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Simulating Residual Stresses in Simple Multi-Material Composite Structures

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Sandia National Laboratories

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Outline

- Introduction and Motivation
- Objectives
- Manufacturing and Experimentation
- Finite Element Model
- Simulation Results
- Summary and Conclusions

Introduction and Motivation

- The ability to accurately predict residual stresses from curing in a composite aids in accurately predicting failure of the composite.
- Previous work has shown that a CTE-based approach with a calibrated stress free temperature was successful in predicting residual stresses in simple carbon fiber structures.
  - Does this approach work with other materials or ply orientations?
  - Does the addition of temperature dependent material properties increase the accuracy of the simulations?

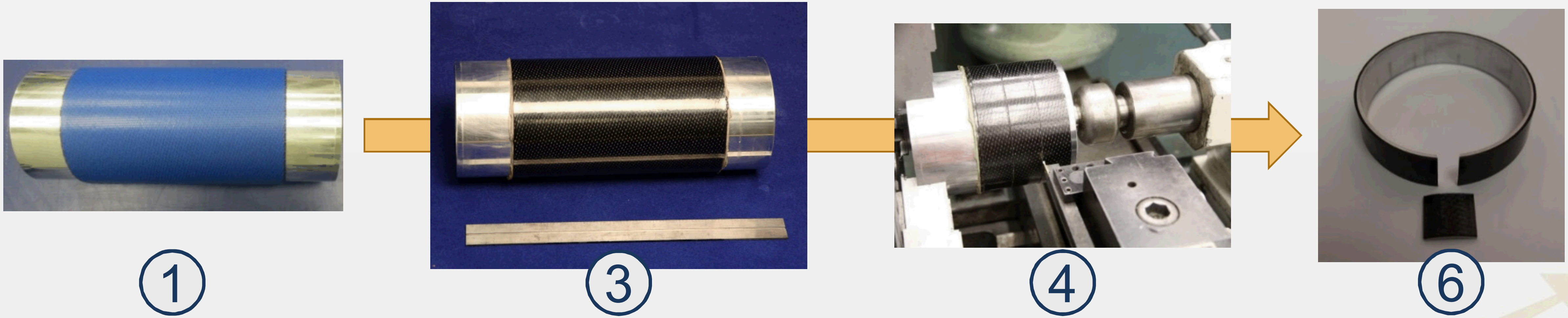
Objectives

- Simulate and experimentally validate multiple multi-material split rings
  - Assess split rings comprised of aluminum bonded to a carbon fiber or glass fiber composite.
  - Assess an aluminum/carbon fiber split ring with the plies oriented at 45°.
  - Assess possible improvements by including temperature dependent mechanical properties and CTEs.

Manufacturing and Experimentation

Manufacturing Process

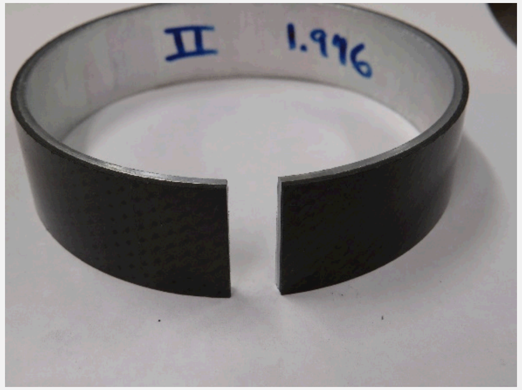
1. Symmetrical hand layup of CNC cut plies
2. Vacuum bagged with silicon caul for outer composite surface.
3. Cured in an autoclave at 177°C and pressure for 4 hours.
4. Machined to 25.4 mm wide rings.
5. Scribe lines created ~48 mm apart.
6. A 32.5 mm sector was removed between scribe lines.



Geometry and Materials

- Designed to visually exhibit residual stress
  - Co-bonded carbon/glass fiber and aluminum
- Aluminum
  - 6063-T6 number 4, schedule 10 extruded pipe (108.2 mm inner diameter)
  - Machined to a thickness of 2.0 mm
  - Bonding surface was cleaned and primed
- Composites
  - 8-harness satin weave fabrics
    - AS4C carbon fibers and 7781 e-glass fibers
  - Pre-impregnated with an epoxy based resin
    - (TCR 3362)
  - Symmetrical layup
- Variations:
  - Carbon Fiber, 4 plies
  - Carbon Fiber - 45° skew, 4 plies
  - Glass Fiber, 6 plies

