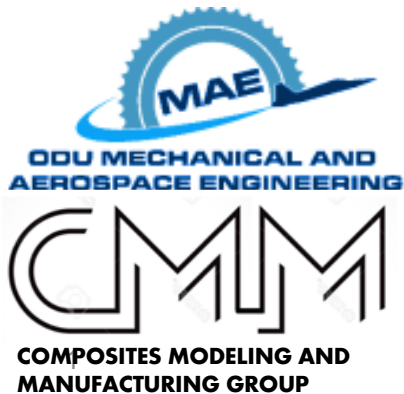


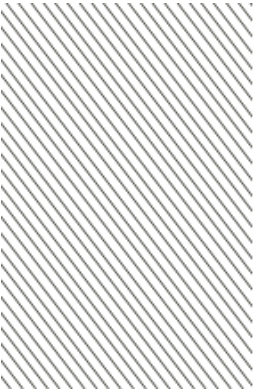
**RESIDUAL DEFORMATION ANALYSIS IN COMPOSITE
SHELL STRUCTURES MANUFACTURED USING
AUTOMATED FIBER PLACEMENT**



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Research Topic



RESIDUAL DEFORMATION OF AUTOMATED FIBER PLACEMENT MADE COMPOSITES THROUGH FINITE ELEMENT ANALYSIS

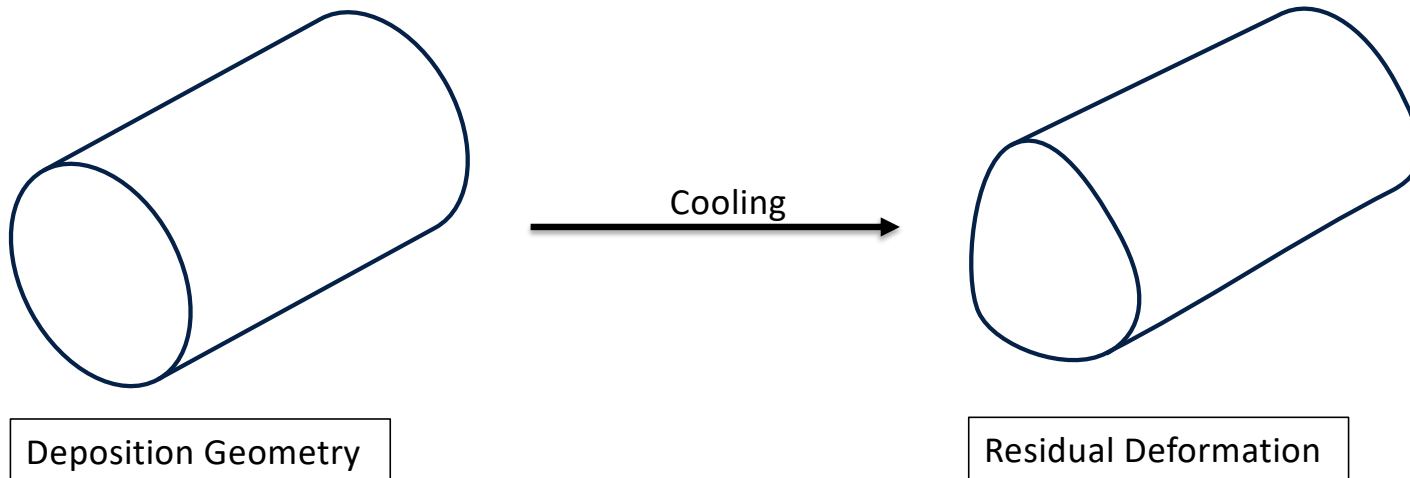
Why?

- **Can residual deformation be simulated with composite complex layups?**
- **Can geometric linearity and temperature dependent properties be used to improve the results?**
- **What else can be used to further develop this method?**

RESIDUAL STRESS

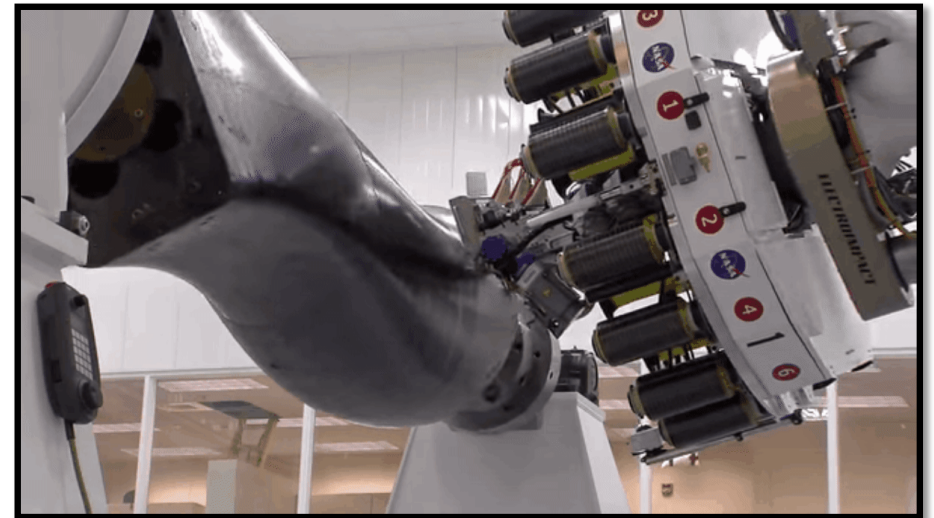
When the elastic properties of the composite develops, the cooldown process of the composite results in Residual Stresses which leads to a morphology in the final geometry.

Which leads into the research into modeling the residual deformation through shell elements in finite element analysis.



