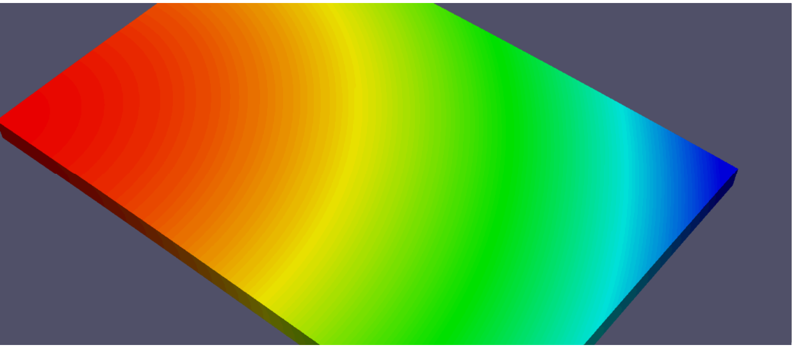
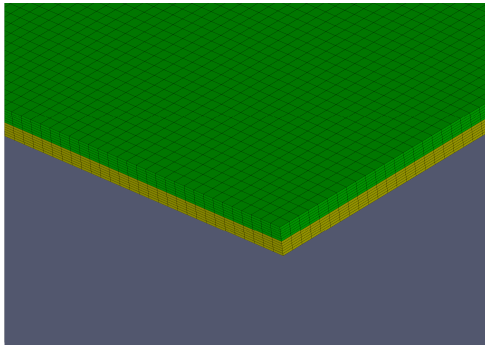
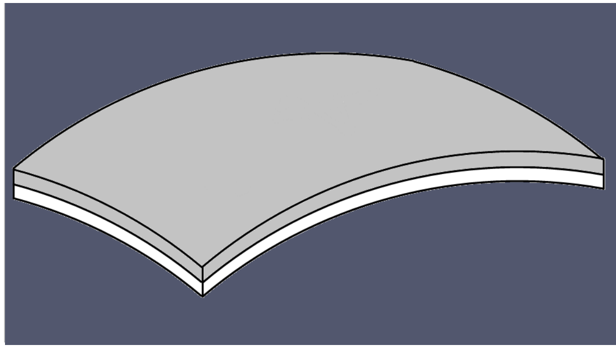
SAND2015-10421PE

Exceptional service in the national interest

Sandia National Laboratories







ASC V&V: Residual Stress Modeling

Alex Hanson & Stacy Nelson

ORG. 8259, Multi-Physics Modeling and Simulation

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Outline

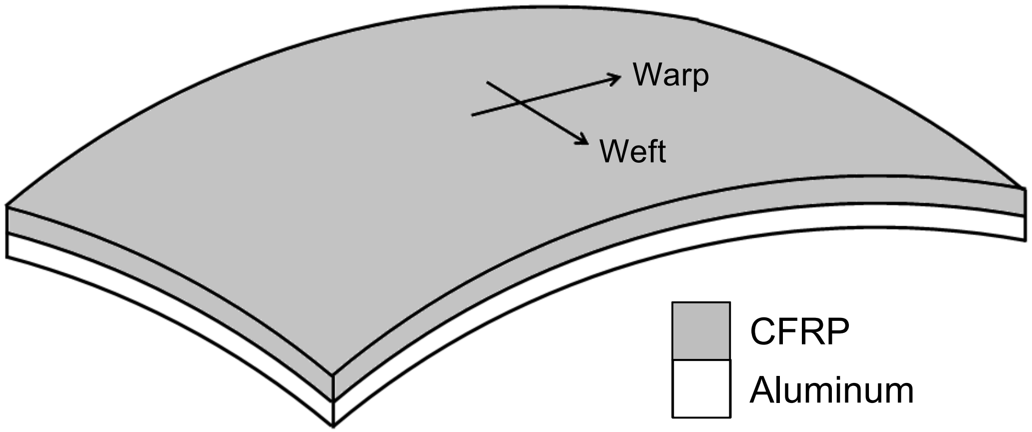
- Current Presentation Objectives
- Preliminary Model Details
  - Test specimen description and measured experimental data
  - Finite element model description
    - Material properties
    - Discretization study
    - Sample results and post-processing methodology
- Modeling Approaches
  - CTE mismatch only
  - CTE mismatch + “shrinkage”
  - Additional curing cycle considerations
- Conclusions & Future Considerations

