Evaluation of Temperature Gradients During Cure of a Thick Carbon Fiber/Epoxy Composite

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Background

- Drive system accounts for ~10% of rotorcraft vehicle weight.
- Polymer matrix composite materials are of interest for use in hybrid gears.
  - Lightweight alternative to all metallic structure
  - High strength to weight ratio and high stiffness offers designs with very high power to weight ratio.
  - Additional benefits include vibration and noise damping.

Hybrid gear prototype, Credit: ARL, RDECOM, NASA

- The use of composites in drive systems has been limited to housings and shafts

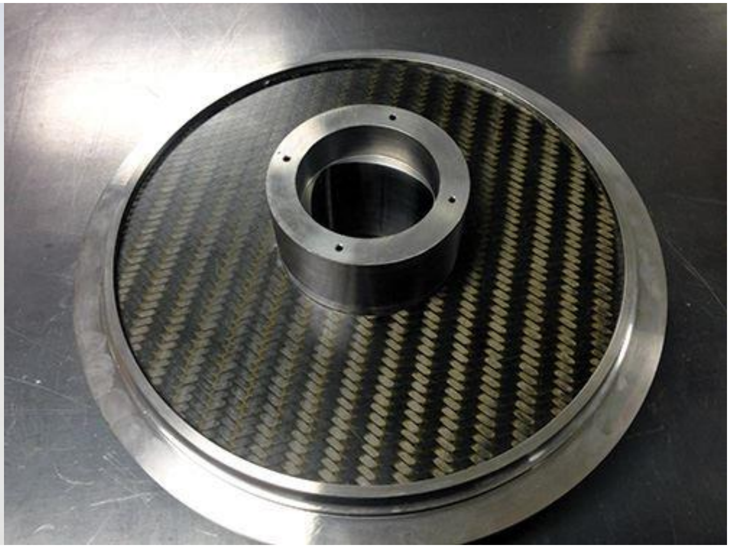
Background

Hybrid Composite-Steel Gear

- Significant amount of work has been done replacing the steel in a gear hub with composite.
  - Benefits, weight savings
  - Demonstrated success in testing

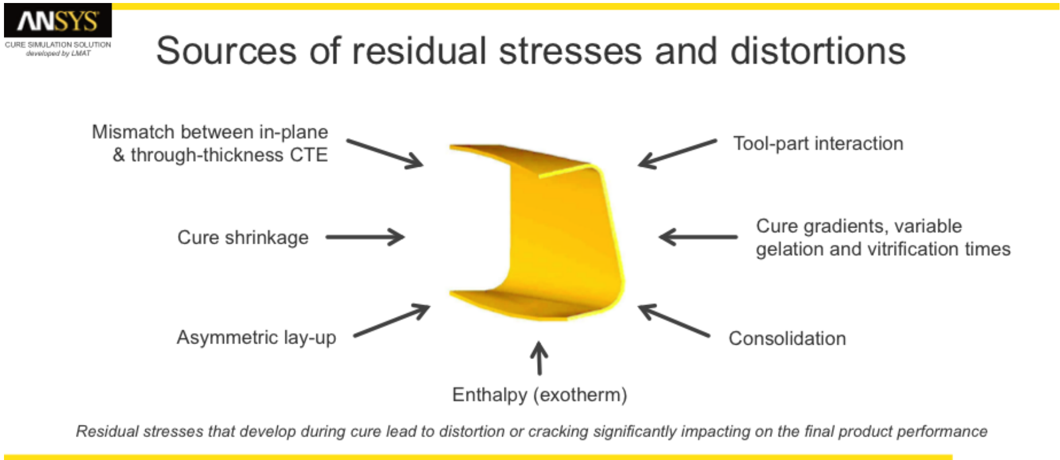
Curing Thick Composites

- Appropriate build up for power transfer requires composite thicknesses approaching 1 to 1.5” in thickness.



