List of Figures

Carbon fiber tows consist of thousands of individual fiber filaments. \ldots	9
Finite composite element that shows typical polymer matrix/fiber orientation.	11
The polymer matrix distributes shear stress along the fiber surface, creating	
an axial tensile stress within the fiber [8]	12
Test setup schematic for open-loop resistive heating with temperature mon-	
itoring	22
Resistive heating with temperature monitoring experimental setup	23
Thermocouple positioning without twisting (left) and with twisting (right).	
Notice how the tip of the thermocouple protrudes through the tow in the first	
picture. Twisting the samples helped to hold the thermocouple in a position	
to better measured internal temperature.	23
Current sensing circuit used to measure current flow and material resistance.	24
Post-processing circuit and associated equations for indirect current measure-	
ment	24
Signal conditioners used to measure and output temperature signals required	
for feedback control	25
Experimental schematic used for feedback temperature control	25
a. Simulink model created to house the temperature control algorithm (top).	
b. Temperature feedback control loop used to compute the corrective control	
voltage (middle). c. PID controller (bottom) located within the temperature	
feedback loop (b). \ldots	26
Typical temperature and voltage responses measured for an input voltage of	
10V	27
	Carbon fiber tows consist of thousands of individual fiber filaments Finite composite element that shows typical polymer matrix/fiber orientation. The polymer matrix distributes shear stress along the fiber surface, creating an axial tensile stress within the fiber [8]

2.10	$ Average \ temperature \ response \ of \ the \ sample \ for \ various \ input \ voltages \ (Run1=0.05) \ (Run1=0$	5V
	and Run20=10.0V)	29
2.11	Measured average maximum temperature per input voltage (a) and current	
	(b) applied	30
2.12	Material temperature exhibits a linear relation to electrical power. \ldots .	30
2.13	Measured heating and cooling time constants for open-loop resistive heating	
	tests	31
2.14	Sample resistance as a function of temperature	31
2.15	Power requirements measured during high-temperature, open-loop resistive	
	heating tests.	32
2.16	Open-loop control scheme [9]	33
2.17	Theoretical heating element used in developing a system model	34
2.18	Block diagram representation of the open-loop temperature controller	37
2.19	Block diagram of temperature control, via an open-loop controller	37
2.20	Simulated temperature response for an input of $6V$ and a temperature win-	
	dow of 10° C (left). Corresponding voltage signal generated to cause the	
	presribed heating (right).	38
2.21	Measured temperature response induced by the presribed voltage signal (left).	
	Comparison of the simulated temperature and the average measured temper-	
	ature (right)	39
2.22	Typical feedback control structure [9]	39
2.23	Transfer function for a PID controller	40
2.24	Representative temperature response taken during the implementation and	
	tuning of a PID controller	42
2.25	The first few attempts at selecting gains resulted in marginal control	43
2.26	Through a trial-and-error process, control gains that decreased the overshoot	
	(left) were chosen. Some temperature nonlinearities appear when the same	
	gains are used for a higher desired temperature (right)	43
2.27	Temperature dependent nonlinearities within the "plant" result in different	
	responses	44
2.28	Temperature response versus a varied proportional gain, K_p	45