Current Presentation Objectives

- Develop modeling methodology that can be used to simulate the formation of residual stresses in co-cured and co-bonded composite structures
- Preliminary efforts are based a simple, co-bonded Al and CFRP plate
  - Determine ideal material models (elastic vs. elastic-orthotropic)
  - Determine an approach for simulating an approximation of a composite's rheological behavior during curing
  - Determine an optimum approach while minimizing model complexity
    - Planned sensitivity study, material model calibration, and uncertainty quantification require a robust and computationally inexpensive modeling method

Preliminary Model

- Co-bonded Aluminum-CFRP plate
  - 4.0 x 6.0 inch plate
  - Aluminum
    - AL 6061-T6
    - thickness = 0.0625 inch
  - CFRP
    - 4 plies of an 8 harness satin weave prepreg
    - thickness = 0.063 inch



Location	Radius of Curvature (in)
Warp, Center	38
Warp, Edge	33
Weft, Center	38
Weft, Edge	28

Material Model Consideration

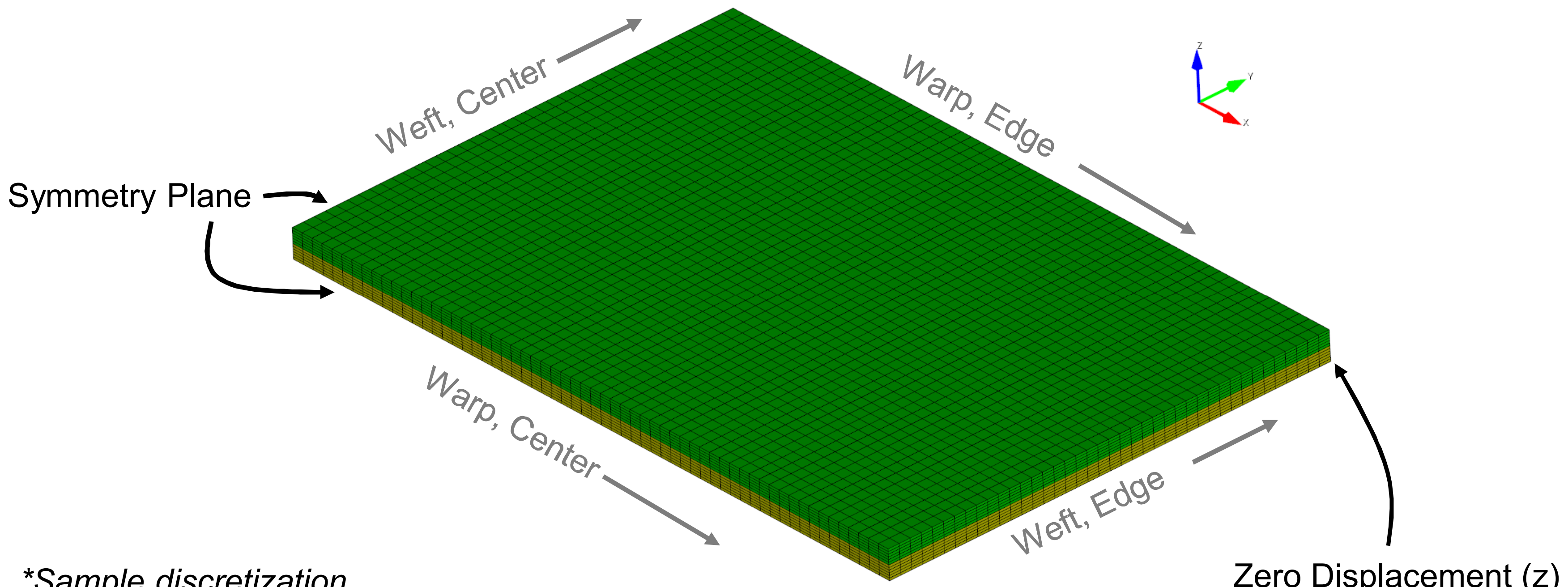
- Aluminum
  - Elastic-Isotropic
- CFRP
  - Elastic-Isotropic
  - Elastic-Orthotropic

