Residual Stresses in Polymer Matrix Composites – Characterization & Modeling

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Integrity ★ Service ★ Excellence

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Outline

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- Motivation & Background
- Predicting Residual Stresses
- Processing to Performance
- Experimental Characterization of Residual Stresses
- Summary & Conclusions

Motivation

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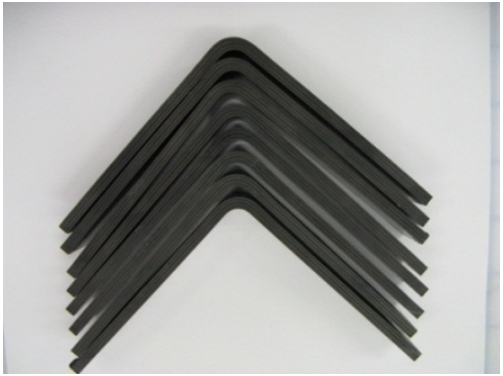
- Residual stresses of thermosetting OMCs pose a significant cost and schedule challenge



- Implement ICMSE approach to:
  - Predict residual stresses as function of cure cycle and postcure method
  - Optimize cure cycle
  - Minimize need for retooling, rework, and redesign

Background

- Residual stress formation during curing primarily a result of:
  - Thermal expansion mismatch
  - Interlaminar interactions
  - Cure shrinkage effects

- CTE mismatch insufficient approximation for parts with increasing complexity

- Residual stresses modify reference configuration and effective part strength

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Material Properties for Process Modeling

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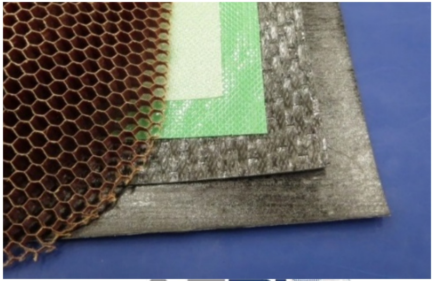
- **Material characterization testing for material property cards**

Properties for Heat Transfer Analysis
Density
Cure kinetics
Thermal conductivity
Heat capacity
Glass transition temperature (T_g)

Properties for Nonlinear Mechanical Analysis
Viscosity
Resin modulus
Cure shrinkage
Coefficient of thermal expansion
Poisson's Ratio

- **Create material characterization property cards for software usage**
  - **Epoxy, BMI, & PI laminate materials**
  - **Film adhesives**
  - **Honeycomb**
  - **Composite tooling materials**



Process Modeling Workflow

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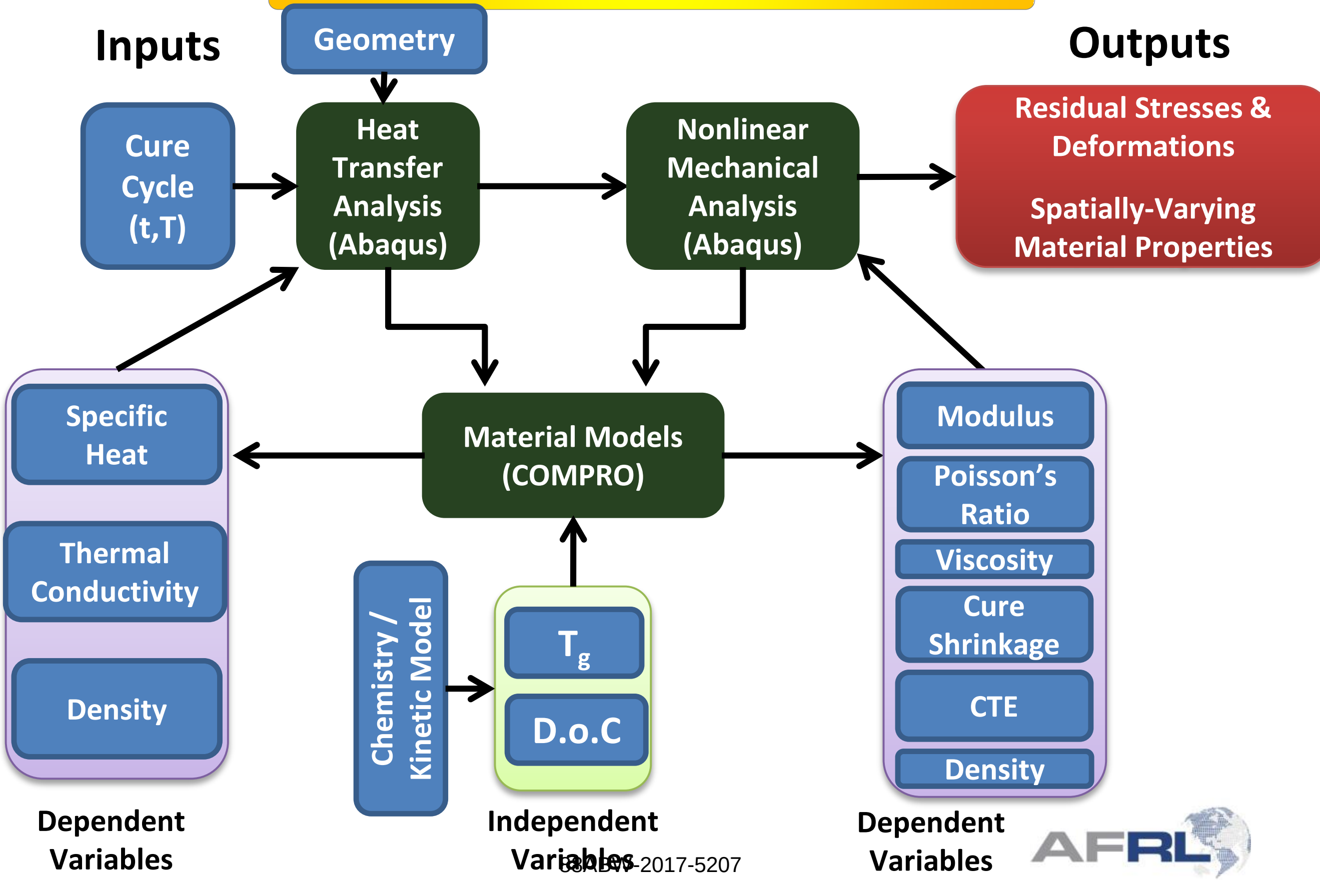