Curing Thick Composites- Exotherm

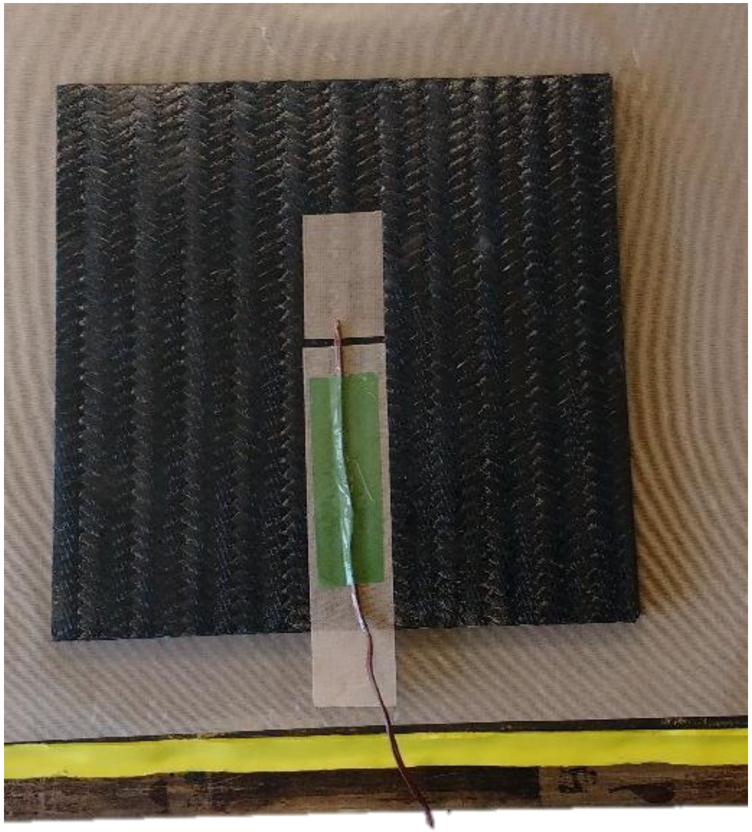
- The predominant sources of heat throughout cure include oven air convection, heat transfer through the tool and internal heat generated by the exothermic cure reaction of the resin.
- The rate of heat transfer through the panel scales with thickness.
  - Slow diffusion of heat generated at throughout the cure profile contributes to temperature variation between surface and center plies
  - Excess heat buildup in the center of the component causes the resin to vitrify sooner than the surface. This profile is a common source of process-induced stress in thick composite parts.
- In severe instances, this may result in an uncontrolled temperature increase and degradation of the material, among the previously mentioned concerns.



https://www.lmat-uk.com/software/ansys-composite-cure-simulation/

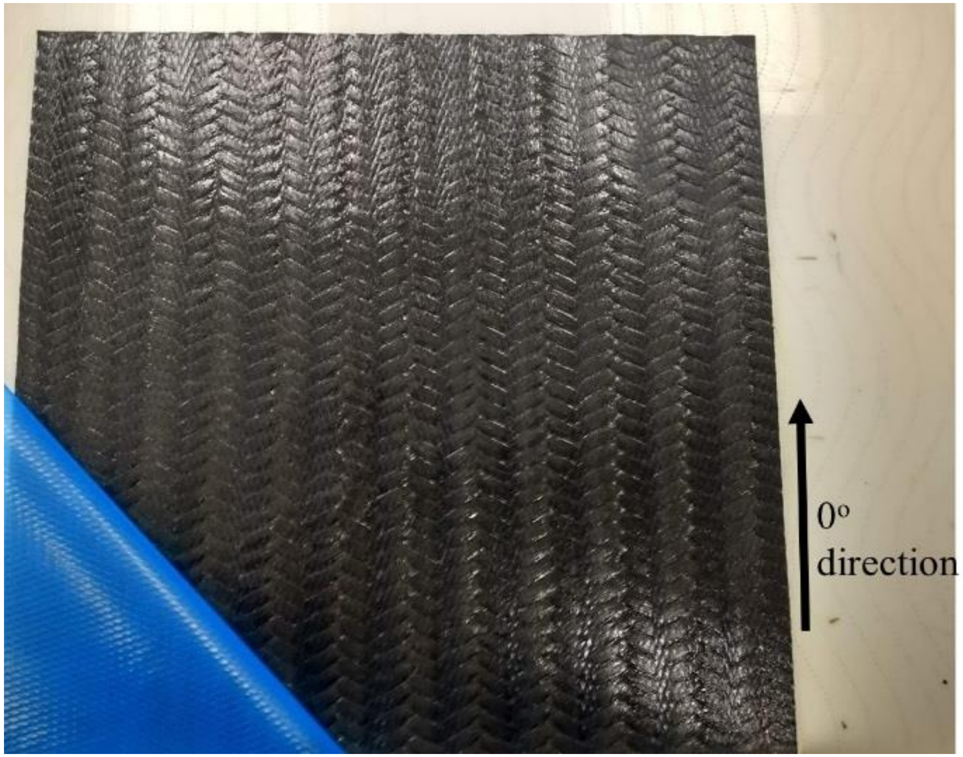
Objectives

- Monitor internal resin temperature through the thickness of a PMC as it cures.
  - Evaluate the development of temperature gradients that might lead to residual stress, deformation or inconsistent performance.
  - Measure influence on through thickness thermal and mechanical properties



Composite Materials and Fabrication

- A braided carbon fiber/epoxy (T700S/TC380) prepreg was used in this study. Toray's T700S fiber was braided by A&P Technology in a 0º, ±60º quasi-isotropic fiber orientation, and impregnated with TC380 epoxy resin by Tencate Advanced Composites.