Property	Aluminum	CFRP
E_{11}	71.3 (GPa)	63.86 (GPa)
E_{22}		62.74 (GPa)
E_{33}		8.59 (GPa)
G_{12}	26.9 (GPa)	3.44 (GPa)
G_{23}		3.27 (GPa)
G_{31}		3.25 (GPa)
v_{12}	0.33	0.048
v_{23}		0.408
v_{31}		0.055
CTE_{11}	23.4e-6 (1/K)	3.40e-6[1] / 1.13e-6[2] (1/K)
CTE_{22}		3.36e-6[1] / 1.13e-6[2] (1/K)
CTE_{33}		72.0e-6[1] / 28.3e-5[2] (1/K)

[1] Glassy Region
[2] Rubbery Region

Model Description

- Quarter symmetry conditions were applied for efficiency
- Applied Thermal boundary conditions simulate heating requirements of the prepreg's cure cycle



Sample discretization

Mesh Convergence Study

- Confirm that simulated solutions converge to the same continuum value
- Determine appropriate mesh size for all ensuing models

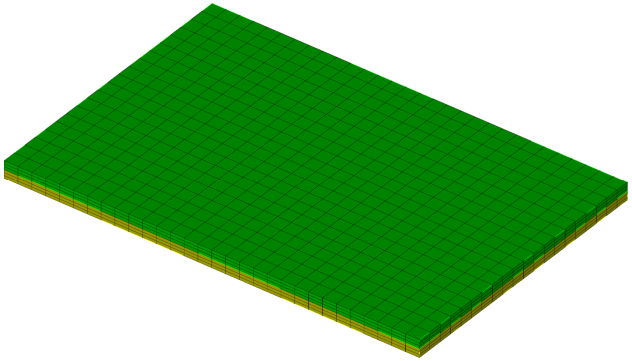


Plate-I

- 3,600 elements
- 3 elements through each layer

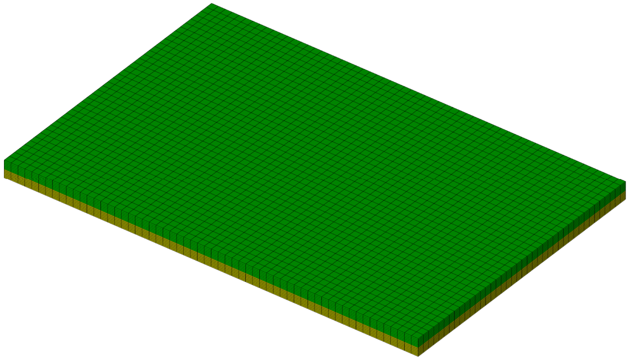


Plate-II

- 28,800 elements
- 6 elements through each layer

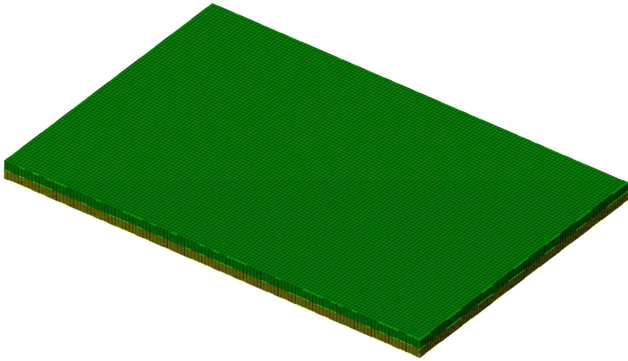


Plate-III

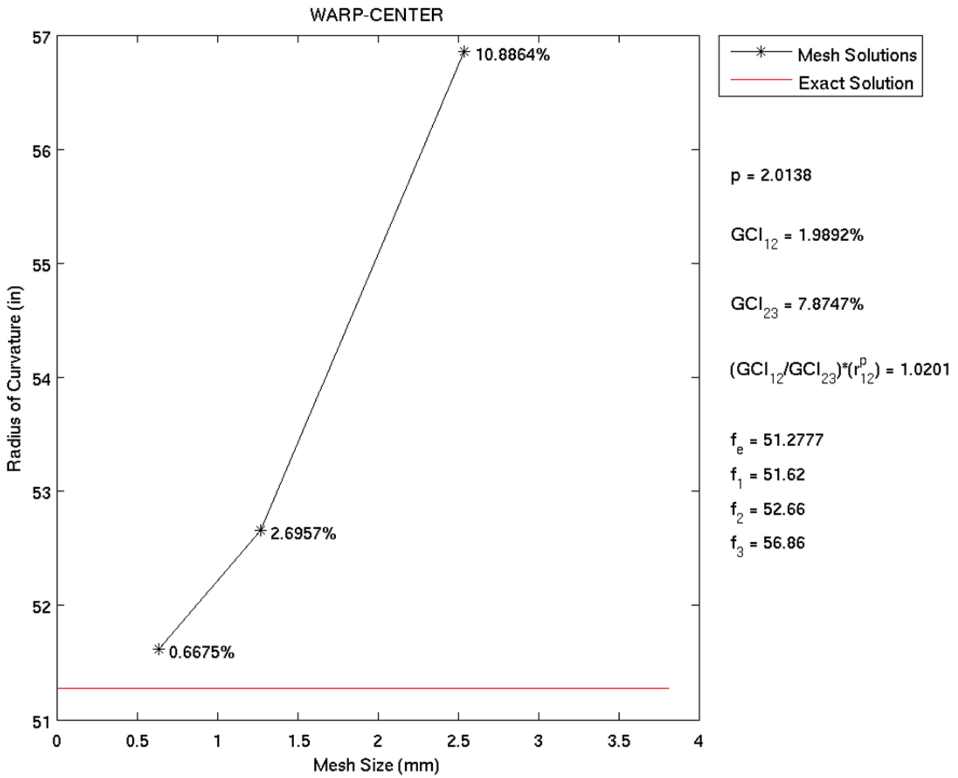
- 230,400 elements
- 12 elements through each layer