Carbon Fiber, 4 plies

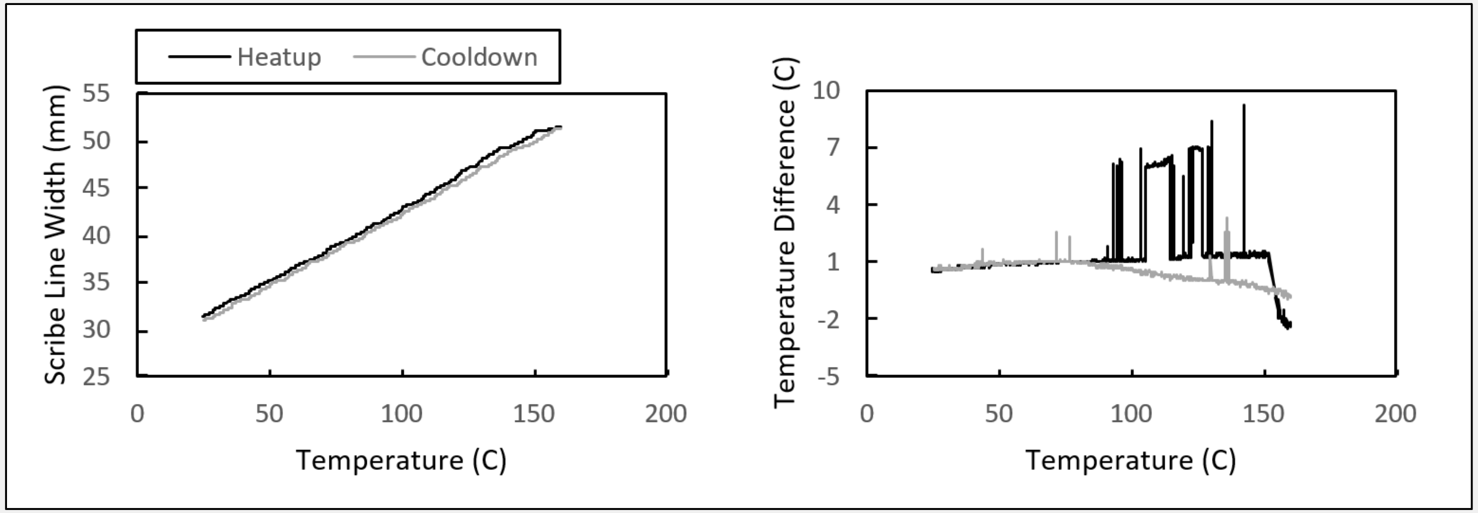


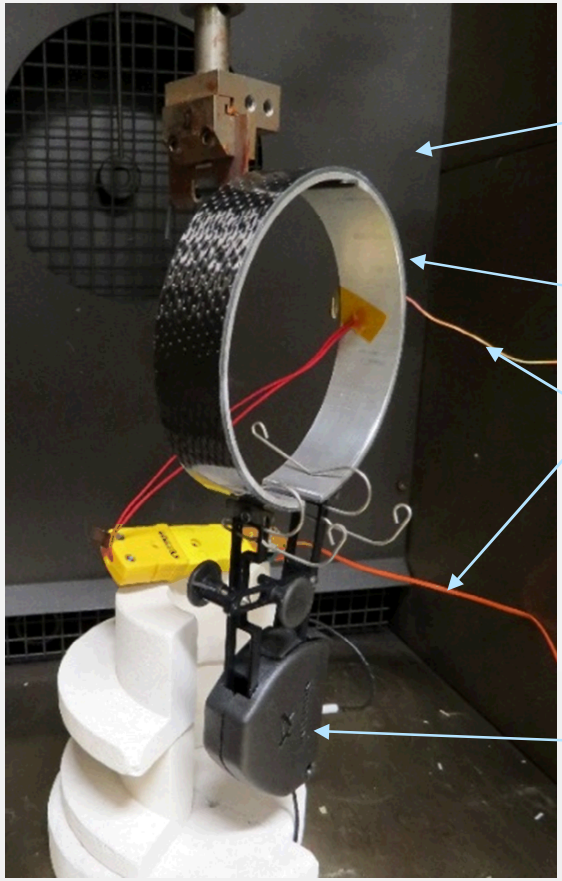
Carbon Fiber - 45° skew, 4 plies

Glass Fiber, 6 plies

Experimental Measurement

- The distance between two scribe lines was measured using an extensometer.
- The specimen was heated from room temperature to 170°C and then cooled back to room temperature
  - Heating and cooling was controlled at a rate of 0.5°C/min
    - Too high of a rate results in a hysteresis loop
  - Results during the cooldown minimized the difference between the aluminum and composite.