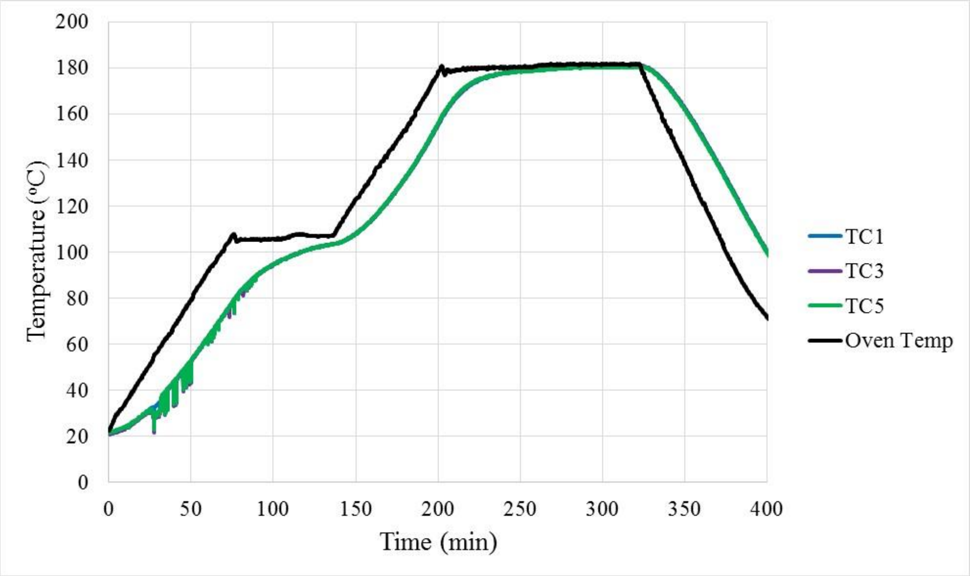
- Fiber areal weight (FAW) was 536 gsm, cured ply thickness (CPT) was 0.053 mm (0.021") and resin content was 38 wt%. Approximately 40 plies required for 1" thick laminate and 56 plies for a1.5" thick laminate.
- Panels were cured out of the autoclave to facilitate temperature measurement.
- Aluminum tool (14"x14"x0.5") and caul plate (8"x8"x1/8") were used for panel fabrication.

Composite Materials and Fabrication

The recommended vacuum bag only cure cycle proceeded as follows:

- Ramp from room temperature to 107°C (225°F) at a rate of 1.1 °C/min (2 °F/min).
- Hold at 107°C for one hour.
- Ramp to 180°C (356°F) at a rate of 1.1°C/min (2 °F/min).
- Hold for two hours
- Cool at a rate < 3°C/min (5 °F/min) to below 49°C (120°F).

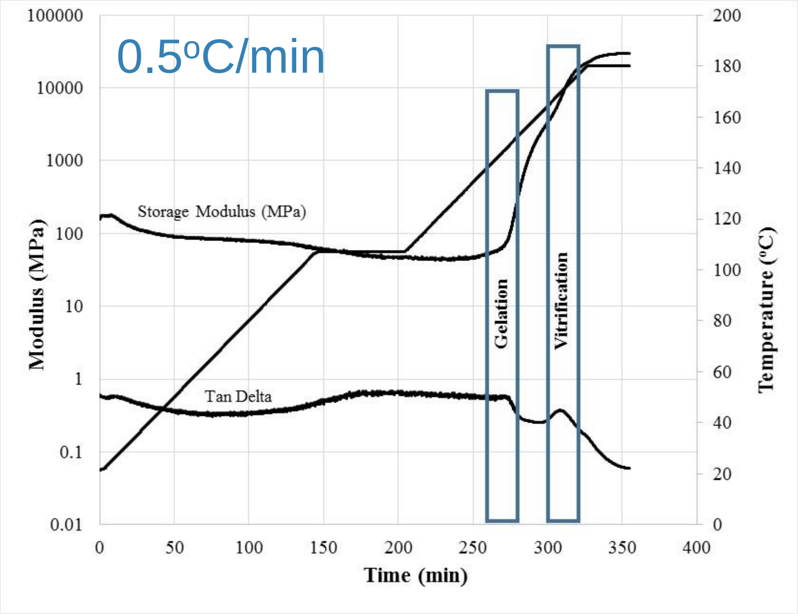
  Following this cure cycle, a two hour post cure at 180°C is recommended.