Gap Analysis of Current SOTA

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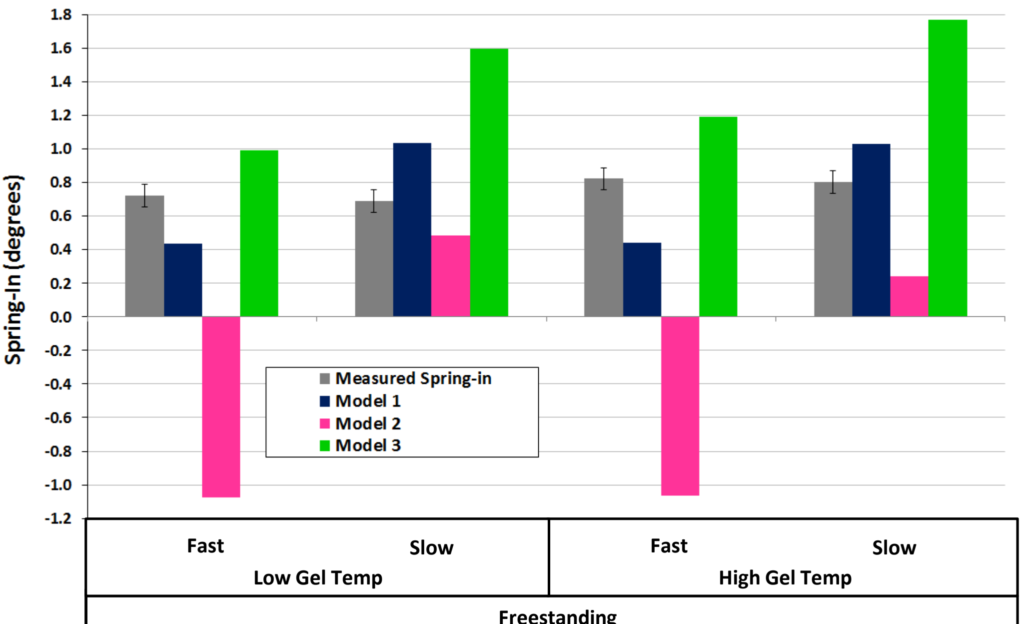
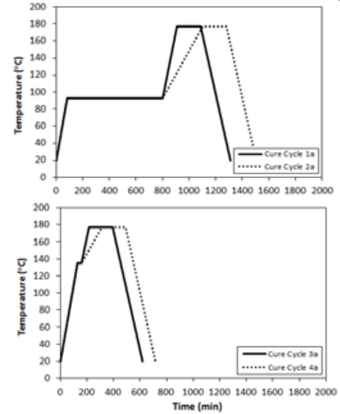
- **Current process models represent the mechanical behavior of the polymer using elastic or pseudo-viscoelastic models**

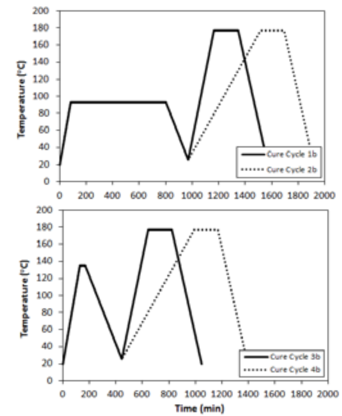
Angle Bracket Spring-in for 8 Different Cure Cycles



Integrated Post Cures (1-4)



Freestanding Post Cures



Elastic-Viscoplastic Model

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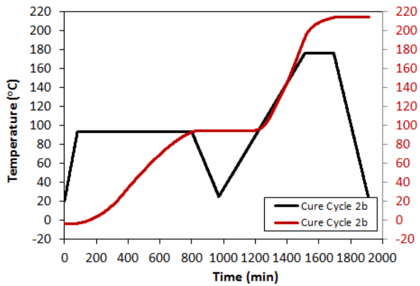
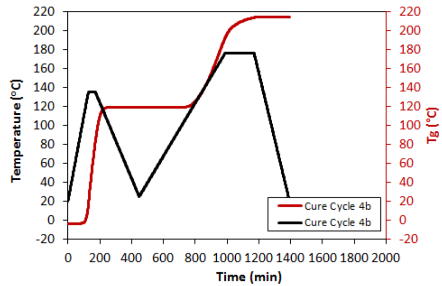
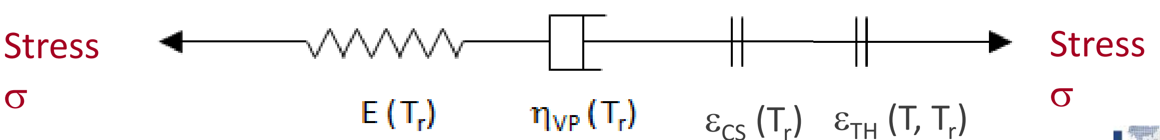
- **Key to accurately predicting residual stresses**
  - Capturing numerous excursions of material above and beyond the evolving glass transition temperature during typical cure cycles





- **Elastic-Viscoplastic (E-VP) Model with the following assumptions**
  - Viscous component allows unrestricted creep in rubbery region and elimination of residual stresses
  - Creep is negligible when the material is solidified



