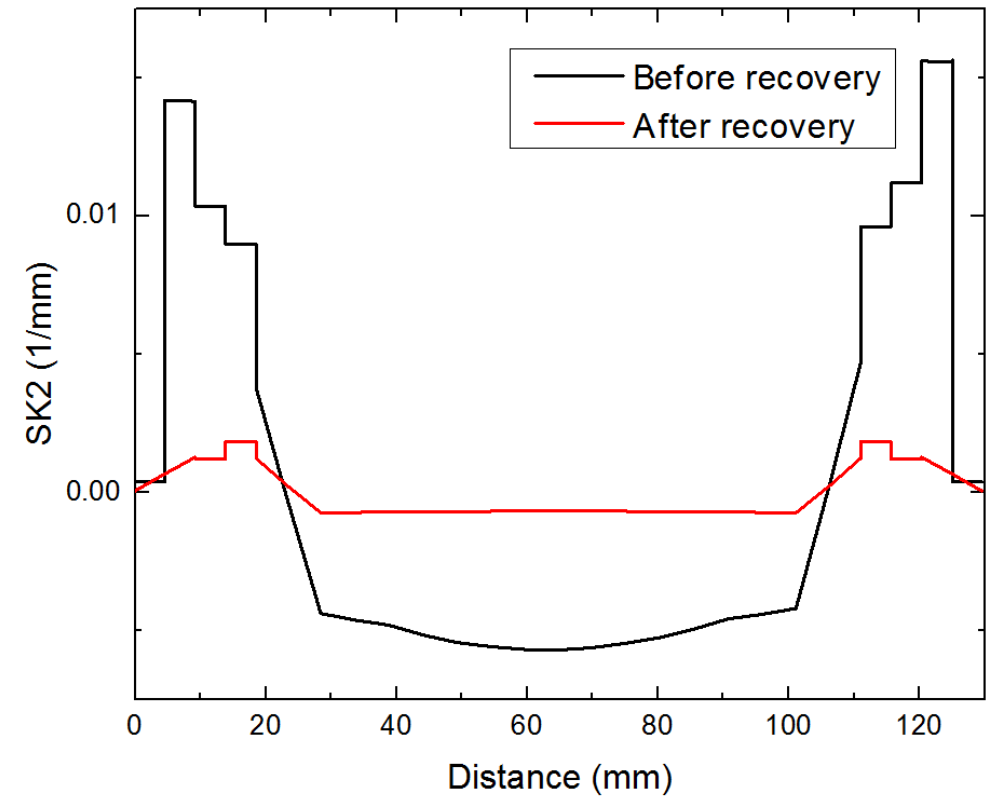


Residual curvature after recovery of 24 h

Lenticular Boom Coiling and Deploying (cont.)



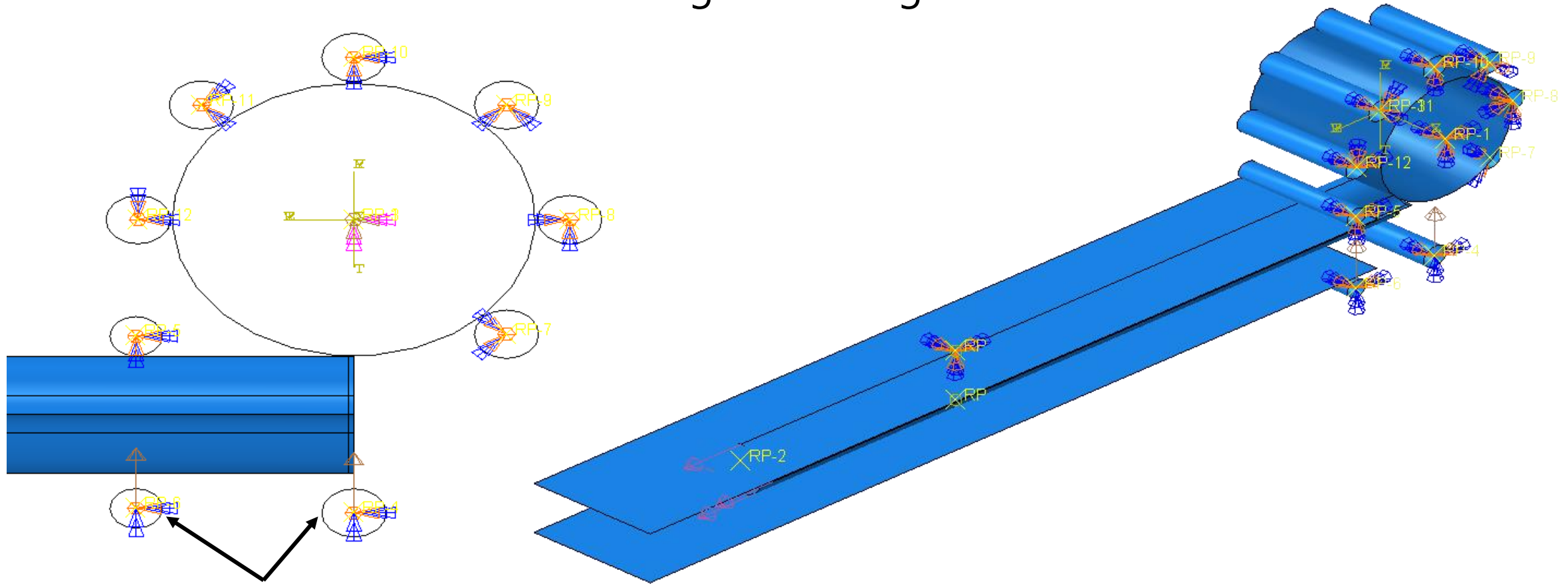
Curvature in the length direction



Curvature in the hoop direction

Lenticular Boom Coiling and Deploying (cont.)

Rollers with forces applied: 2 nip rollers & 7 around the hub
Tension force removed after finishing the coiling



Moving up during flattening

Lenticular Boom Coiling and Deploying (cont.)

Tension force and plates removed after coiling



Summary

- CBT simulated with finite element software Abaqus
 - Nonuniform deformation observed
 - Viscoelasticity implemented, with direct integration method capable of capturing relaxation and residual deformation
 - Simulation under different temperatures achieved with a shift factor
- Potential application of CBT simulation for the calibration of material properties demonstrated
- With simplifications, coiling and deploying process of a lenticular boom simulated
 - Major residual deformation in the hoop direction
 - Residual deformation greatly reduced after recovery

Thank You!

Backup

Column Bending Test

Simulation of the experiment of 5 continuous loading cycles under temperatures of 40 °C, 60 °C, 80 °C, 100 °C, 120 °C

Folding generating consistent strain and curvature under different temperatures