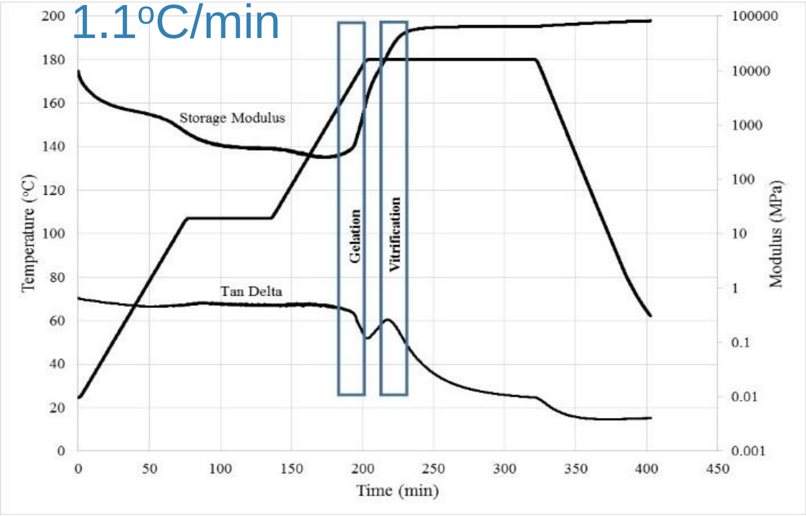


Thermocouple data from 10 ply panel

Prepreg Cure Characteristics- DMA

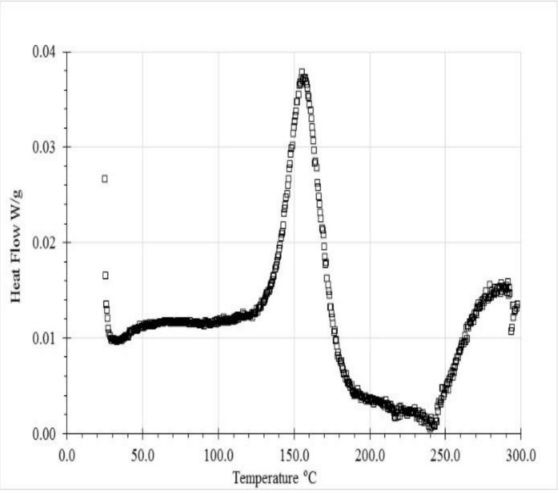
- The viscoelastic behavior of TC380 epoxy resin throughout the cure cycle was characterized by DMA.
- Following a 0.5ºC/min (1ºF/min) ramp rate the vitrification temperature was observed approximately 310 minutes into the cure cycle, as the material reached 170ºC.
- Increasing the ramp rate to 1.1ºC/min (2ºF/min), the vitrification temperature was observed 225 minutes into the cure cycle, after the material reached 180ºC.