AUTOMATED FIBER PLACEMENT

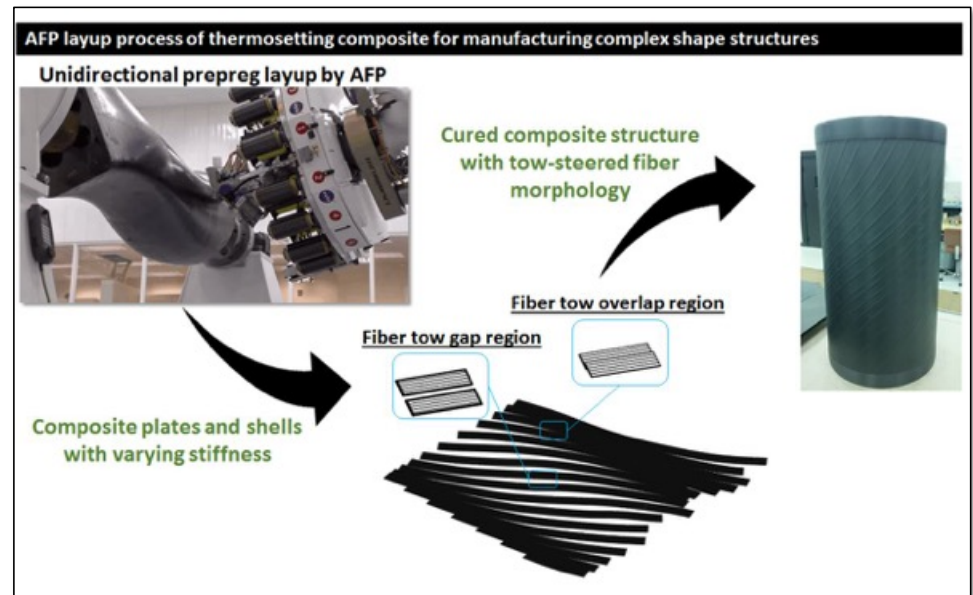
- Manufacturing technique where multiple, narrow prepreg tows are placed one ply at a time. Individual control of tow feeds allows for changes in fiber tow angle.
- Advantages of AFP
 - Allows complex layups
 - Automated process
 - Cut/restart function minimizes material waste
 - Tailor to specific loading conditions



Integrated Structural Assembly of Advanced Composites (ISAAC) at NASA Langley

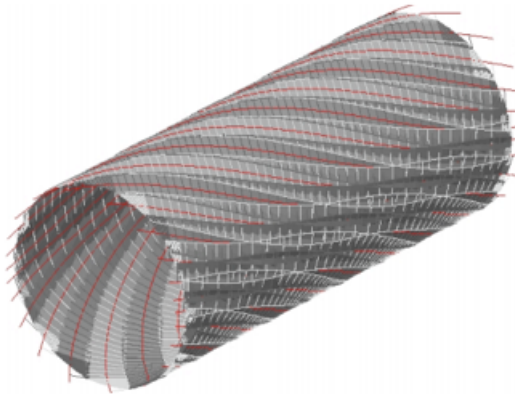
TOW STEERED COMPOSITE SHELLS

- By incorporating fiber tows with and without overlaps the composite structure can be designed for its targeted mechanical performance
- The shell's circumferential fiber tow path was tailored to carry a bending load, and resembles an I-beam



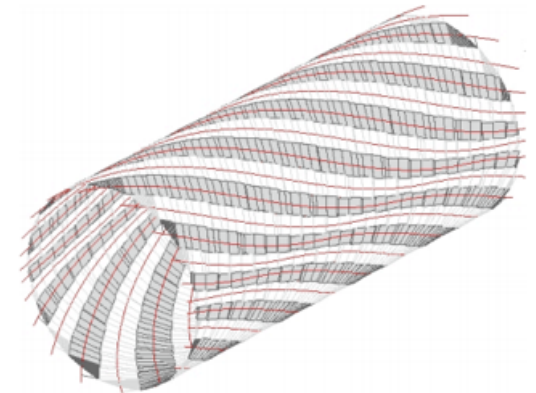
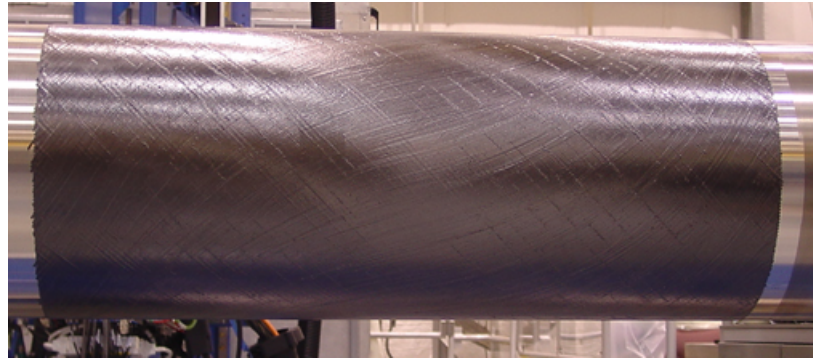
The robot shown is the Integrated Structural Assembly of Advanced Composites (ISAAC) at NASA Langley

TWO COMPOSITE MODELS



Shell A

- Overlapping plies
- Thicker in crown and keel
- Variable thickness
- Made with all 24 tows placed in a single run.