Mesh Convergence Study

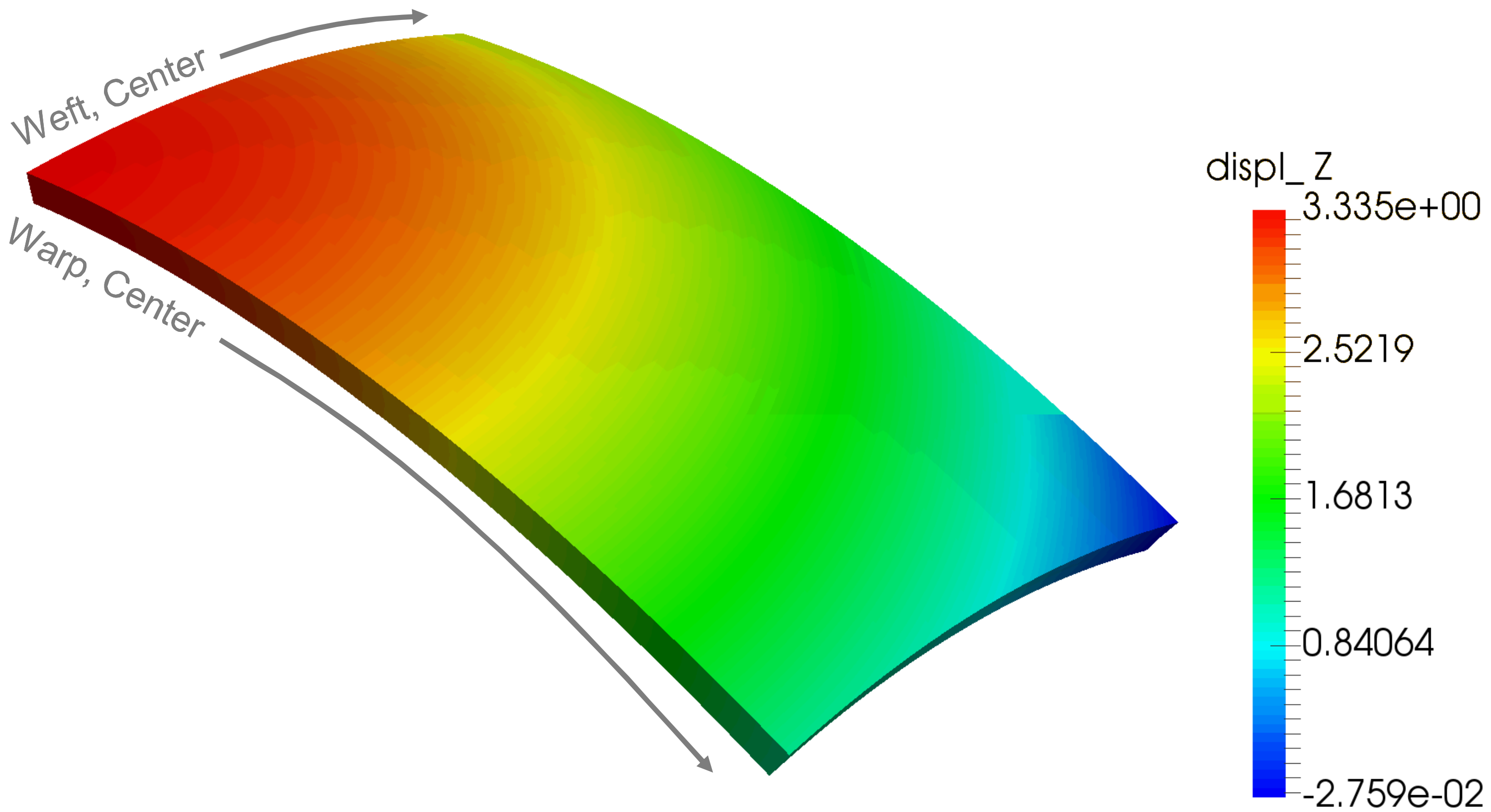
- Richardson's Extrapolation

$$f_{exact} = f_1 + \frac{f_1 - f_2}{r^{\mathrm{p}} - 1}$$

- Mesh Convergent
  - plate-II
  - 2.7% error (center)
  - 3.3% error (edge)
  - < 4 min runtime (12 cores)