Results for DOE Angle Brackets

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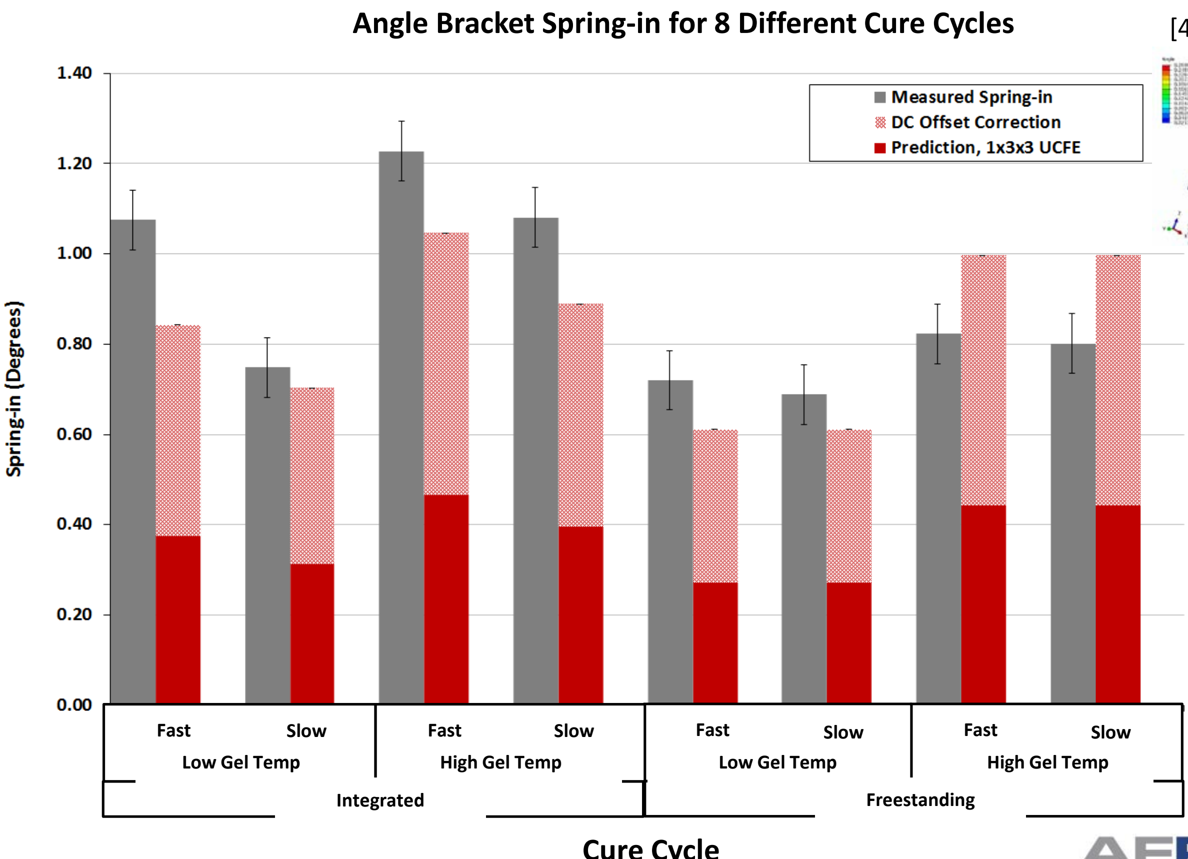
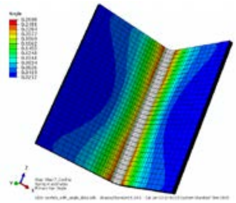


[45/90/-45/0]$_{2s}$



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Processing to Performance

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Process Modeling

Heat Transfer Analysis (Abaqus + COMPRO) → Nonlinear Mechanical Analysis (Abaqus + COMPRO)

Transform Processing Outputs to Damage Inputs

Residual Stresses & Deformations → Non-Mechanical Strains

Spatially-Varying Material Properties → Non-Mechanical Strains

Damage Modeling

Failure Predictions (BSAM)

Case Study – Angle Bracket

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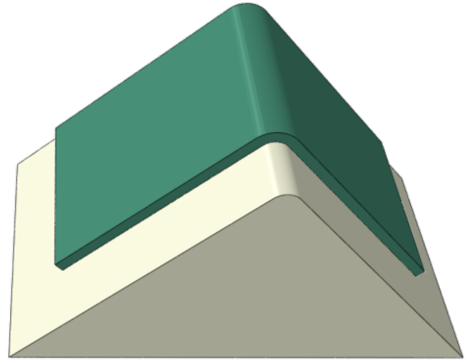
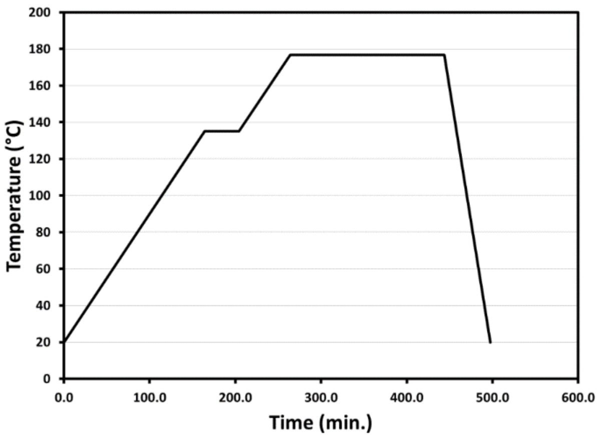
- **Layup:** $[45/90/-45/0]_{2s}$
- **Material:** 5320-1/IM7
- **Residual stress states:**
  - i. No residual stresses
  - ii. $\alpha\Delta T$ mismatch
  - iii. 135°C gel temp
    0.7°C/min ramp rate