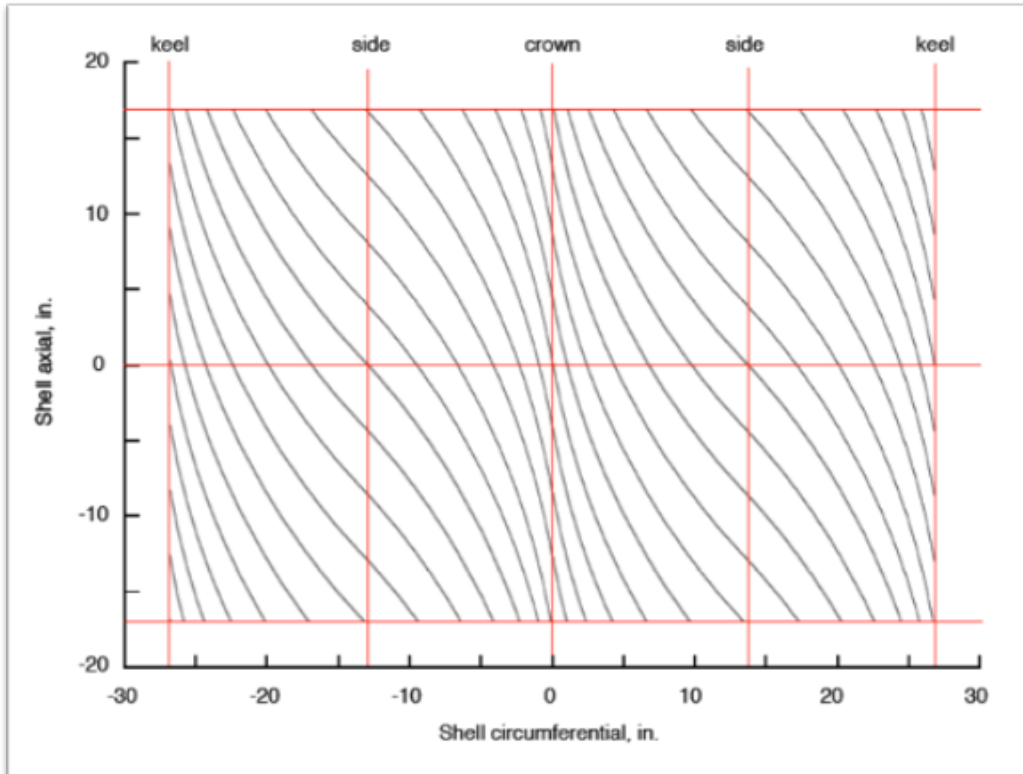
Shell B

- No overlapping plies
- Uniform thickness
- Individual tows placed
- Made using cut/restart capability

- Two Finite Element Models were developed based on AFP-made composite shells:
- Overlapping plies, Shell A
 - Without overlapping plies, Shell B

Both models featured a piecewise stiffness matrix, based on laminate thicknesses and fiber angles.

COMPLEX COMPOSITE LAYUP



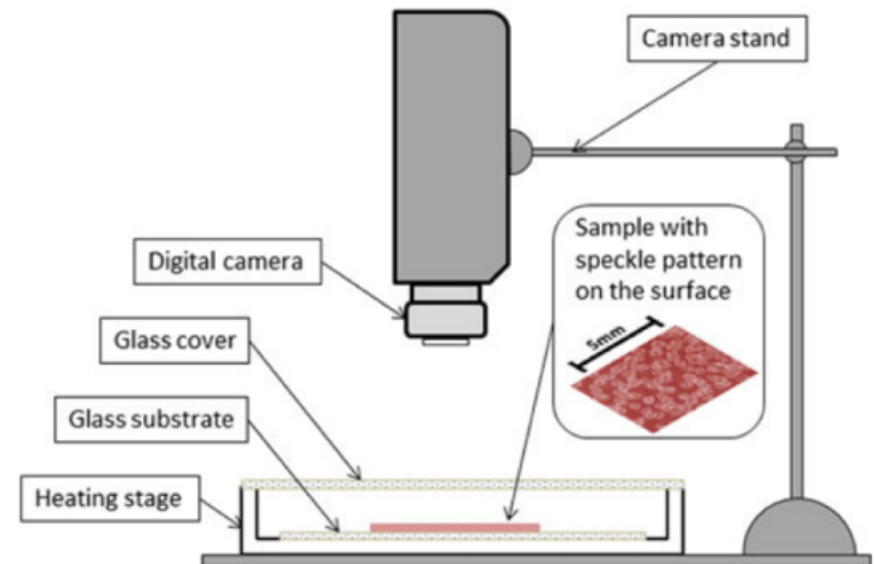
- The shells were modeled using finite element analysis.
- The orientations used for the plies was derived from the as-designed fiber orientations.
- Degree of cure can contribute to the residual deformation.
- The phenomenon before cooldown was not modeled.

Laminate has nominal 8-ply $[\pm 45/\pm \theta]_s$ layup
Up to 16 plies thick on crown/keel for shell A

Ply Angles vary continuously from 10° to 45° from Crown/Keel to Side respectively

DIGITAL IMAGE CORRELATION

- Digital Image Correlation (DIC) was used to calculate the ply Coefficients of Thermal Expansion (CTEs)
- The material used in the present work was Hexply® IM7/8552 prepreg with low tack behavior.
- A thermocouple was placed next to the sample to measure the temperature.
- A glass cover was used for a more consistent temperature

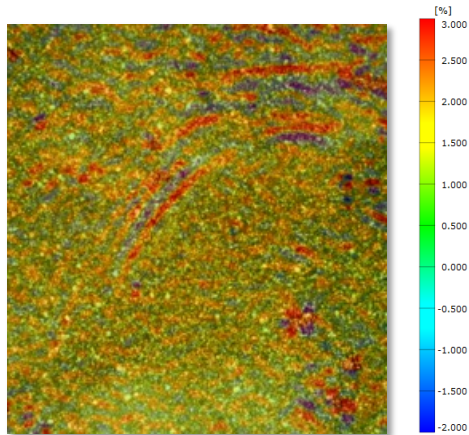


Experimental Setup for the DIC for the CTE

COEFFICIENT OF THERMAL EXPANSION

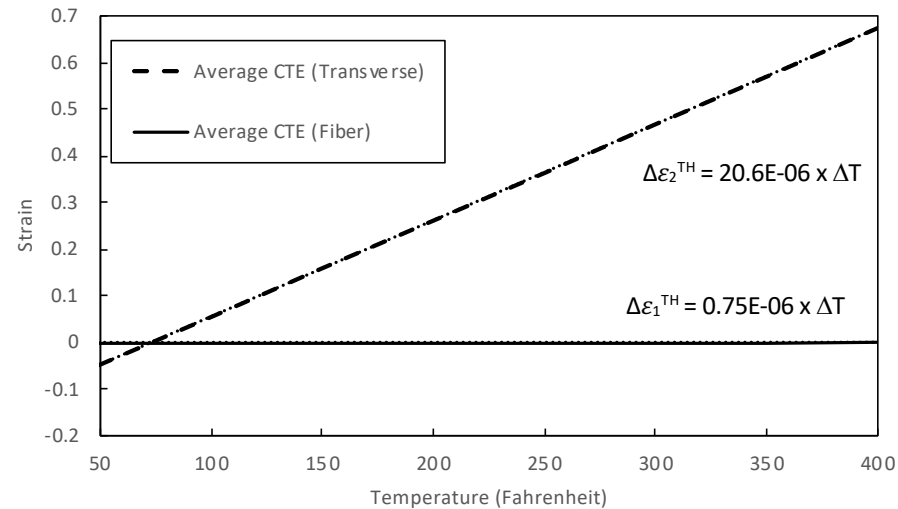


Speckle pattern for Digital Image Correlation analysis



Strain Profile at 367 ° F

- A speckle pattern was painted on the surface of the material and a reference image was taken at room temperature of 68° F.
- The experiment was initiated by ramping the temperature to 86° F and then increasing the temperature in 36° F increments up to 302° F, and at smaller intervals of 18° F up to 367° F



MICROMECHANICAL SELF-CONSISTENT EQUATIONS

The lamina properties were calculated using Schapery's homogenization for CTE.