2.29	By increasing K_i to a value of 0.05, the steady-state error disappears, but	
	the initial slope remains (left). Calculated initial slopes as a function of	
	increasing proportional gain solidifies its effect on the temperature response	
	(right)	46
2.30	Integral gain effects on controlled temperature response	46
2.31	The measured temperature response demonstrated a weaker dependence on	
	the value of the derivative gain at low levels of K_d	47
2.32	Ramping temperature responses measured for varying proportional gains	
	(left) and integral gains (right)	47
2.33	PI controller used to control temperature through a full, curing-schedule-type	
	profile (left). The associated error for the third combination of controller	
	gains as a function of time (right)	48
2.34	Temperature response measured for higher temperatures (left). Associated	
	electrical power and energy for each test (right).	49
2.35	Tracking ability of the PI controller for a high temperature "curing-type"	
	schedule	49
2.36	schedule. Controlled temperature (left) and resulting electrical power (right) measured	49
2.36	schedule. Controlled temperature (left) and resulting electrical power (right) measured for the cure of CFRP sample. Controlled temperature (left) and resulting electrical power (right) measured	49 50
2.36 2.37	schedule. Controlled temperature (left) and resulting electrical power (right) measured for the cure of CFRP sample. Controlled temperature Temperature profile (left) and dynamic error (right) measured during an	49 50
2.36 2.37	schedule. Controlled temperature (left) and resulting electrical power (right) measured for the cure of CFRP sample. Temperature profile (left) and dynamic error (right) measured during an actual curing schedule. Schedule.	49 50 51
2.362.372.38	schedule. Controlled temperature (left) and resulting electrical power (right) measured for the cure of CFRP sample. Temperature profile (left) and dynamic error (right) measured during an actual curing schedule. Infrared detection scheme as found in an Inframetrics 760 IR Camera [10].	 49 50 51 52
 2.36 2.37 2.38 2.39 	schedule. Controlled temperature (left) and resulting electrical power (right) measured for the cure of CFRP sample. Temperature profile (left) and dynamic error (right) measured during an actual curing schedule. Infrared detection scheme as found in an Inframetrics 760 IR Camera [10]. Experimental setup for thermographic imaging of CFRP samples during re-	49505152
 2.36 2.37 2.38 2.39 	schedule. Controlled temperature (left) and resulting electrical power (right) measured for the cure of CFRP sample. Temperature profile (left) and dynamic error (right) measured during an actual curing schedule. Infrared detection scheme as found in an Inframetrics 760 IR Camera [10]. Experimental setup for thermographic imaging of CFRP samples during resistive heating. Schedule.	 49 50 51 52 54
 2.36 2.37 2.38 2.39 2.40 	schedule.Controlled temperature (left) and resulting electrical power (right) measuredfor the cure of CFRP sample.Temperature profile (left) and dynamic error (right) measured during anactual curing schedule.Infrared detection scheme as found in an Inframetrics 760 IR Camera [10].Experimental setup for thermographic imaging of CFRP samples during resistive heating.Measured temperature responses (left) and associated electrical power supply	 49 50 51 52 54
 2.36 2.37 2.38 2.39 2.40 	schedule.Controlled temperature (left) and resulting electrical power (right) measuredfor the cure of CFRP sample.Temperature profile (left) and dynamic error (right) measured during anactual curing schedule.Infrared detection scheme as found in an Inframetrics 760 IR Camera [10].Experimental setup for thermographic imaging of CFRP samples during resistive heating.Measured temperature responses (left) and associated electrical power supply(right).(right).	 49 50 51 52 54 54
 2.36 2.37 2.38 2.39 2.40 2.41 	schedule.Controlled temperature (left) and resulting electrical power (right) measuredfor the cure of CFRP sample.Temperature profile (left) and dynamic error (right) measured during anactual curing schedule.Infrared detection scheme as found in an Inframetrics 760 IR Camera [10].Experimental setup for thermographic imaging of CFRP samples during resistive heating.Inframetrics 760 IR Camera [10].Measured temperature responses (left) and associated electrical power supplyInfraft, and associated electrical power supplyStill images captured for various lengths at a temperature of 60°C.Infrare	 49 50 51 52 54 54 55
 2.36 2.37 2.38 2.39 2.40 2.41 2.42 	schedule.Controlled temperature (left) and resulting electrical power (right) measuredfor the cure of CFRP sample.Temperature profile (left) and dynamic error (right) measured during anactual curing schedule.Infrared detection scheme as found in an Inframetrics 760 IR Camera [10].Experimental setup for thermographic imaging of CFRP samples during resistive heating.Inframetrics 760 IR Camera [10].Measured temperature responses (left) and associated electrical power supplyInfrate of 60°C.Still images captured for various lengths at a temperature of 60°C.Inframetrics (right) via IR image	 49 50 51 52 54 54 55
 2.36 2.37 2.38 2.39 2.40 2.41 2.42 	schedule	 49 50 51 52 54 54 55 55
 2.36 2.37 2.38 2.39 2.40 2.41 2.42 2.43 	schedule	 49 50 51 52 54 54 55 55