Temperature Control Chamber

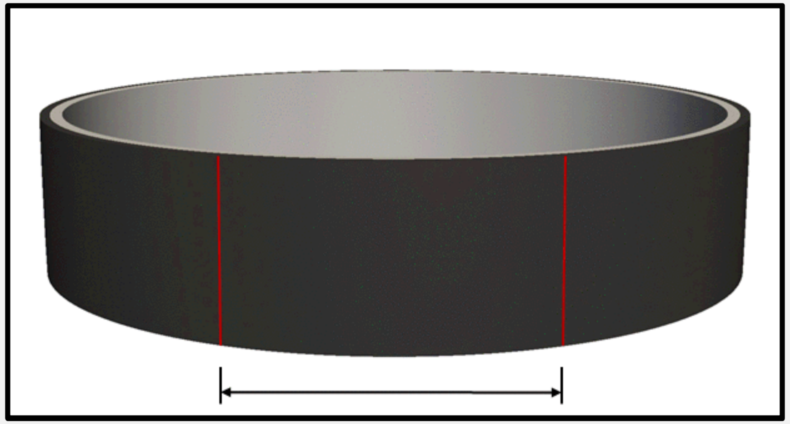
Bi-Material Split Ring

Thermocouples

Extensometer

Stress Free Temperature Determination

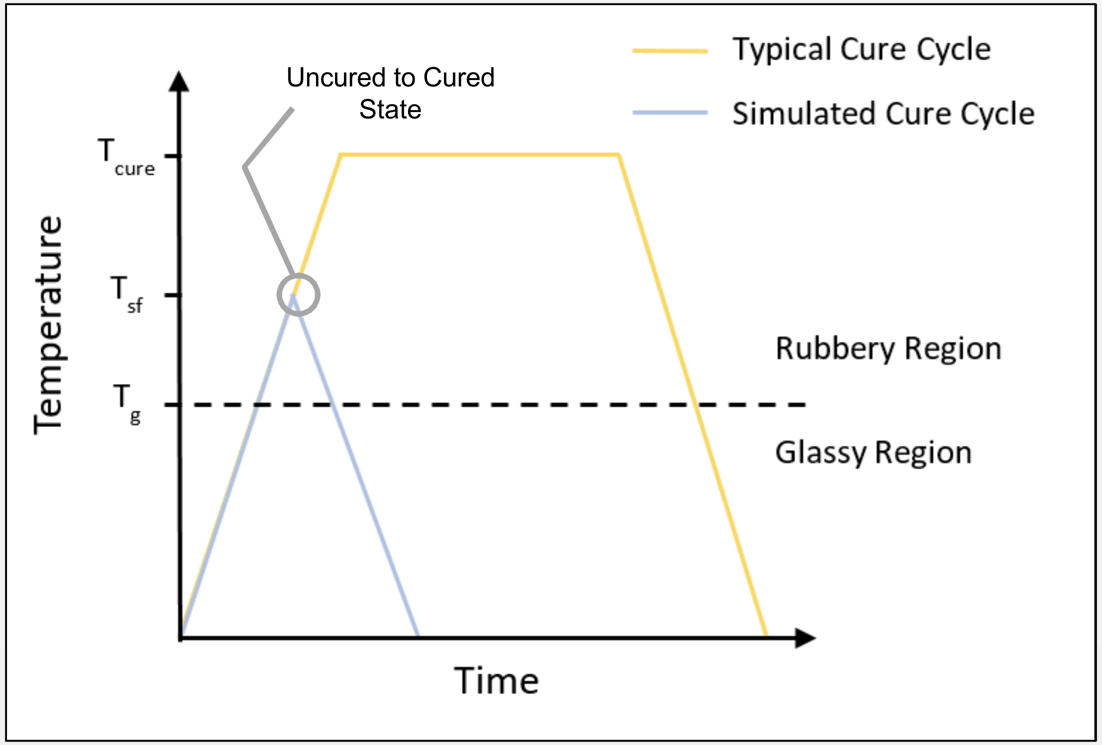
- The scribe lines were measured at room temperature before the split ring was cut.
- The stress free temperature is the temperature at which the scribe lines return to the room temperature measurement.