Sample Results



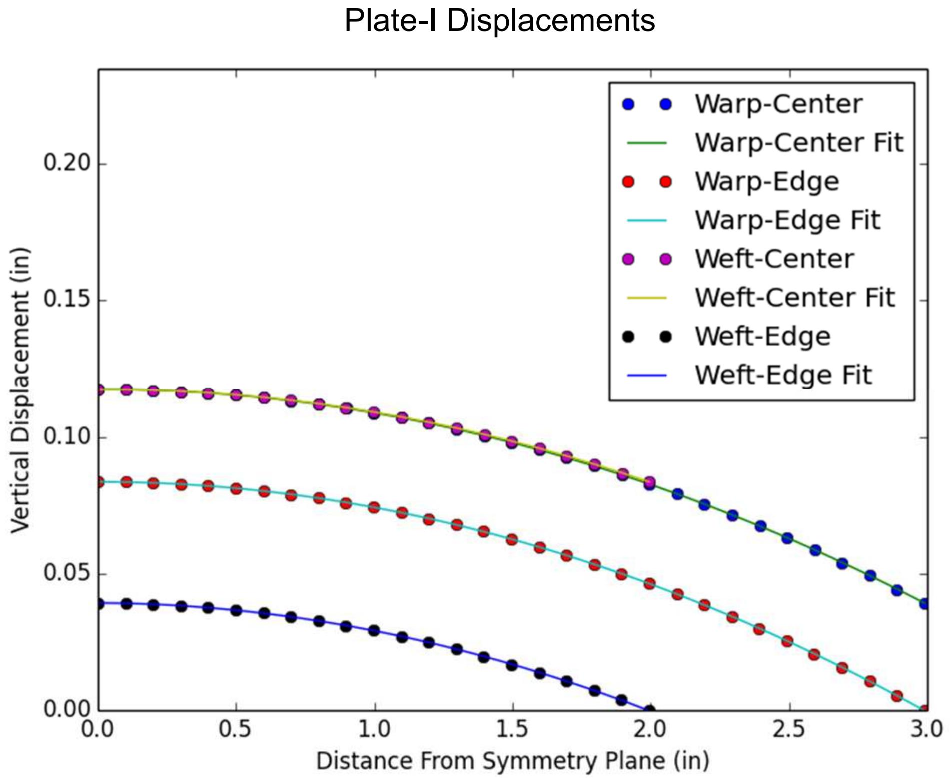
Post-Processing Methodology

- Quadratic Fit

$$f(x) = Ax^2 + Bx + C$$

$$\kappa = \frac{f''}{(1 + f'^2)^{3/2}}$$

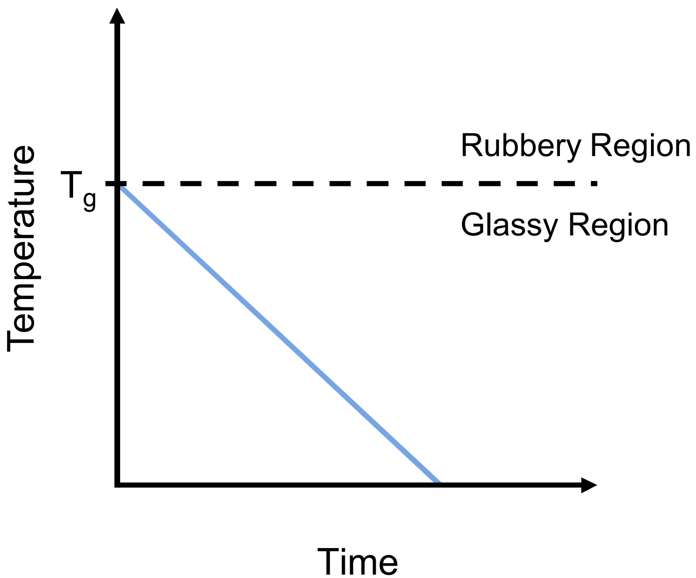
$$r = \frac{1}{\kappa} = \frac{(1 + (2Ax + B)^2)^{3/2}}{2A}$$



Modeling Approach #1

Cooldown Only

- Begin at T_g and cool to room temperature
- CFRP modeled as elastic, isotropic
- Simplest approach
- Considers CTE effects only