2.44	Electrical power and sample resistance (left) and thermographic imaging	
	(right) of twisted samples. As the number of twists increased, the resis-	
	tance and electrical power decreased, but temperature distribution remained	
	"even."	57
2.45	Temperature gradient obtained on a sample during resistive heating \ldots .	58
2.46	Temperatures measured by small and large thermocouples on the same sam-	
	ple differed drastically	59
3.1	Spread tow line and re-spooled coated tow.	63
3.2	DSC measured on virgin U-Nyte Set 201B resin (exotherm down)	64
3.3	a. Cure temperature characterization results (exotherm up) on the U-Nyte	
	Set 201A resin (left). b. Rheology results on this resin illustrate a significant	
	increase in viscosity at a gel temperature of 180° C (right)	64
3.4	Experimental setup for measuring the bending stiffness of heated samples	66
3.5	Two thermocouples were used to measure the sample temperature for full-	
	scale rigidization testing	67
3.6	Instrumented design for measuring bending force and deflection. \ldots .	68
3.7	Instrumented test fixture shown with a hardened tow sample	68
3.8	Undeflected and deflected composite sample prior to resistive heating (left)	
	and the same sample after resistive heating (right)	70
3.9	Deflected composite sample modeled as a string	70
3.10	Tension forces, F_1 and F_2 , arise within the material as a result of the applied	
	load, W	71
3.11	Raw data obtained from inducing transverse deflection at the midpoint of	
	the fixed sample.	74
3.12	The remaining data only captured the deflected state of the sample (left).	
	Hysteresis in the measurement appears when including the unloading data	
	(right)	74
3.13	Typical force versus deflection data obtained for the transverse deflection of	
	a rigidized sample.	75
3.14	First and second-order polynomial fits were applied to force versus deflection	
	data	76

3.15	Instantaneous slopes were used to quantify the stiffness of a sample. \ldots	77
3.16	Typical curing profile (left) and specific profiles designed from DSC data on	
	the U-Nyte Set resins (right).	78
3.17	Actual temperatures measured during the cure of a U-Nyte Set 201B-coated	
	sample (left). Electrical power and total consumed energy were also recorded	
	for this process (right)	78
3.18	Incorporating a $f\!low$ region into the temperature profile caused the U-Nyte	
	Set resin particles to melt fully during their curing cycles	79
3.19	Bending stiffness comparison of rigidized tow samples	79
3.20	Post-rigidization DSC analysis indicates that both resins fully cured through	
	resistive heating.	80
3.21	Resin weight loss measured as a function of temperature determines its userful	
	range	82
3.22	Heating schedules used to measure the effect of cure temperature on sample	
	stiffness.	83
3.23	Stiffness and energy data (left) and DSC plots (right) for samples cured at	
	various curing temperatures	83
3.24	Successfully rigidizing composite materials requires a combination of consol-	
	idation and curing	84
3.25	Normalized measured stiffness values with respect to expended energy	85
3.26	Heating schedules used to test the effect of curing time on the composite	
	stiffness.	86
3.27	Measured stiffness (left) and DSC plots (right) for each sample	86
3.28	The cost of rigidization can be visualized by normalizing the stiffness values	
	per applied electrical energy.	87
3.29	Samples were prescribed heating rates ranging from 30° C/min to 120° C/min	
	in this study	88
3.30	Measured stiffness and energy (left) along with normalized measured stiff-	
	nesses for samples cured at varying heating rates	88
3.31	Measured and desired temperature signals for the maximum heating rate	
	tested of 120° C/min	89

4.1	The inflatable structure shown partially completed	93
4.2	The completed "inflatable" boom before applying rigidizable CFRP material.	94
4.3	Three test configurations were used to evaluate possible techniques for incor-	
	porating rigidizable materials onto the boom	95
4.4	The boom's resistance to bending/buckling was measured in a cantilevered	
	configuration.	96
4.5	Thermal imaging of a coated fiber tow sample with Kapton laminate. $\ . \ .$	97
4.6	$Successful \ matrix \ consolidation \ and \ material \ rigidization \ occurred \ in \ all \ three$	
	configurations.	98
4.7	Internal resistive heating of the inflatable, rigidizable boom	99
4.8	The resistive heating schedule selected was based on successful results from	
	previous sample tests.	99
4.9	The rigidization process drastically increased the load bearing capacity of the	
	boom	100