Angle Bracket – Processing

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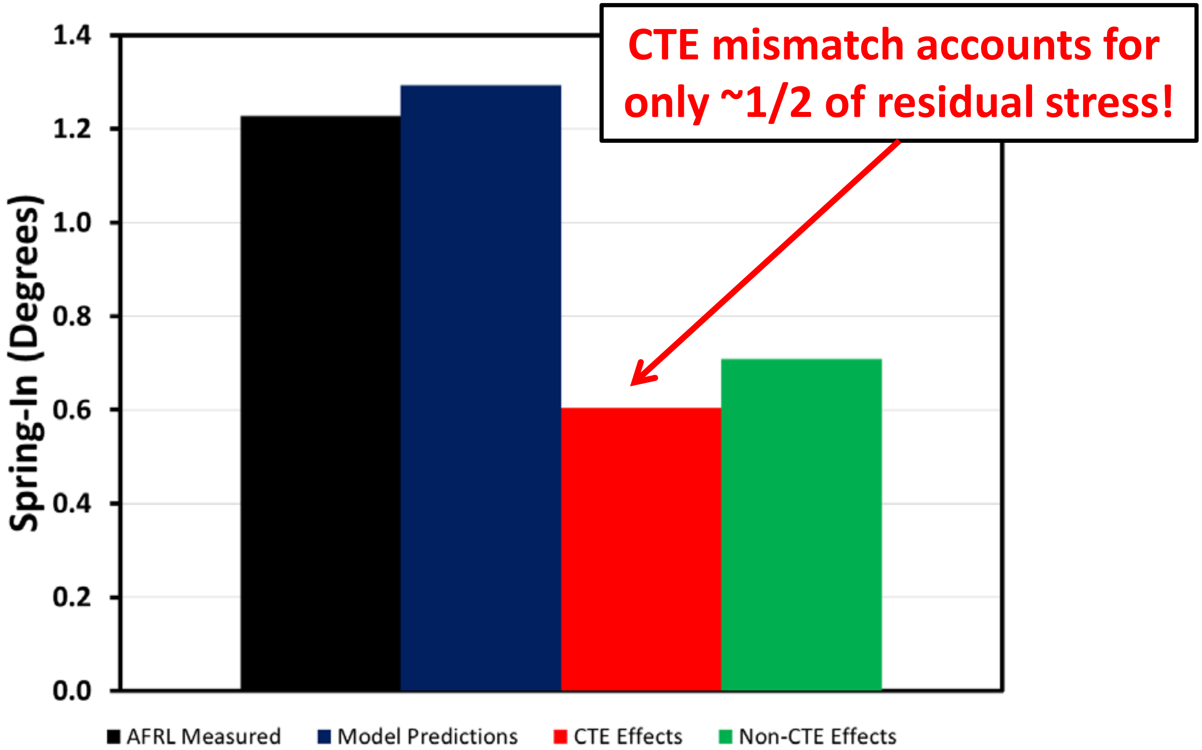

Angle Bracket – Damage

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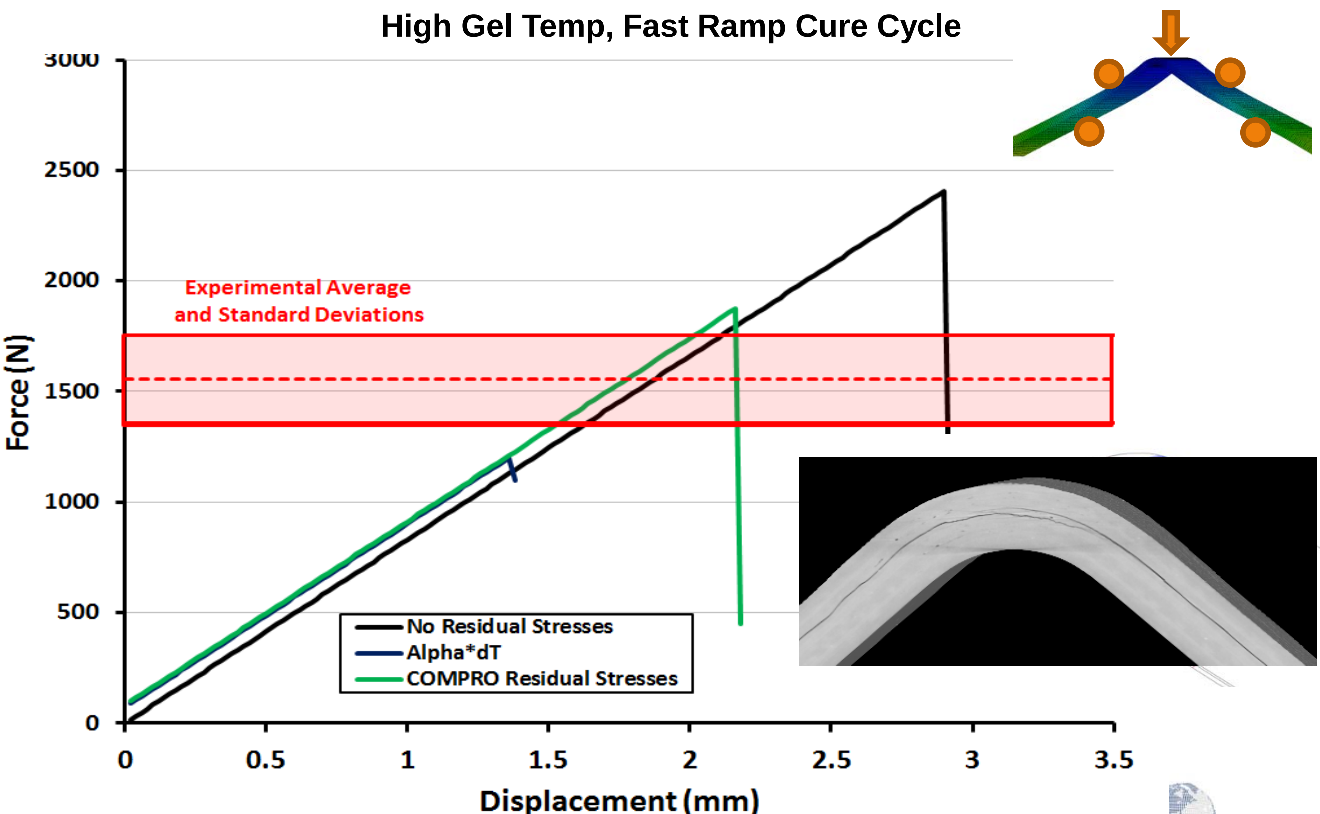