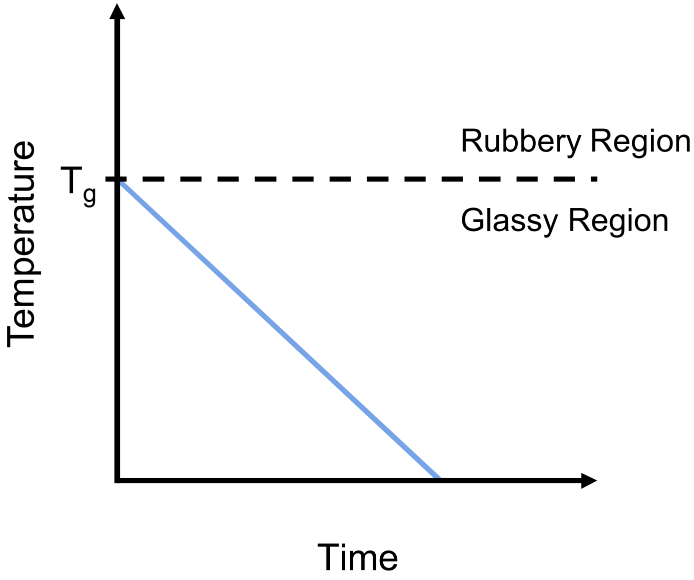


Location	Radius of Curvature (in)	
	Experiment	Model
Warp, Center	38	44.7
Warp, Edge	33	44.6
Weft, Center	38	44.8
Weft, Edge	28	44.1

Modeling Approach #2

<u>Cooldown Only</u>

- Same as Approach #1
- CFRP modeled as elastic, 3D orthotropic

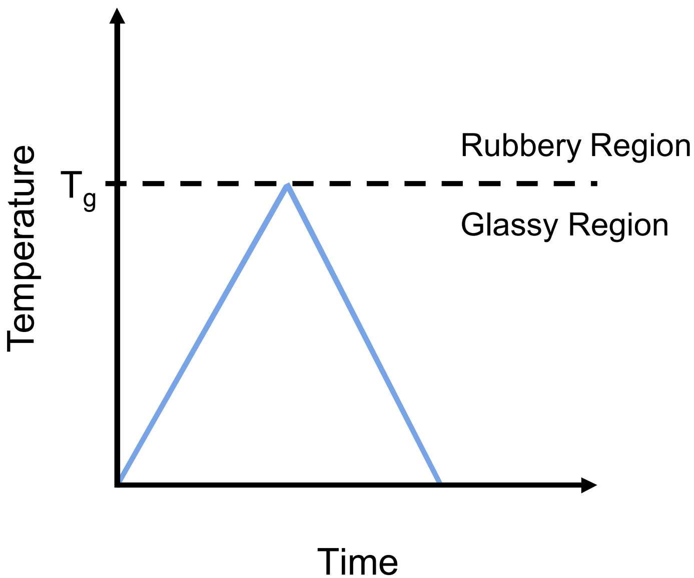


Location	Radius of Curvature (in)	
	Experiment	Model
Warp, Center	38	52.7
Warp, Edge	33	49.1
Weft, Center	38	53.4
Weft, Edge	28	47.4