- The properties were derived from room temperature to higher elevated temperatures.
- Constant carbon fiber properties were assumed with changing epoxy properties.

Observations:

- Fiber dominated properties were not affected significantly
- G12 was the most affected
- CTE in the fiber direction did not change,
- CTE in the transverse direction increased by 0.1%

Table 1. Carbon fiber properties

Material constants	Fiber Properties	Matrix Properties		Lamina properties	
		Room Temperature	Properties at 354 °F	Room Temperature	Properties at 354 °F
Longitudinal modulus (Msi), E ₁	29.7	0.435 (isotropic)	0.287 (isotropic)	19.48	19.43
Transverse modulus (Msi), E ₂	2.17			1.36	1.04
In-plane shear modulus (Msi), G ₁₂	3.77	0.167 (isotropic)	0.105 (isotropic)	0.756	0.528
Out-of-plane shear modulus (Msi), G ₂₃	8.63			0.583	0.441
Major Poisson's ratio, ν ₁₂	0.26	0.30		0.347	0.346
Longitudinal CTE (10 ⁻⁶ /F°), α ₁	-0.5	22.78 (isotropic)		0.75	0.90
Transverse CTE (10 ⁻⁶ /F°), α ₂	8.3			20.05	20.05

ANALYSIS RESULTS

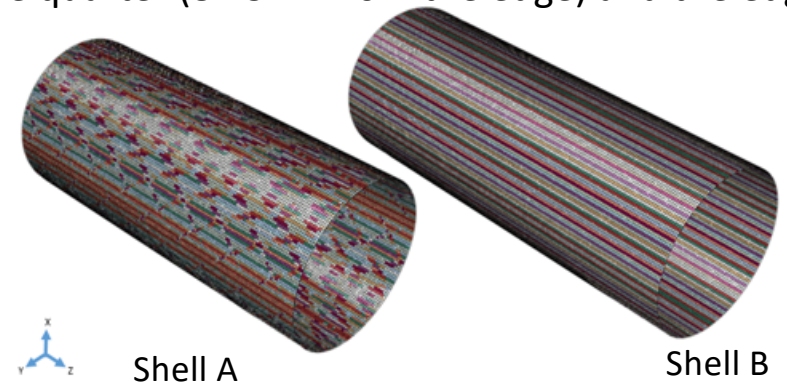
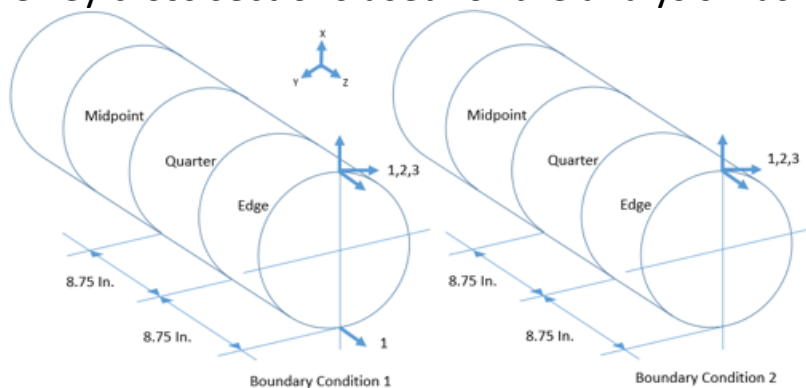
Combinations of linear vs non-linear geometry, and temperature dependent vs a constant temperature was used. The temperature was varied from 72 °F and 352 °F with the former used on the constant temperature analyses.

The model has simple boundary conditions which consisted of a pin and a roller to not over-constrain the response. The models shown consists of S4R elements. Each section had a unique fiber orientation, stacking sequence and thickness.

The two models are depicted with their unique sections:

- Shell A has 174 different sections
- Shell B has 71 different sections

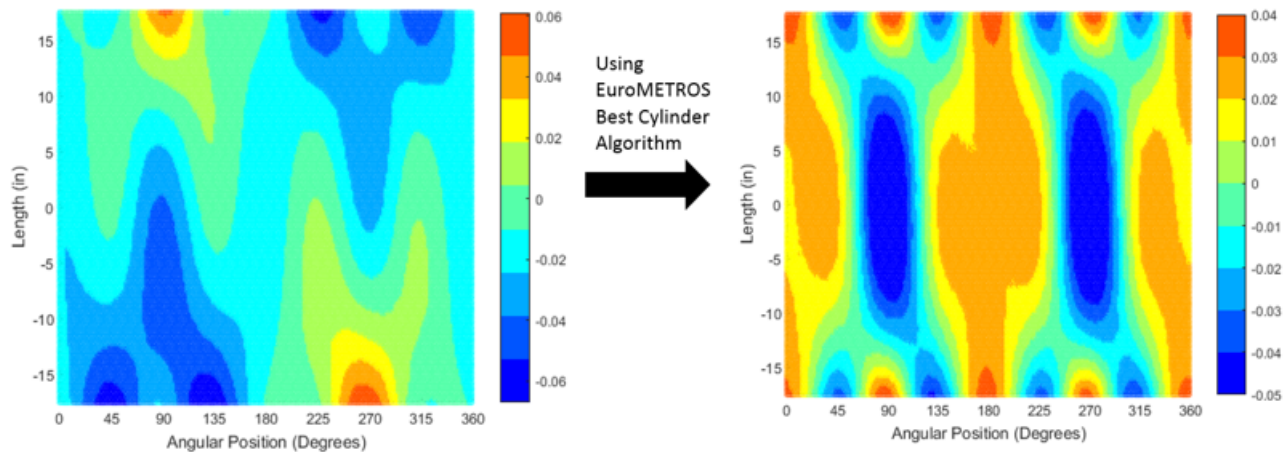
The key cross sections used for the analysis was the mid length, the quarter (8.75 in. from the edge) and the edge.