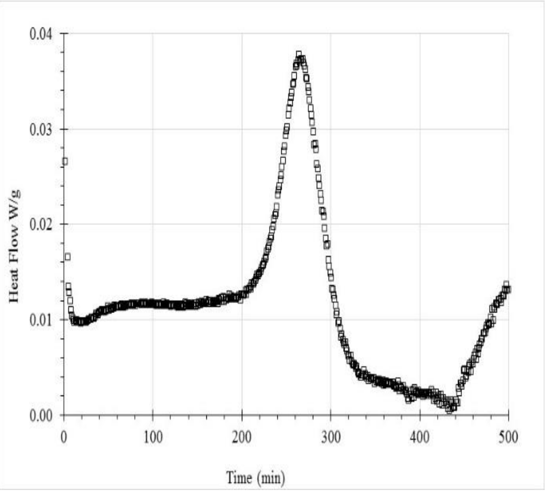




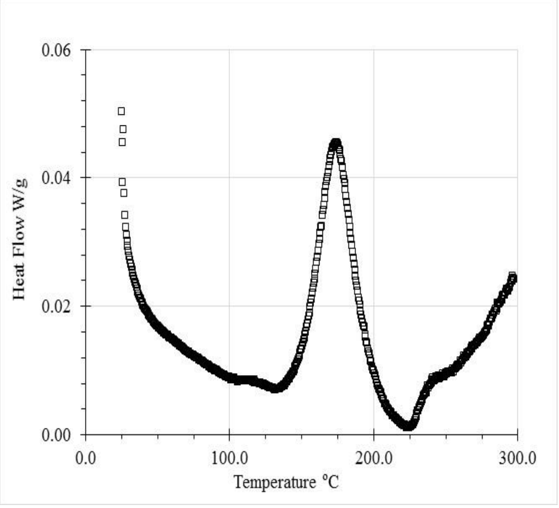
Prepreg Cure Characteristics- DSC

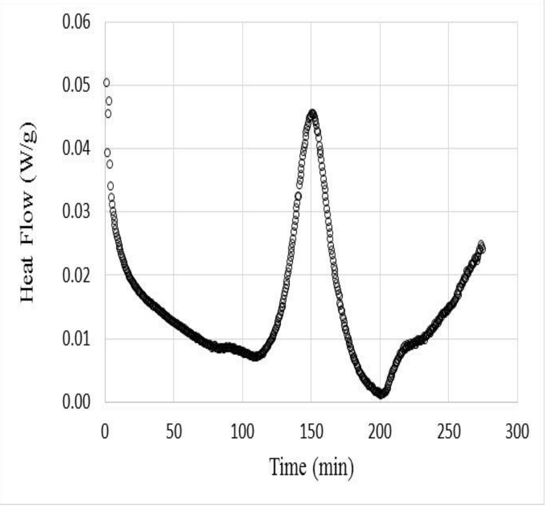
0.5°C/min





1.1°C/min

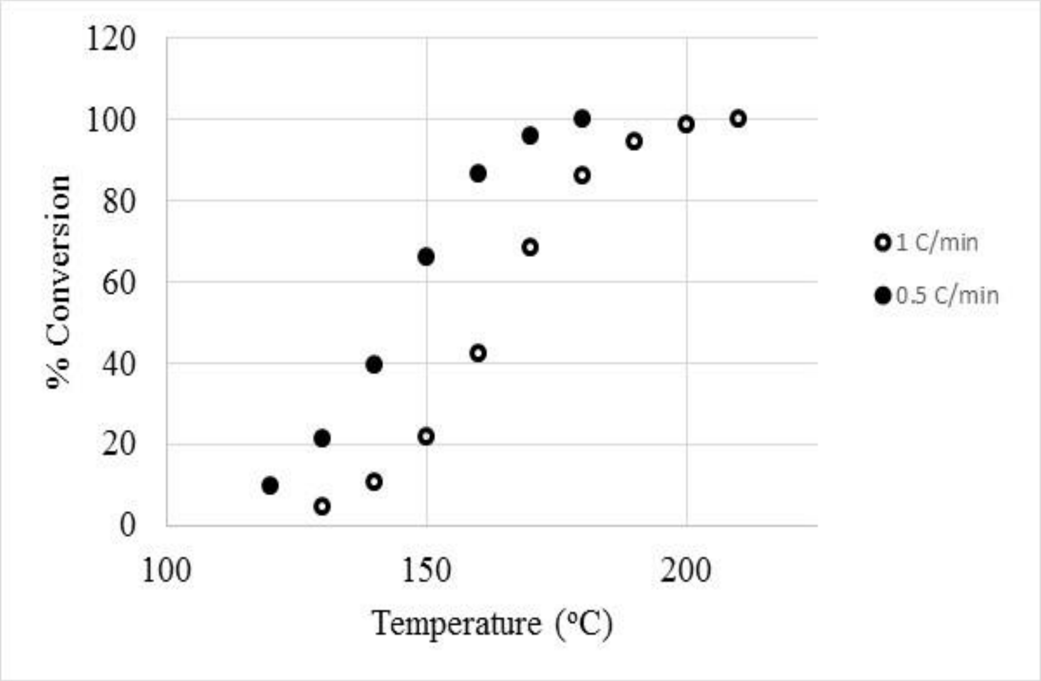




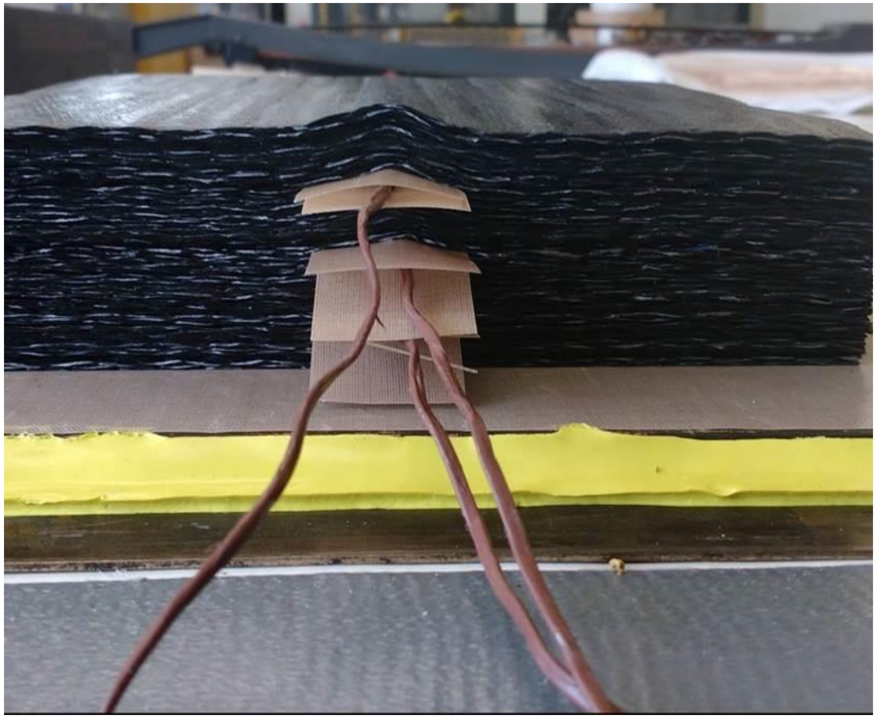
- Following a 0.5°C/minute ramp rate, the measured resin cure temperature is 158°C. Time to cure temperature is 265 min.
- Following a 1°C/min ramp rate the cure temperature is measured as 177°C and the time to cure is 152 min.
- A slower ramp rate leads to a relatively lower cure temperature, however the time required to cure is increased.

Prepreg Cure Characteristics- Conversion

- The DSC data illustrate a significant variation in the degree of cure with increasing ramp rate.
- The area under the exotherm was integrated to generate resin conversion curves as a function of temperature; $\alpha = \Delta HT/\Delta Hto_{tal}$
- Following a 1.1^{o}C/min ramp rate, a section of the panel reaching 180oC may be 85% cured, whereas a panel section lagging at 170^{o}C would have reached 68% conversion.
- As resin modulus increases with conversion, variation in cure state within a panel may lead to residual stresses and resin cracking in the final structure.