Finite Element Model

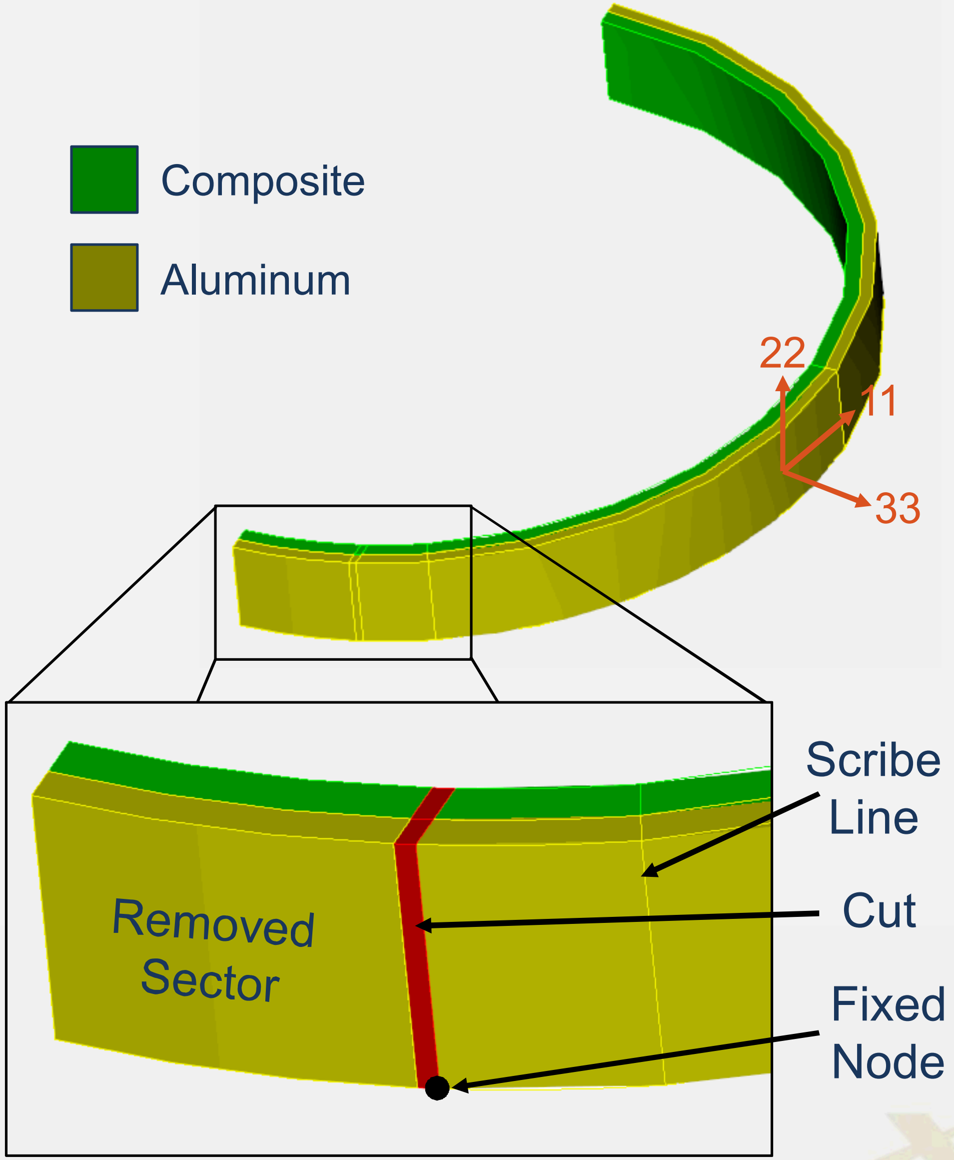
Modeling Methodology

- Residual stress development
  - CTE mismatch
  - Polymer Shrinkage
    - Adjust temperature cycle to have a maximum temperature equal to the stress free temperature
    - Experimentally determine stress free temperature
  - Assume a perfect bond between the aluminum and composite
- Instantaneous change from an uncured to cured state at the stress free temperature
  - Compliant, uncured elements are deactivated
  - Cured carbon fiber elements are activated with zero stress
- Isothermal specification of the temperature cycle
  - No heat transfer analysis done, so temperature hold of the cure cycle is irrelevant
  - Modified to have a maximum temperature equal to the stress free temperature



Model Description

- Analysis Software
  - Simulated using Sandia developed SIERRA Adagio
    - Lagrangian, three-dimensional code for the FEA of solid structures
    - Suitable for implicit, quasi-static analyses
- Finite element models
    - Aluminum is tied to the carbon fiber (assumes a perfect bond)
    - Discretized with 8-noded hexahedral elements
  - Bi-material split ring
    - Modeled using cylindrical coordinates
    - Modeled in quarter symmetry for computational efficiency
      - Acceptable for 45° skew case because the 11 and 22 directions are approximately equal
    - Single node fixed to prevent rigid body motion in non-symmetric direction
    - A partition was modeled at the scribe line location
    - The cut width and removed sector were modeled as a separate partitions that were excluded from the last simulation step to simulate the cutting process