POST PROCESSING

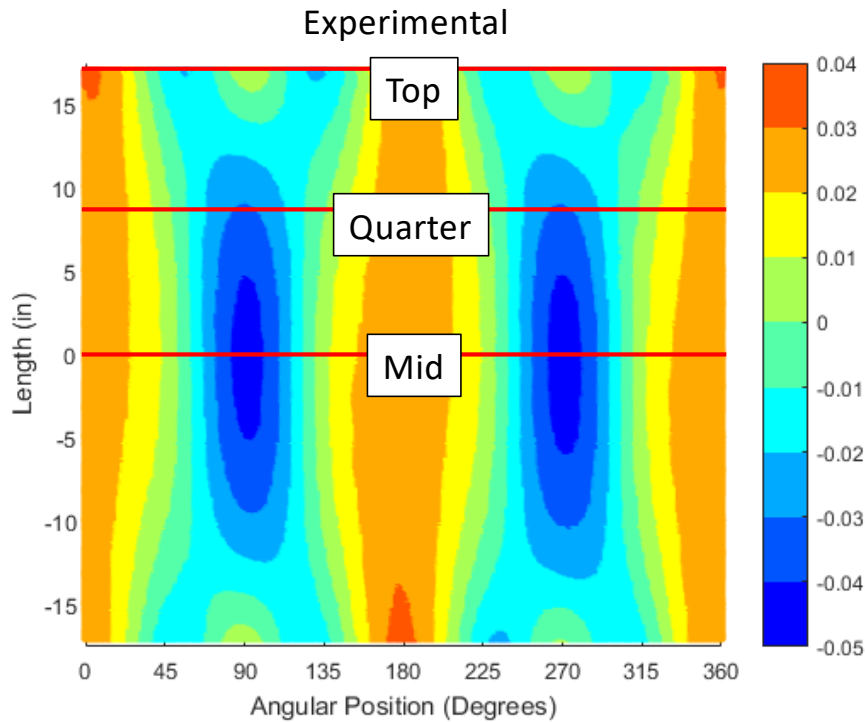
The predicted out-of-roundness of the model was determined using a best fit cylinder algorithm.

$$\{(x, y, z), (a, b, c), r\} \text{ minimize } \sum_{i=1}^m d_i^2 ;$$
$$d_i = (x_i, y_i, z_i) - r((x, y, z), (a, b, c))$$

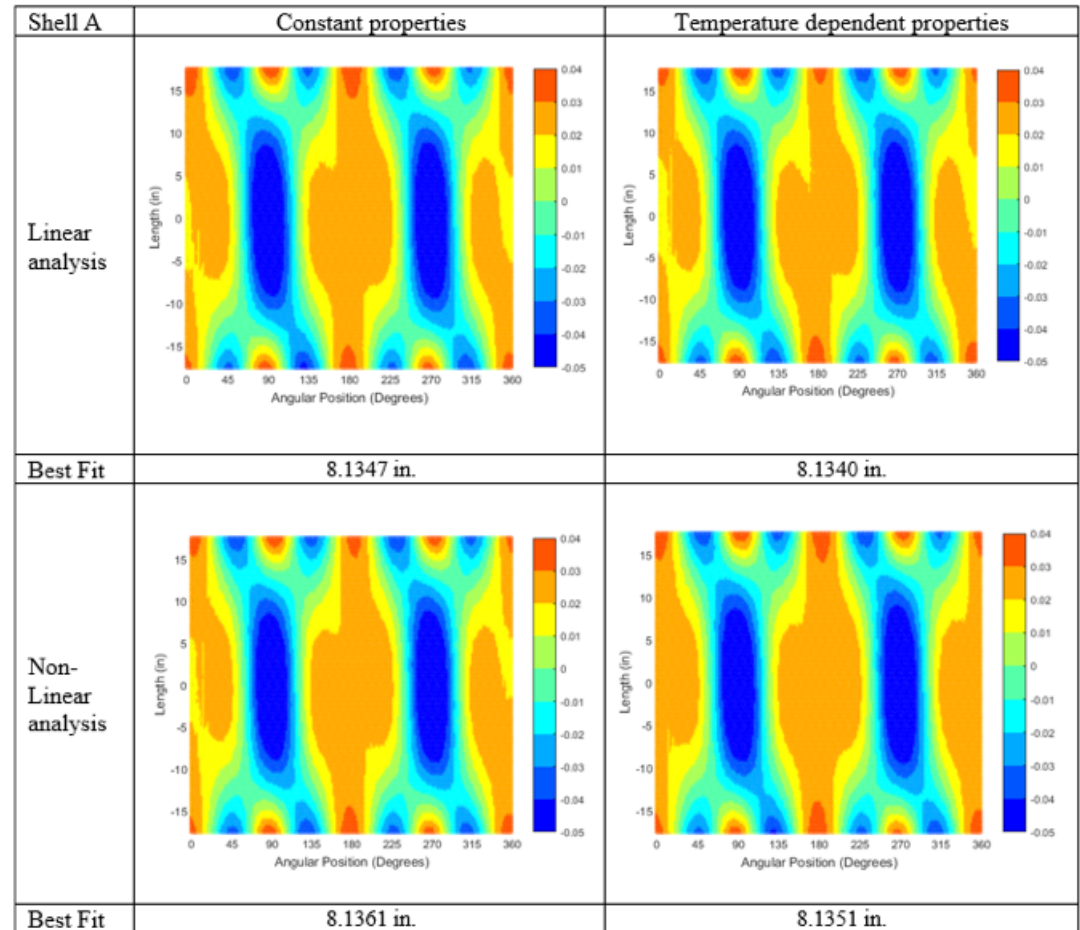


Credit to EUROMETROS for the algorithm

SHELL A (WITH TOW OVERLAPS)