Angle Bracket – Performance

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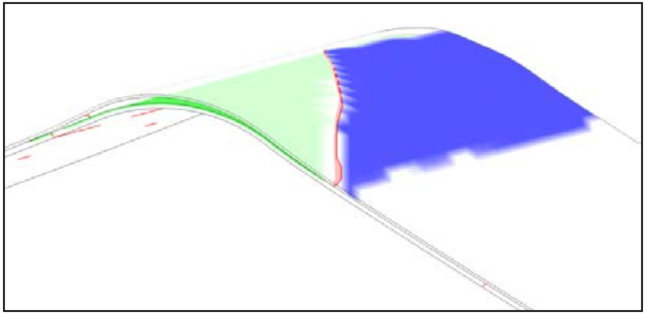
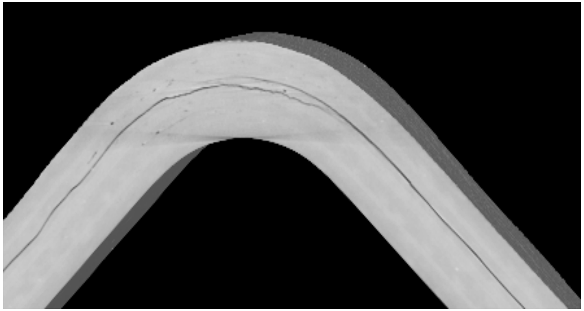
Case	Failure Load (N)
No Residual Stresses	2400
CTE Mismatch	1200
Full Processing Simulation	1875
Experiments	1550 +/- 200





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Moiré Interferometry

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•What Is It?

– Full-field optical technique that measures in-plane displacements on a surface

•How Does It Work?

– Laser light is diffracted according to the grating frequency, laser wavelength, and angle of incidence. Grating deformations create a pattern that is a contour map of in-plane displacements.

•Capabilities:

– Displacement sensitivity is 0.417 mm per fringe contour. Can be improved by at least a factor of 10 through digital phase-shifting analysis.

•Advantage:

– Quantitative displacements over the entire field of view

Moiré Interferometry

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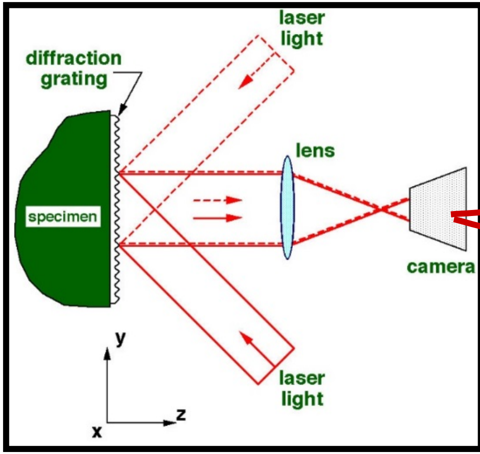
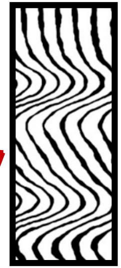




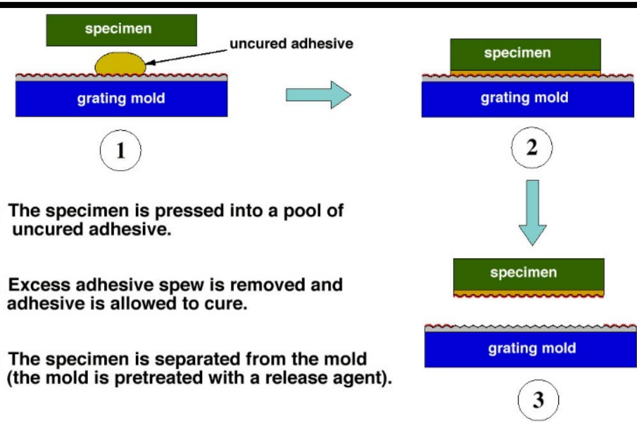
$$U_x(x,z) = \frac{1}{f} N_x(x,z)$$

$$U_z(x,z) = \frac{1}{f} N_z(x,z)$$

$$\varepsilon_x = \frac{\partial U_x}{\partial x} = \frac{1}{f}\left[\frac{\partial N_x}{\partial x}\right]$$

$$\varepsilon_z = \frac{\partial U_z}{\partial z} = \frac{1}{f}\left[\frac{\partial N_z}{\partial z}\right]$$

$$\gamma_{xz} = \frac{\partial U_z}{\partial x} + \frac{\partial U_x}{\partial z} = \frac{1}{f}\left[\frac{\partial N_z}{\partial x} + \frac{\partial N_x}{\partial z}\right]$$



1) The specimen is pressed into a pool of uncured adhesive.

2) Excess adhesive spew is removed and adhesive is allowed to cure.

3) The specimen is separated from the mold (the mold is pretreated with a release agent).

Strain Redistribution due to Saw Cut
(basic concept)

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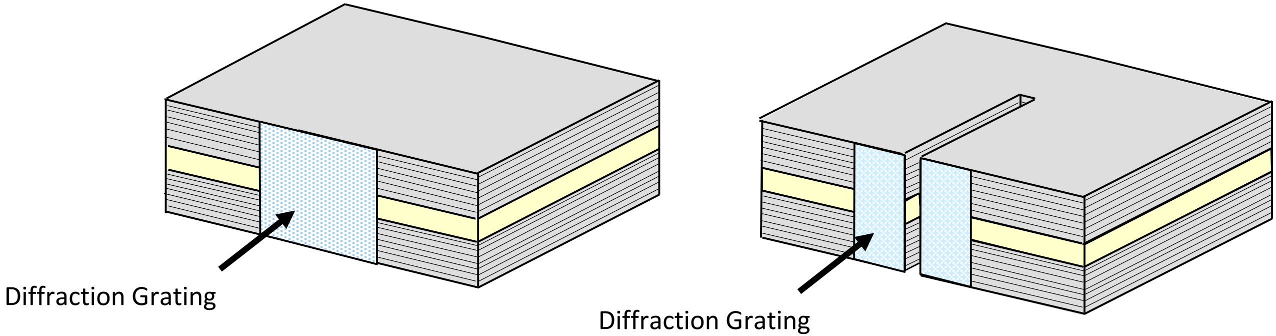
- Apply diffraction grating
- Measure 'null' field
- Cut specimen
- Measure change in surface strains



Strain Redistribution due to Saw Cut
(textile composite)