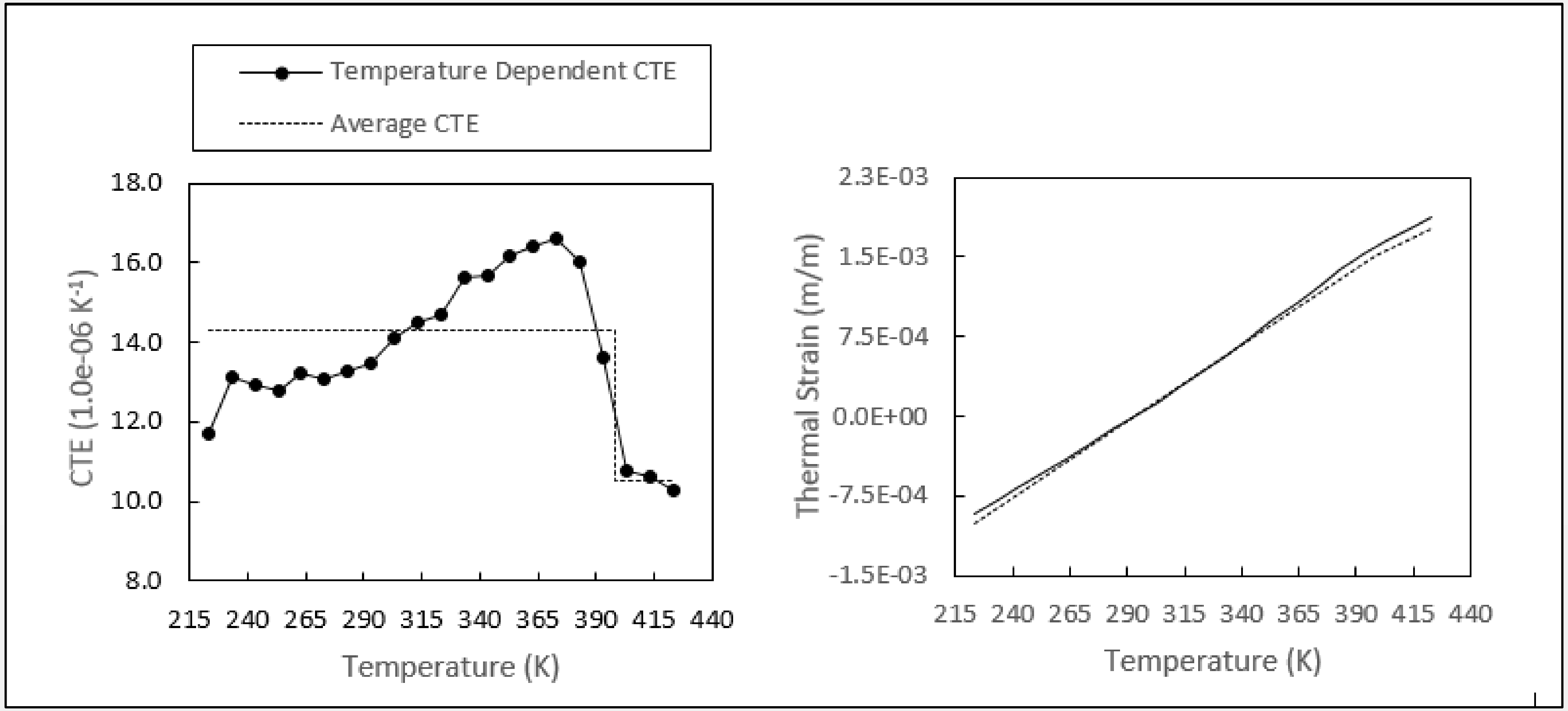
Material Models

- Aluminum
  - Linear-elastic model (no yielding or failure expected)
    - Requires: density, Young's modulus, and Poisson's ratio
  - Isotropic CTE
- Uncured Composite
  - Linear-elastic model
  - Same CTE of Aluminum in the 11 and 22 directions
- Cured Composite
  - Linear-elastic orthotropic model
    - Requires: density, nine elastic constants (E_{11}, E_{22}, E_{33}, G_{12}, G_{13}, G_{23}, v_{12}, v_{13}, v_{23}), and material orientation
  - Anisotropic CTE

- Temperature dependent material models specify required fields as functions of temperature
  - Aluminum temperature dependence taken from ASME BVPC
  - Composite temperature dependence determined through testing
    - Properties above T_g were extrapolated from experiments done at lower temperatures

Constant vs. Temperature Dependent CTEs

- Constant CTEs are comprised of a rubbery region value and glass region value, transitioning at T_g

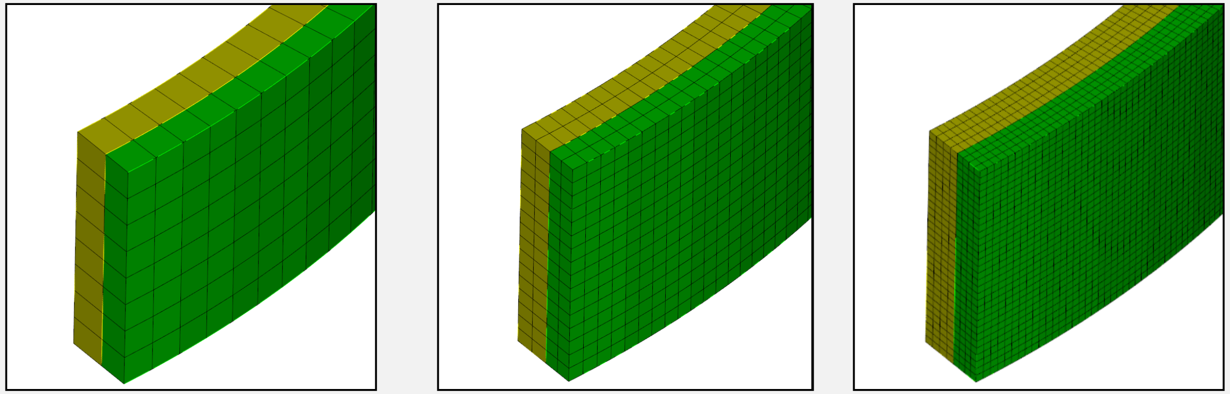


CTE11 for glass fiber composite

Mesh Convergence Study

- Confirm the simulated solutions converge to the same continuum value
- Three levels of uniform mesh refinement starting at one element through the thickness of each material
- Used Richardson's extrapolation to estimate the continuum value

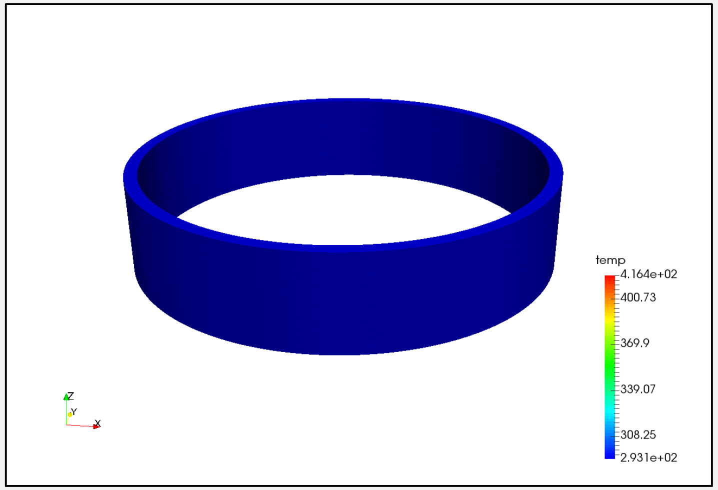
- 4 elements through both the aluminum and composite result in ~1% without significantly affecting computational time