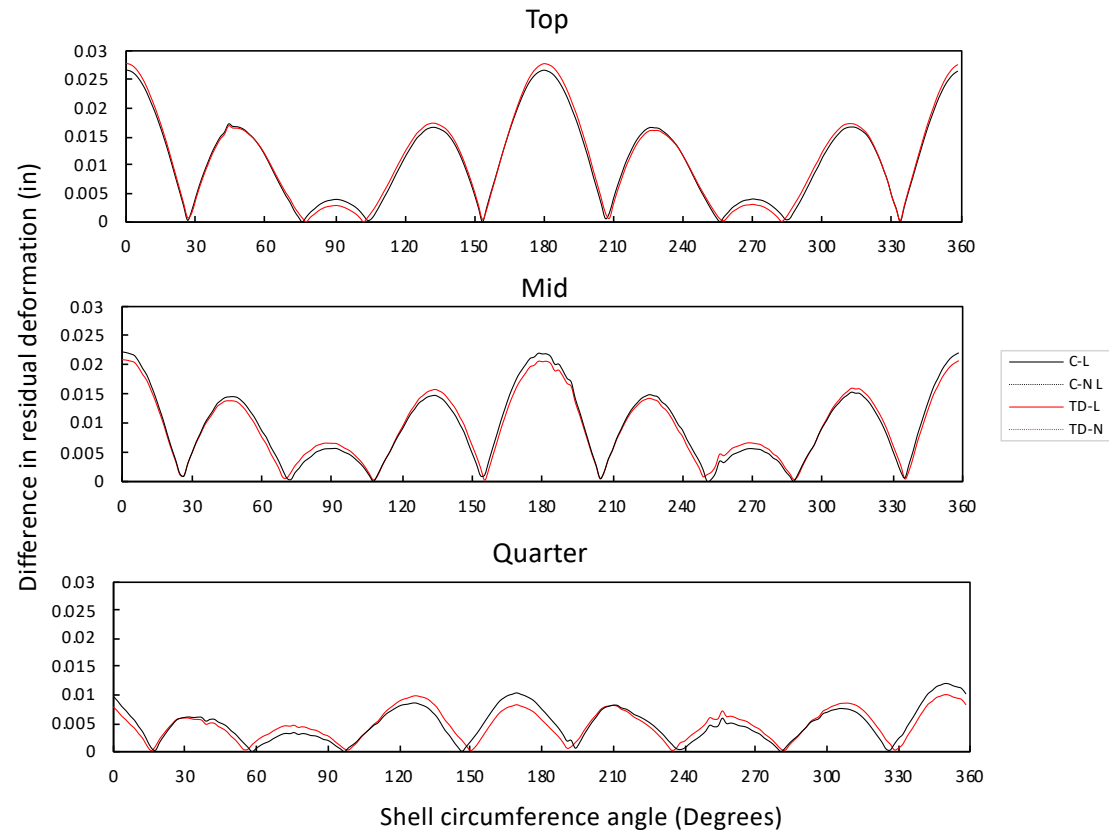


Shell A shows good qualitative agreement between measured and predicted deformations.

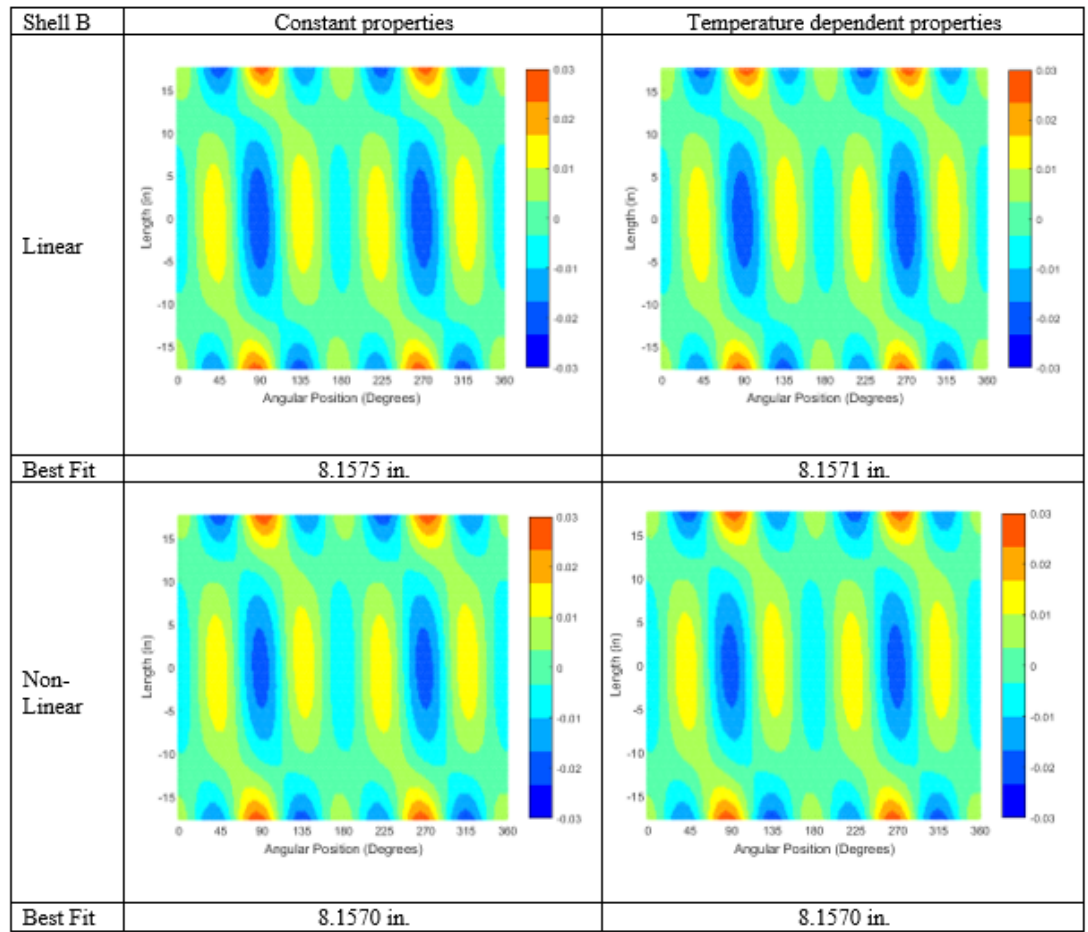
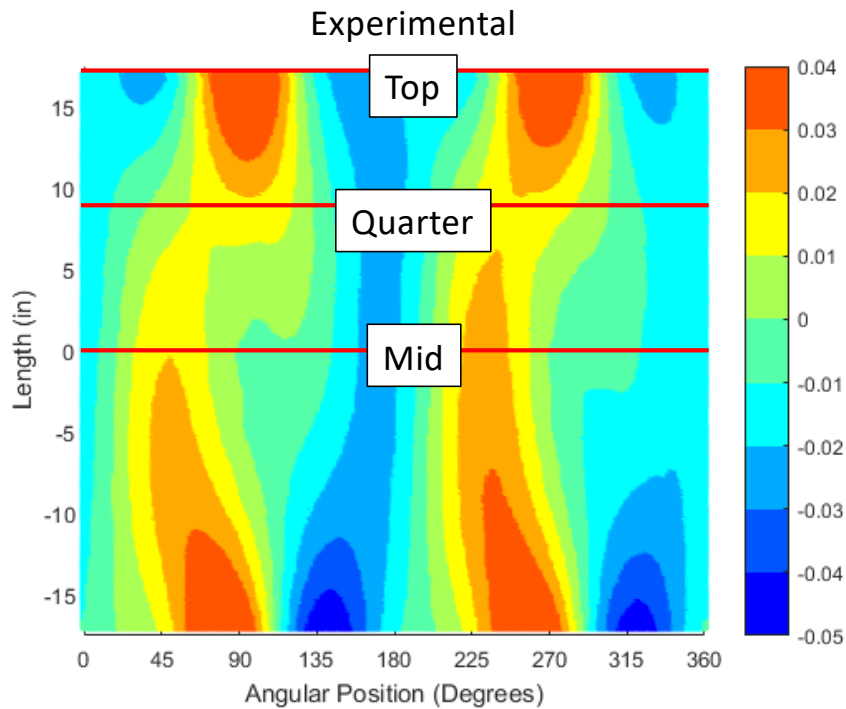