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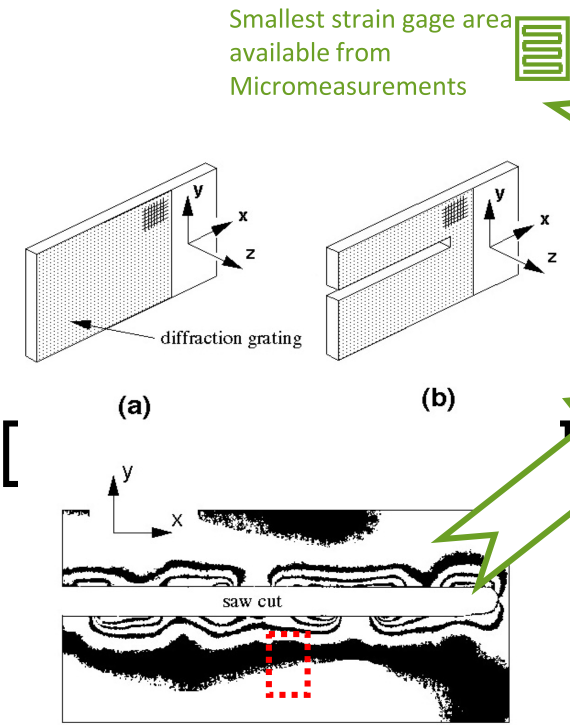

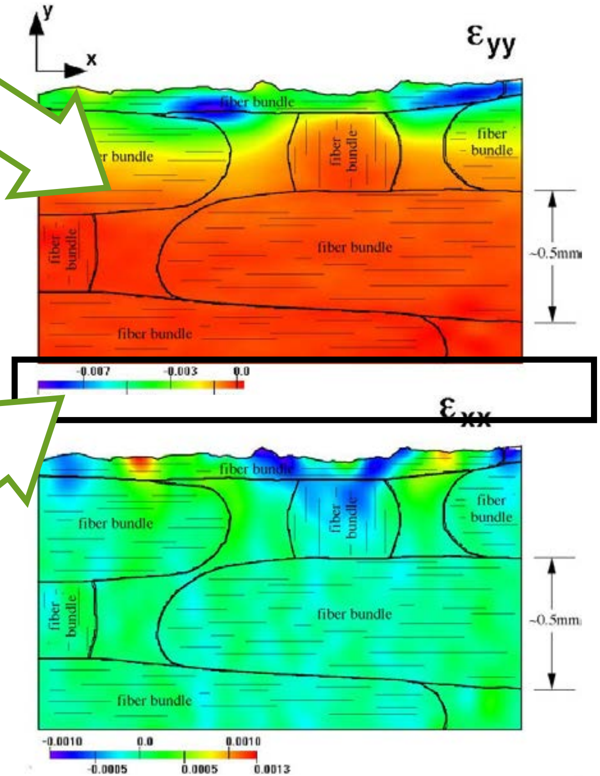

Mollenhauer and Holl, "Characterization of Bundle-Level Residual Strains in Woven Composites Using Moiré Interferometry," *39th International SAMPE Symposium and Exhibition*, Anaheim, California, 1994.

Strain Redistribution due to Saw Cut

(braided composite compared to model)

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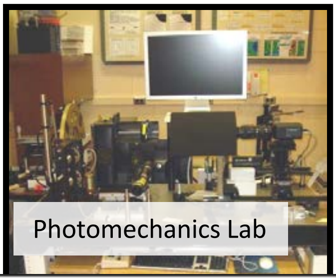
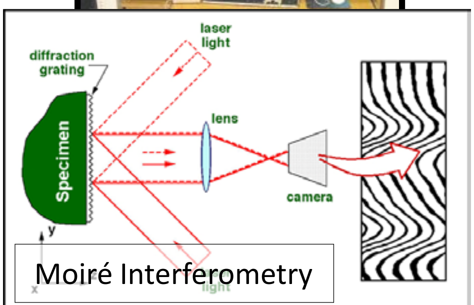
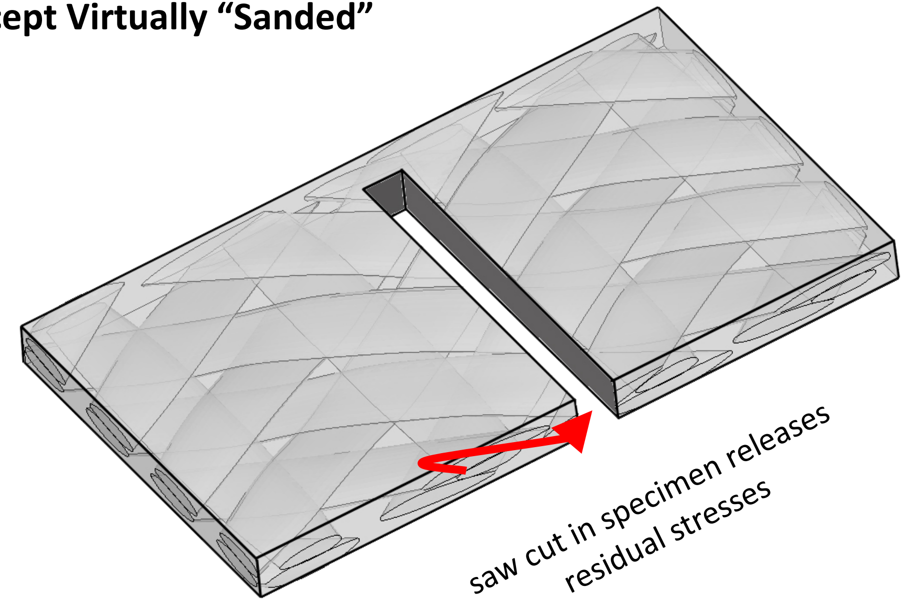
- **Experiment: 5-layer Compacted triax-braid**
- **Model 1: 1-layer Uncompacted triax-braid (i.e. resin rich)**
- **Model 2a: 5-layer Compacted braid (only top layer modeled)**
- **Model 2b: same as 2a except Virtually "Sanded"**







Strain Redistribution due to Saw Cut

(braided composite compared to model)