Modeling Approach #3

<u>Heatup and Cooldown</u>

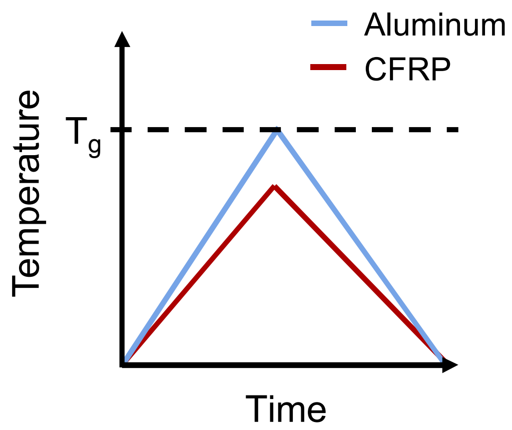
- Heat from room temperature to T_g then return
- Requires element ‘birth’ to change material properties
- Considers CTE effects only



Location	Radius of Curvature (in)	
	Experiment	Model
Warp, Center	38	53.0
Warp, Edge	33	49.3
Weft, Center	38	53.7
Weft, Edge	28	47.6

Approximating Cure Shrinkage

- Adjust the temperature of the CFRP
  - Historical method
  - Good agreement predicting delamination
  - Generally an adjustment of ~10^{o}C



Approach #2

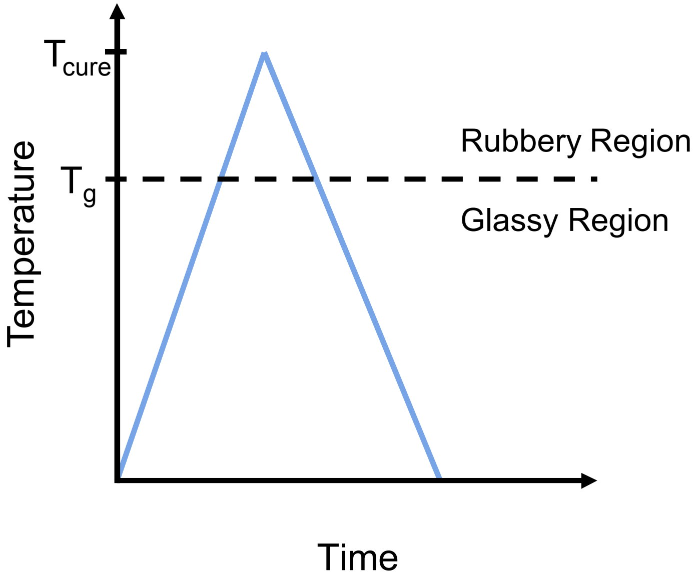
Location	Radius of Curvature (in)			
	Experiment	Adj = 0°C	Adj = 10°C	Adj = 100°C
Warp, Center	38	52.7	51.4	40.9
Warp, Edge	33	49.1	47.8	37.1
Weft, Center	38	53.4	52.1	41.9
Weft, Edge	28	47.4	46.1	35.6

Modeling Approach #4

Sandia National Laboratories

<u>Cure Cycle</u>

- Heat from room temperature to T_{cure} then return
- Requires element 'birth' to change material properties
- Considers CTE effects in both regions