The out-of-roundness for the numerical models

DIFFERENCE IN DEFORMATION SHELL A



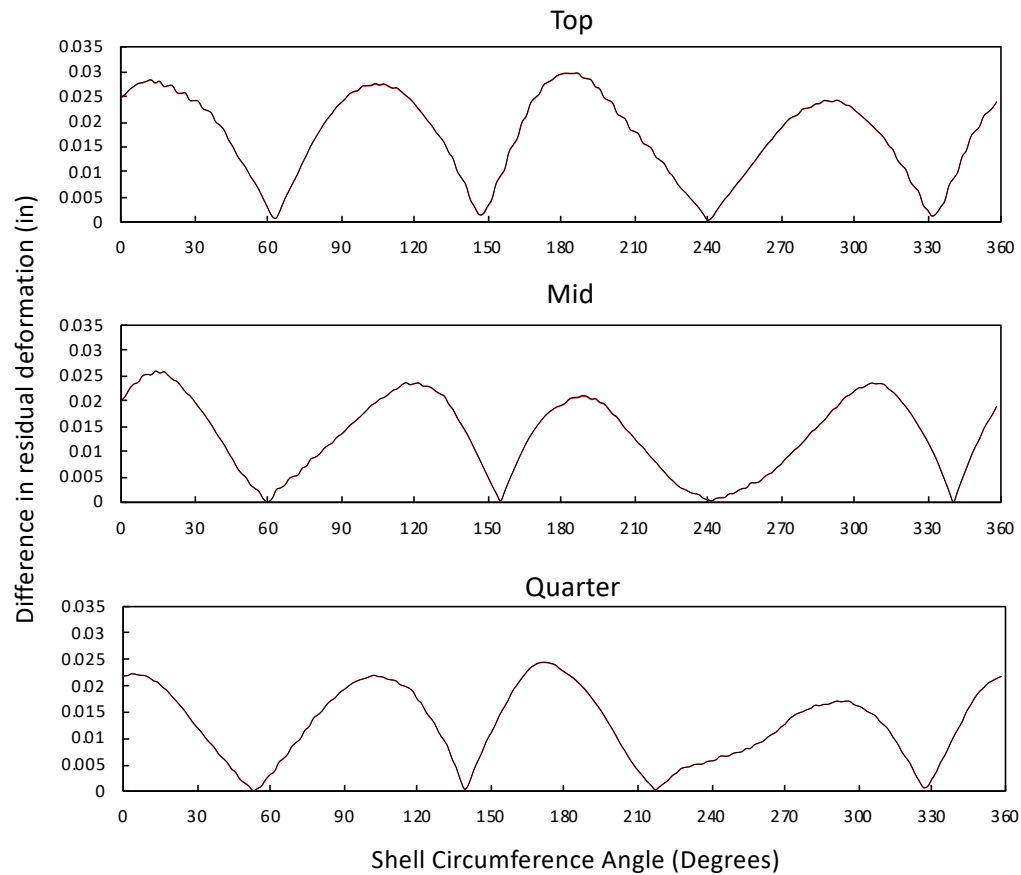
SHELL B (WITHOUT TOW OVERLAPS)