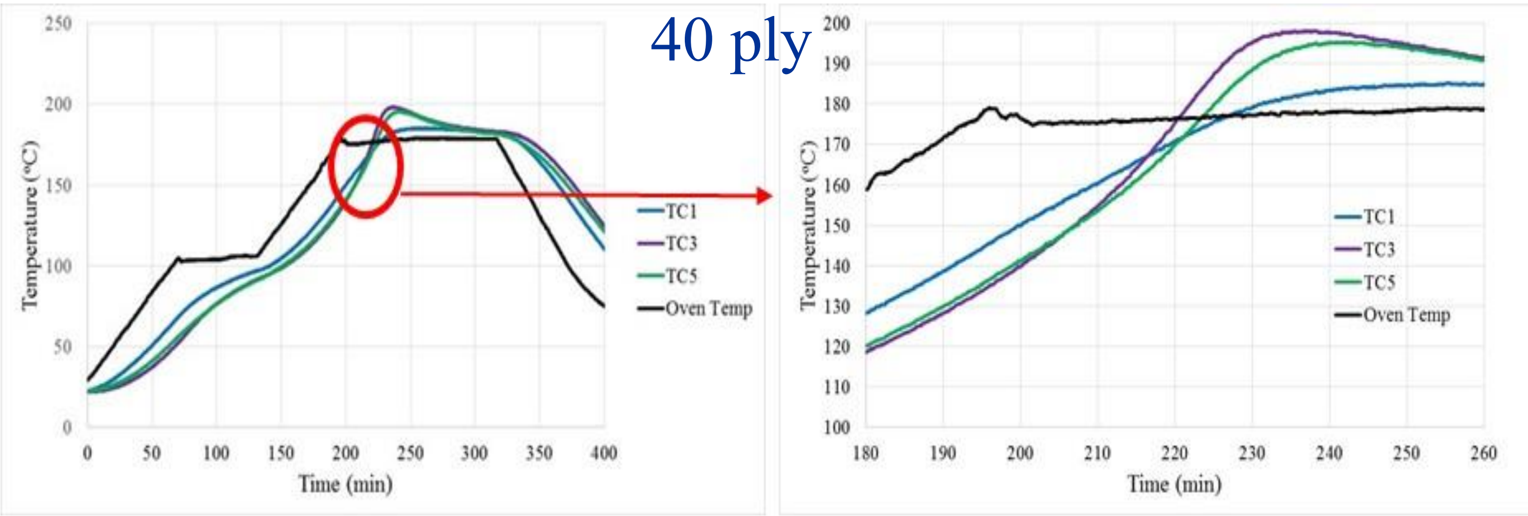
In-Situ Temperature Measurement

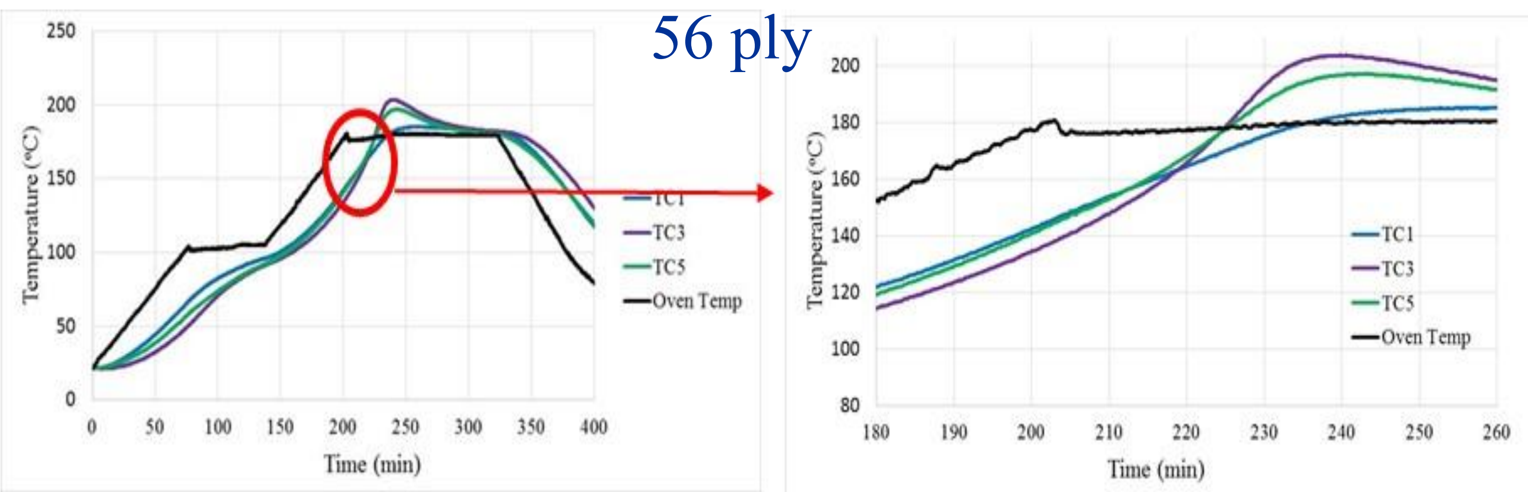


Thermocouples were chosen to provide reliable thermal data during cure.

Teflon release film was placed around the thermocouple to allow re-use.