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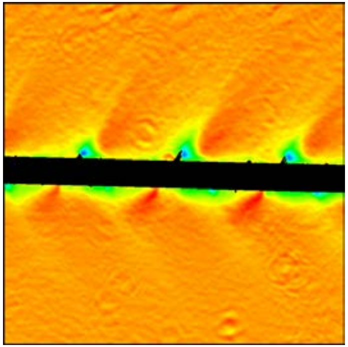
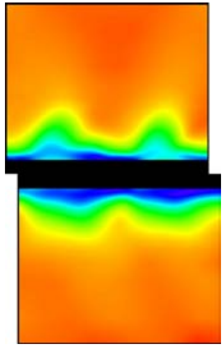
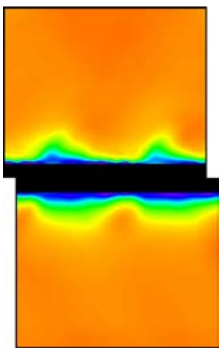


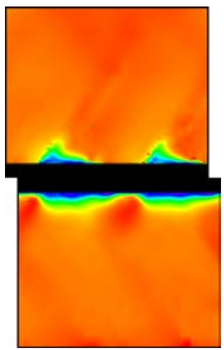
Moiré results



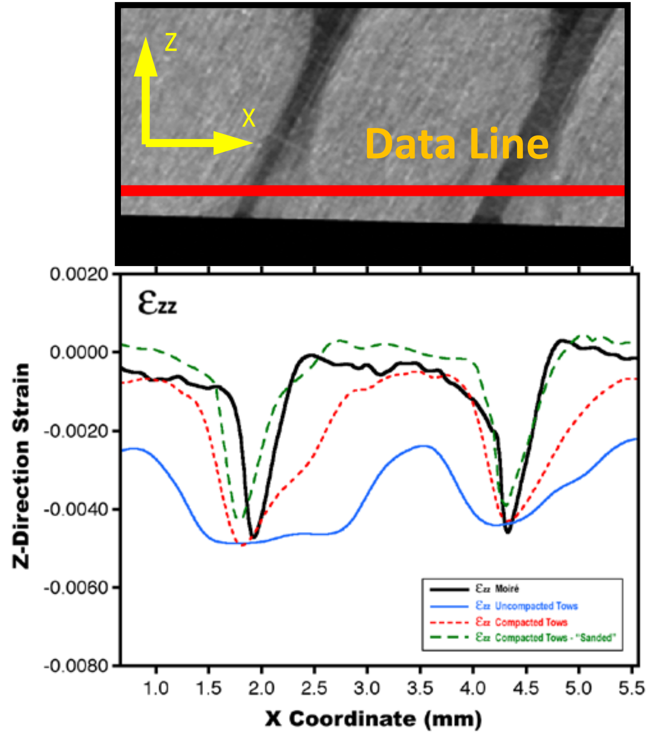
Uncompacted



Compacted



Sanded



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Strain Redistribution due to Saw Cut

(laminated composite: experiment and simulation)

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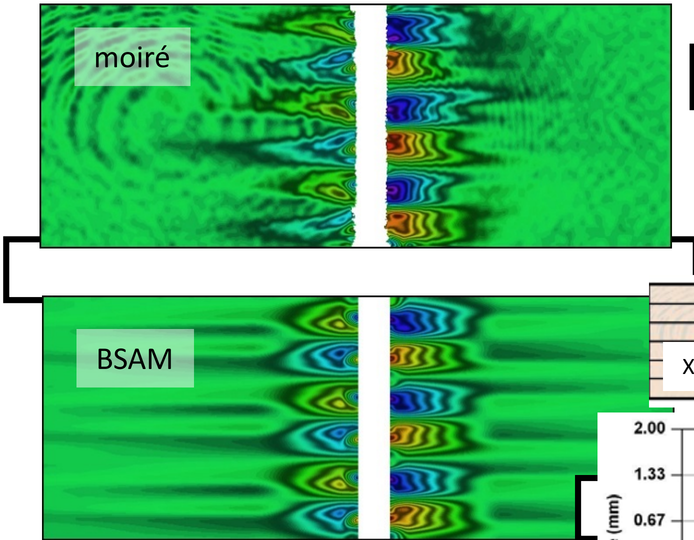
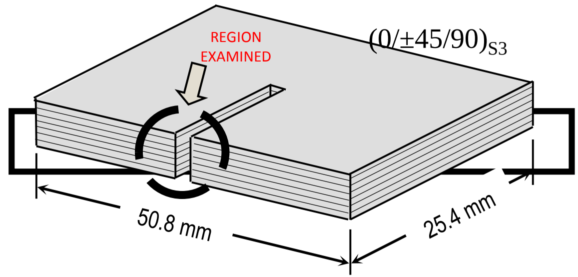
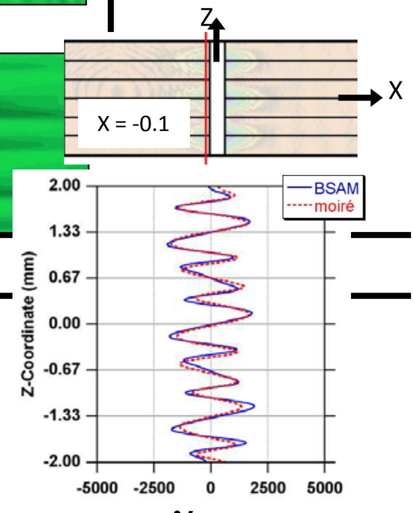
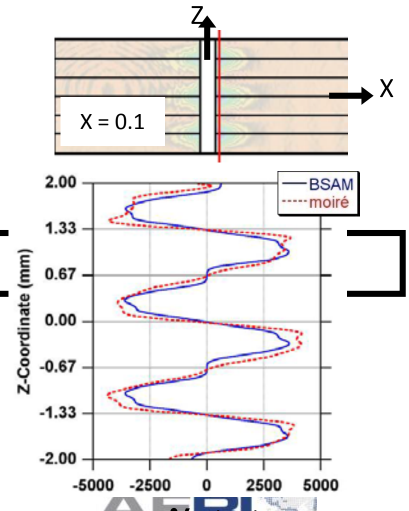
γ_{xz} experimental/analytical comparison









Mollenhauer, D. H., Schoeppner, G. A., and Iarve, E. I., "Experimental/Analytical Examination of Residual Strains in Composite Bonded Joints," *Proceedings of the 14th ICCM*, San Diego, CA, July 14-18, 2003.