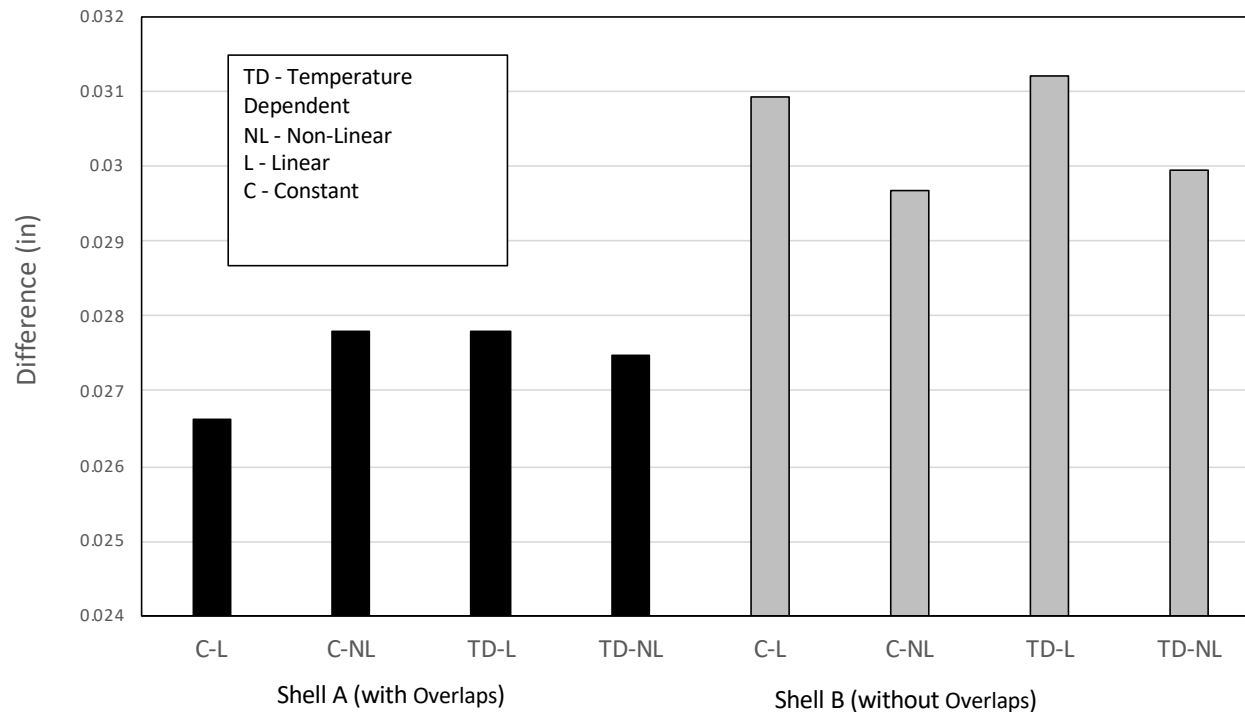
Shell B did not show good qualitative agreement between measured and predicted deformations.

Numerical out-of-roundness plots for Shell B

DIFFERENCE IN DEFORMATION SHELL B



RESULTS DISCUSSION



Material property variations: C = constant; TD = temperature dependent
L = linear; NL = nonlinear

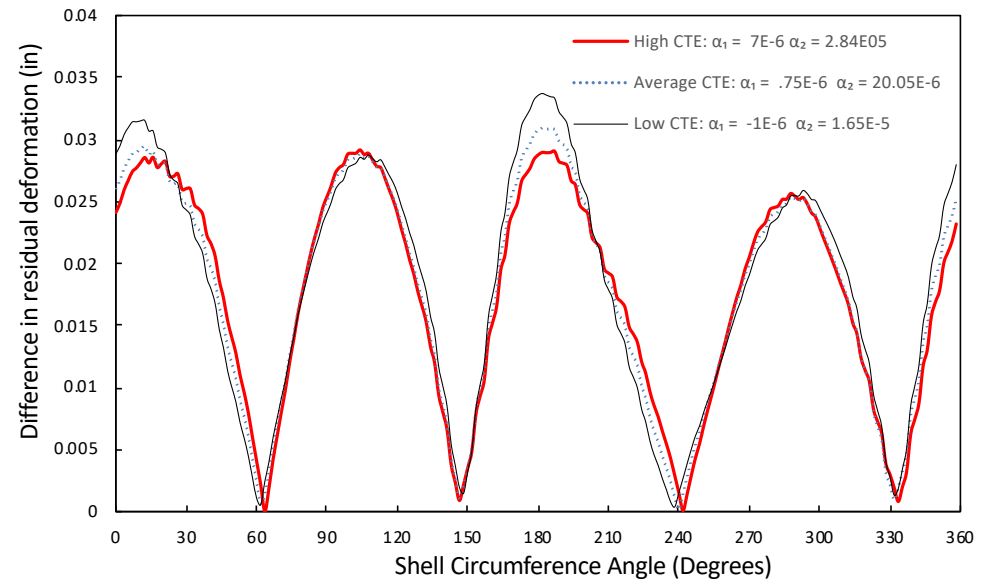
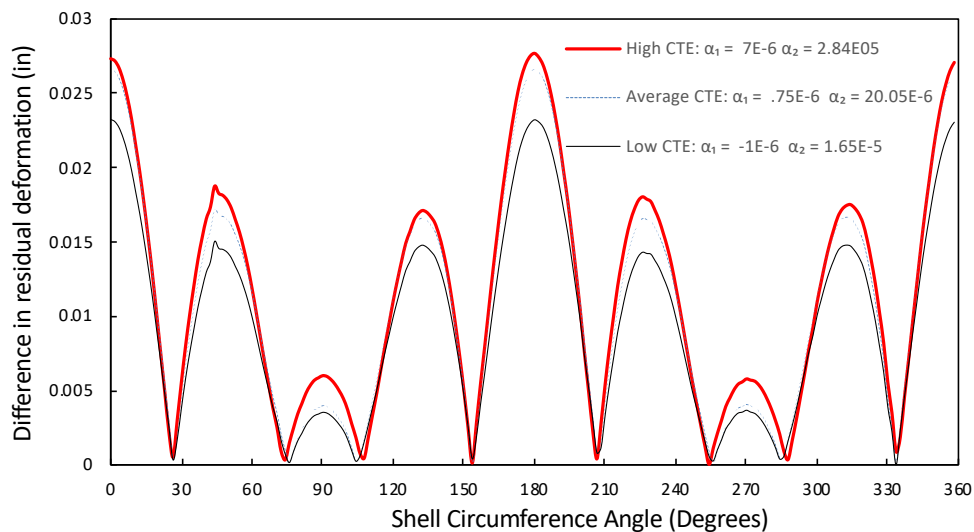
No apparent improvement in residual deformation prediction with:

- non-linear FE analysis(?)
- linear hardening of the laminate properties during cool down.

Other physics can potentially be added for better results such as chemical shrinkage.

SENSITIVITY ANALYSIS

- Changing the CTE for both models shows:
 - With increasing CT deformation for Shell A increases.
 - In shell B it is not very consistent
- Shell A had a higher stiffness than shell B. This shows that shell A is less sensitive, and Shell B cannot be modeled directly with finite element analysis.



CONCLUSION

- Finite element analysis and digital image correlation provide good tools to model the thermal expansion of composite materials. However, the model presented today can be improved with more physics such as chemical shrinkage occurring prior to cool-down stage
- Modeling complex layups is possible using simple shell elements
 - The resulting morphology of the AFP composite with overlaps can be simulated unlike without overlaps.
- Temperature dependent properties can be derived with experimental data
 - Material softening and non-linearity does not affect the analysis.