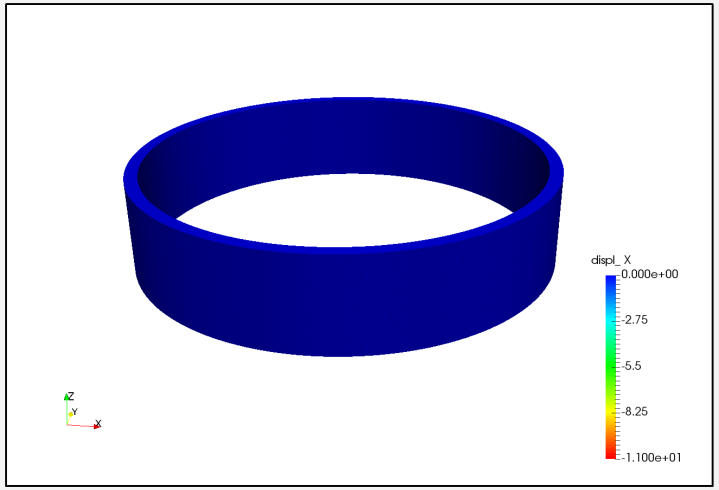


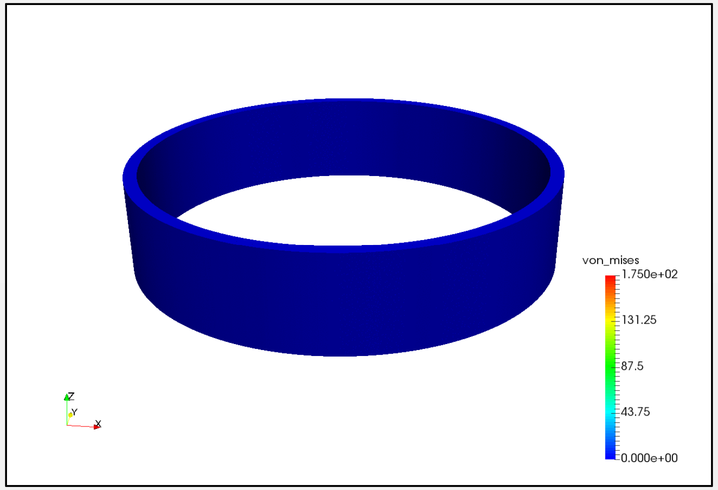
Elements	Carbon Fiber		Carbon Fiber (45° Skew)		Glass Fiber	
	Width (mm)	Error	Width (mm)	Error	Width (mm)	Error
1	17.20	22.9%	21.86	24.53%	37.63	8.4%
2	21.28	4.6%	27.50	5.1%	40.44	1.5%
4	22.10	0.9%	28.67	1.1%	40.95	0.3%
Exact	22.30		28.97		41.07	