In-Situ Temperature Measurement



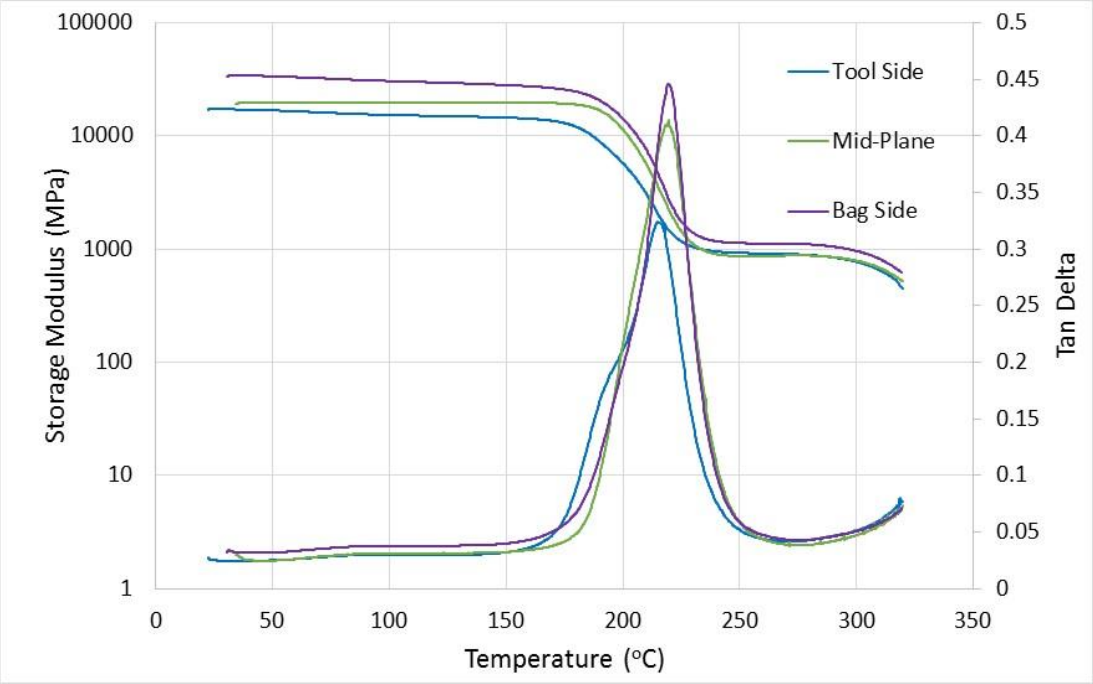


Conversion Estimates

Location	40 ply		56 Ply	
	Temperature (^oC)	Estimated Conversion (%)	Temperature (^oC)	Estimated Conversion (%)
TC1:Tool-Side	170	68	170	68
TC3: Mid-plane	180	85	180	85
TC5: Bag-Plane	170	68	180	85

- At the onset of vitrification, thermocouple data shows an accelerated ramp within the TC3 and TC5 regions of the laminate. An exotherm was recorded from both thermocouples for the thicker panels.
- In the thicker panel the TC3 and TC5 regions reach the 180^{o}C vitrification temperature ahead of the tool side.
- Following the conversion curve corresponding to a 1.1^{o}C/min ramp, an 85% degree of conversion can be assumed for the center and bag-side panel sections on reaching 180^{o}C. At this time in the cure cycle, a tool side temperature of 170^{o}C would correspond to 68% conversion.
- The variation in degree of cure could result in the development of residual stresses due to stiffness mismatch throughout the panel, ultimately impacting mechanical strength and dimensional tolerances.(16) The relative difference in conversion may also yield a gradient in thermal properties throughout the panel thickness.

Tg Data- Before and After Post Cure



Location	40 ply		56 Ply	
	Tg (°C) 2 hr. cure on tool	Post-cured (°C)	Tg (°C) 2 hr. cure on tool	Post-cured (°C)
Tool-Side	211	216	211	223
Mid-plane	213	217	223	225
Bag-Side	213	218	220	224

- The Tg was identified as the maximum of the tan delta peak and is listed following the 2 hour hold at 180°C and, separately, following an additional 1 hour, free-standing post cure at 180°C.
- The Tg measured for coupons taken from the 40 ply part was consistent throughout the panel thickness, and uniformly increased following post-cure.
- However, a variation in Tg was evident in the 56 ply, 1.5" part. Prior to post cure the tool-side Tg lagged that of the mid-plane by 12 degrees, and the bag side Tg by 9 degrees.
- The variation in Tg implies a stiffness mis-match would be in place for the part. The free standing post cure drove Tg of the tool side material up to match that of the remainder of the parts.

Compression Data- Before and After Post Cure

Compression tests were considered appropriate for this study as the compression strength is dominated by resin properties

Location	40 ply		56 Ply	
	Compression Strength (V) 2 hr. cure on tool	Compression Strength (V) Post-cured (°C)	Compression Strength (V) 2 hr. cure on tool	Compression Strength (V) Post-cured (°C)
Tool-Side	6.4 (0.3)	6.6 (0.5)	5.9 (0.6)	5.8 (0.5)
Mid-plane	6.2 (0.7)	6.8 (0.2)	5.3 (0.5)	5.4 (0.4)
Bag-Side	5.8 (1.1)	6.8 (0.4)	5.9 (0.6)	5.3 (0.6)

Compression strength remained consistent throughout the panel thickness, regardless of post-cure.

Summary

- The internal temperature of a series of carbon fiber/epoxy composites was measured throughout the cure profile.
- As panel thickness increased, internal temperature gradients were measured between the tool side plies and the remaining bulk of the composite.
- An increased ramp rate following vitrification for the center portion of the panel and was attributed to heat generated by the exothermic cure reaction.
- This heat was dissipated at the tool side due to the high thermal conductivity of the aluminum tool, resulting in the tool side segment receiving a lower degree of cure relative to the rest of the panel.
- Compression strength remained consistent throughout the panel thickness, regardless of post-cure.
- Post curing the panel equalized the thermal performance throughout the panel thickness. All measured variations in through thickness thermal and mechanical properties were relatively small, however may influence part dimensional stability for complex shapes.