Strain Redistribution due to Saw Cut

(multiple cure cycle effects)

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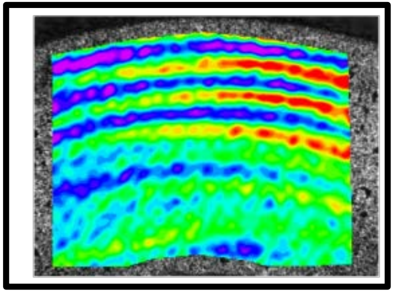
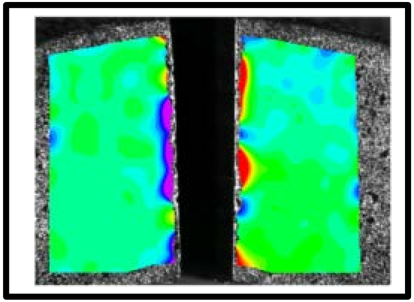
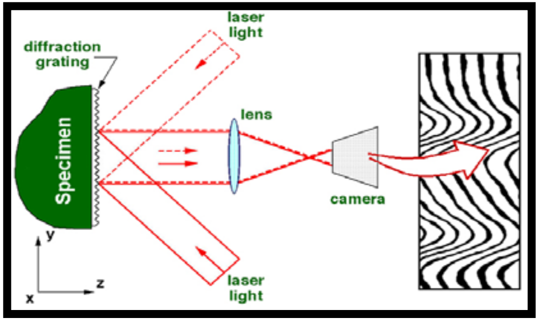
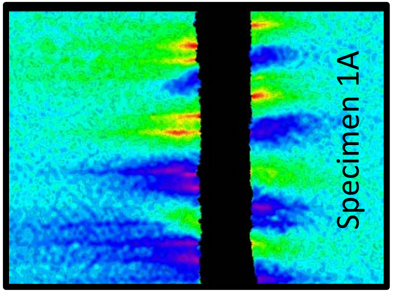
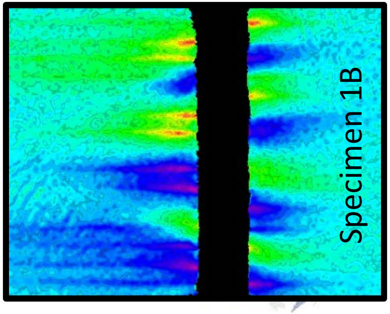
- **Residual Stress Measurements & Analysis**
  - Use full-field techniques for determination of effects of released residual stresses in laminated and textile flanges
  - Develop interim hooks between COMPRO 3D and BSAM via ABAQUS solutions
  - Develop complimentary models in BSAM to evaluate DOE cure cycles











Strain Redistribution due to Saw Cut

(multiple cure cycle effects)

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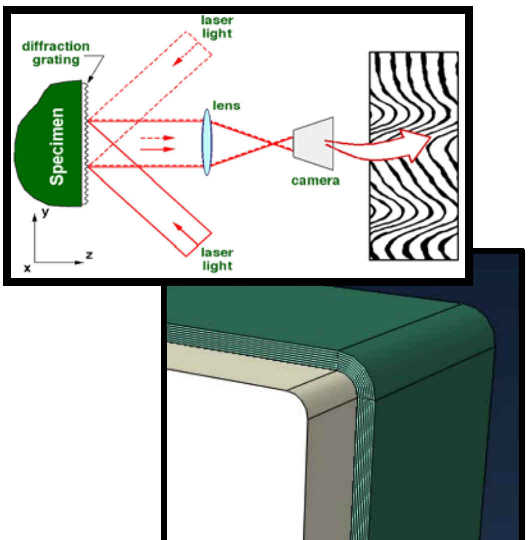
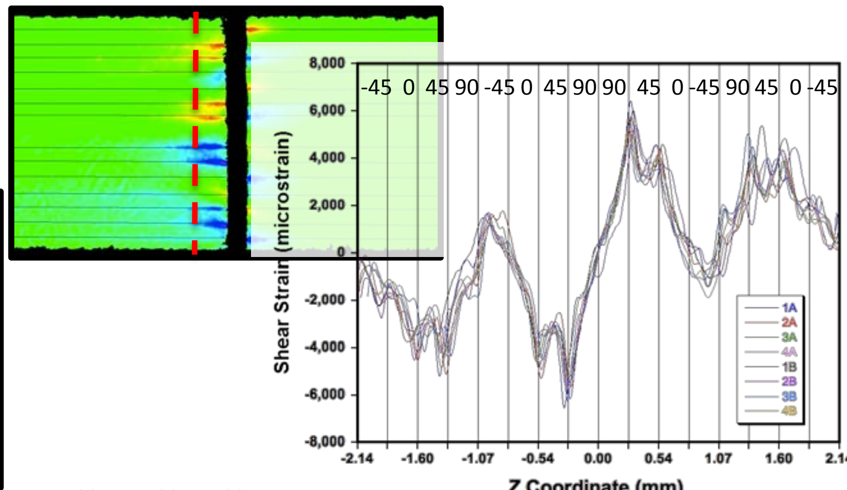
- **Flat leg's of all 8 specimen types completed**
  - **No discernable difference observed**
- **Preliminary look at curved specimens completed**
- **Specimens 2B and 3B obtained for detailed curved specimen examination**

Cure Cycle	Gel Temp, °C (°F)	Post Cure Ramp Rate, °C/min (°F/min)	Post Cure Method
3A	135 (275)	fast, 0.8°C/min (1.4°F/min)	I
2B	93 (200)	slow, 0.3°C/min (0.5°F/min)	FS
4A	135	slow	I
1A	93	fast	I
4B	135	slow	FS
2A	93	slow	I
3B	135	fast	FS
1B	93	fast	FS





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Summary & Conclusions

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- Residual stress prediction and characterization is challenging in polymer matrix composites
- Elastic-viscoplastic constitutive model introduced to capture the evolving mechanical properties during cure
  - *First* model to predict trends for cure cycles with freestanding postcures
- Moiré interferometry utilized to measure residual stresses
  - Accurate, but time consuming, technique