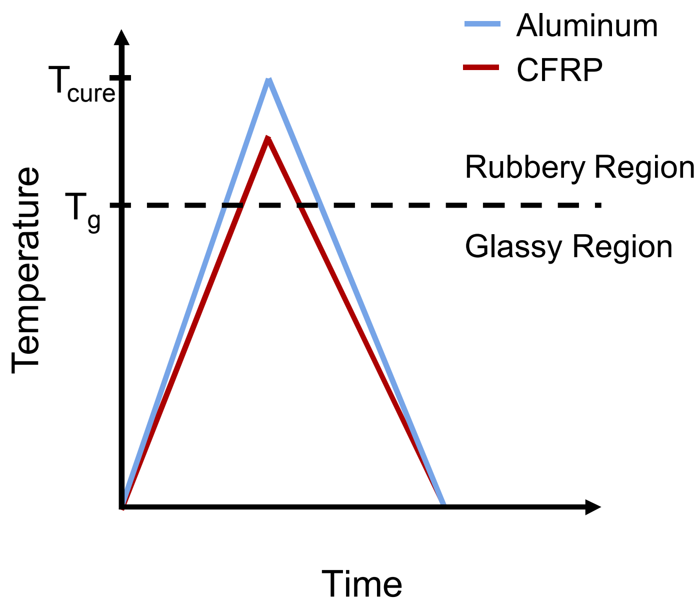
Location	Radius of Curvature (in)	
	Experiment	Model[1]
Warp, Center	38	40.3
Warp, Edge	33	36.5
Weft, Center	38	41.2
Weft, Edge	28	34.9

[1] T_{cure} = 154°C

Modeling Approach #5

Cure Cycle

- Same as Approach #4
- Adjusted CFRP temperature (50ºC) for cure shrinkage



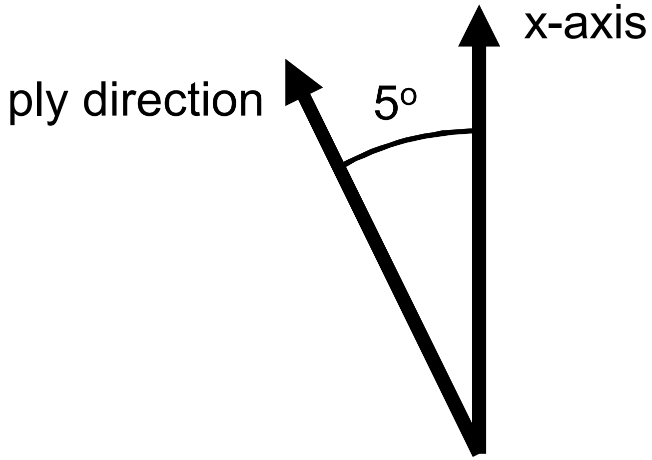
Location	Radius of Curvature (in)	
	Experiment	Model[1]
Warp, Center	38	38.1
Warp, Edge	33	34.3
Weft, Center	38	39.1
Weft, Edge	28	32.7

[1] T_{cure} = 154°C

Skew Sensitivity

Cure Cycle

- Same as Approach #5
- Rotated ply direction by 5°



Location	Radius of Curvature (in)	
	Experiment	Model[1]
Warp, Center	38	38.7
Warp, Edge	33	35.4
Weft, Center	38	39.1
Weft, Edge	28	31.8

[1] T_{cure} = 154°C

Current Conclusions

- The accurate simulation of residual stresses formed during a composite's cure cycle requires consideration beyond CTE mismatch
  - Cannot rely on T_g and CTE alone
  - Cure shrinkage is not negligible
  - It may be important to account for both the glassy and rubbery regions during the post-cure cool down
- Uncertainties in the relevant model parameters significantly effect the simulated response
  - T_g, cure temperature, and % shrinkage
  - Current simulations assume a "perfect" composite
    - Consideration of skew angle, void content, etc. may be important

Planned Future Work

- Apply sensitivity study and uncertainty quantifications techniques to a variation of modeling approach #5
  - Initialize the simulated composite material with an initial strain
    - More accurate method of simulating shrinkage
  - Determine model parameters most relevant for the simulation of residual stresses
  - Account for uncertainty of sensitive parameters in simulated responses
- Apply validated modeling technique to simulate new residual stress experiments
  - Quantify the composite CTE + shrinkage
  - Simulate residual stress formation in both simple and complex structures
    - Bi-material strips (analytical solution for validation)
    - Bi-material plates
    - Bi-material cylinders
- Investigate methods for modeling interlaminar delamination due to large residual stresses
  - Cohesive zone methods
  - Model validation with planned DCB experiments conducted in different environments