Simulation Results

Simulation Results







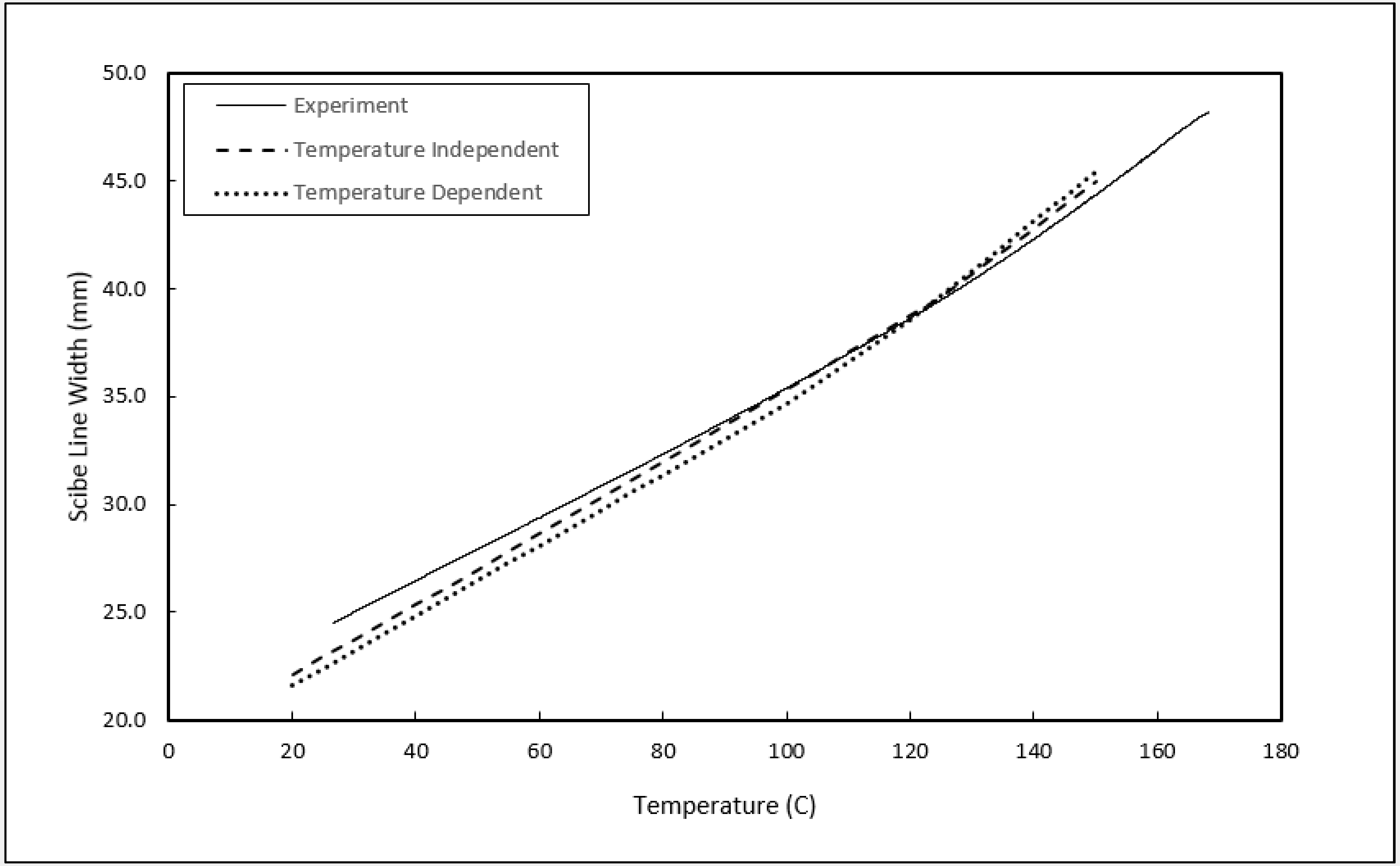
Comparison at Room Temperature

Carbon Fiber			Carbon Fiber (45° Skew)			Glass Fiber		
Experiment (mm)	TIP[1] (mm)	TDP[2] (mm)	Experiment (mm)	TIP[1] (mm)	TDP[2] (mm)	Experiment (mm)	TIP[1] (mm)	TDP[2] (mm)
24.52	22.91	22.38	31.57 30.98	29.50	28.97	40.95 41.02	41.29	41.40

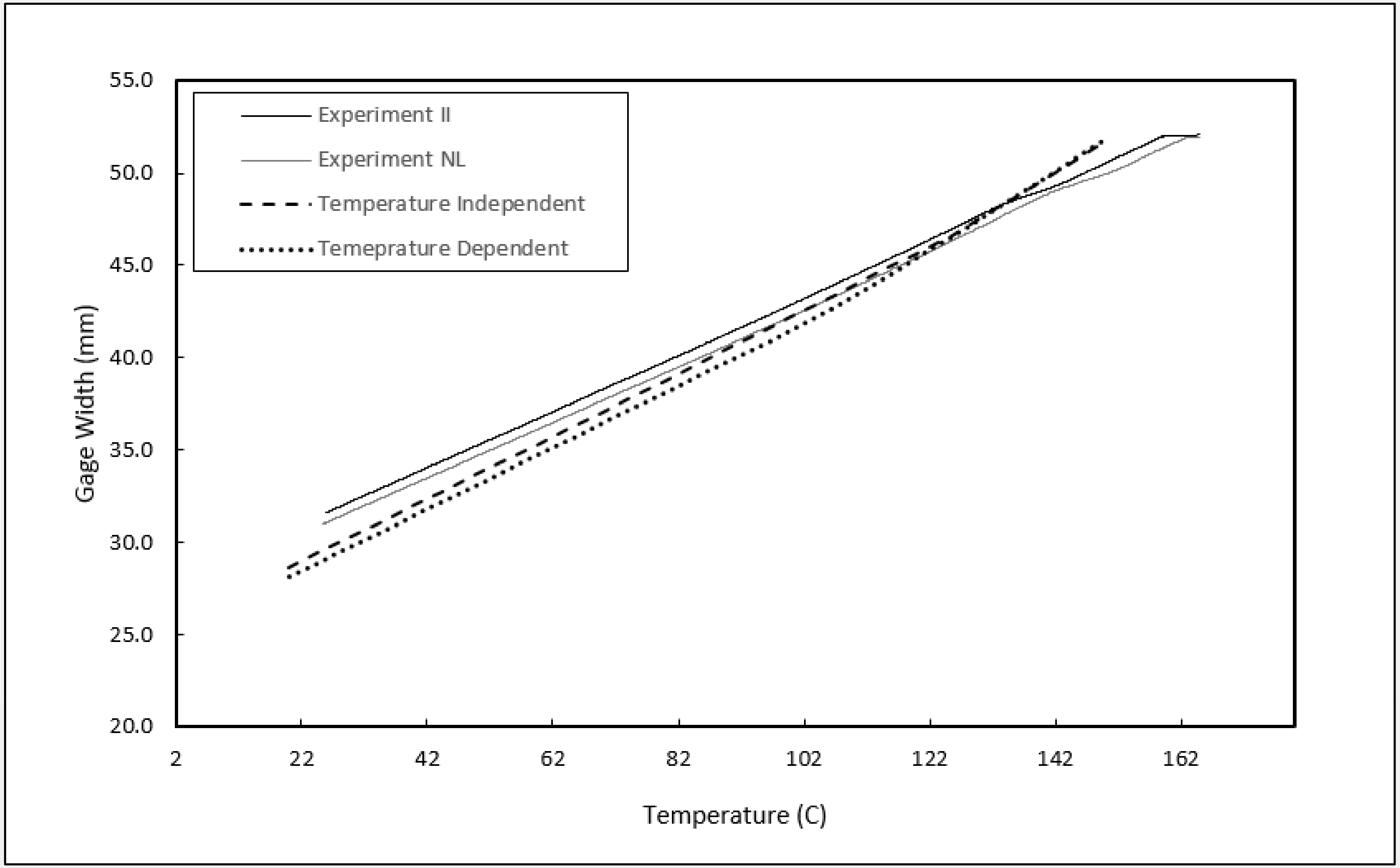
[1]Temperature Independent Properties
[2]Temperature Dependent Properties

- Good agreement with experiments
  - Carbon fiber is within 10% and glass fiber is ~1% error
- Small difference between temperature independent and dependent simulations

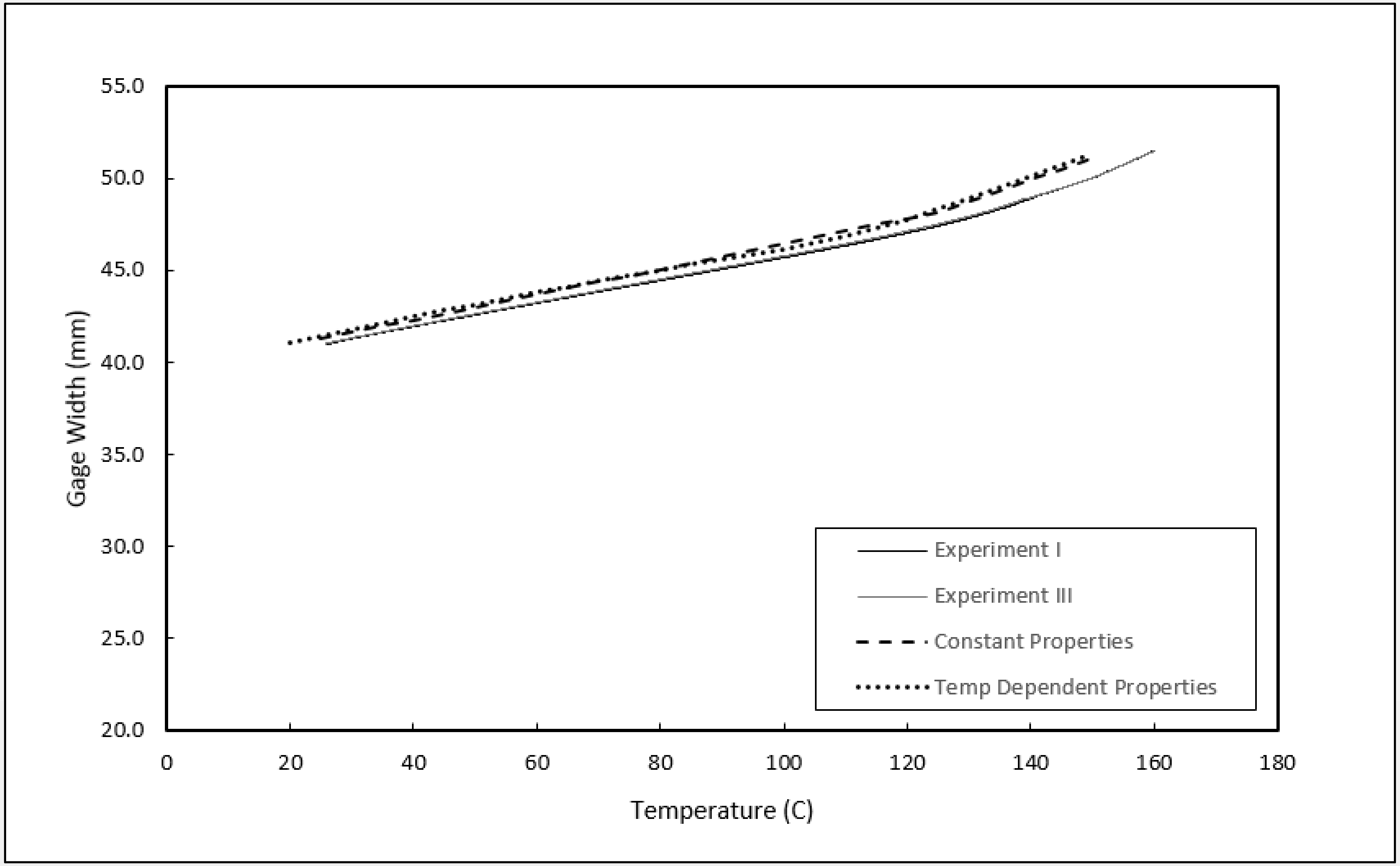
Aluminum – Carbon Fiber Split Ring Results



Aluminum – Carbon (45° Skew) Fiber Split Ring Results



Aluminum – Glass Fiber Split Ring Results



Summary and Conclusions

- The simulations of the bi-material plate and split ring were used to predict the residual stresses generated due to the composite curing process
  - The simulations agree well with all materials and ply orientations for both temperature independent and dependent models
  - Greater agreement below T_g
    - Extrapolating properties above T_g is not sufficient
  - A temperature independent model split between glassy and rubbery regions is sufficient
    - Minimal differences between temperature independent and dependent models
- The simplified modeling approach can be used to predict residual stress reasonably well with a reduced number of material properties and without knowledge of the cure cycle for multiple materials and ply orientations.