Chapter 4

Toward Rigidization of Inflatable Structures

Active rigidization of a simple structure demonstrates how internal resistive heating can be applied to cause permanent physical strengthening of inflatable structures. Rigidizing a real structure brings to light the issues associated with incorporating the rigidizable resin-coated tow onto a separate substrate and provides a useful example of the strength gained through effective rigidization. Using the aforementioned temperature-controlled resistive heating approach and curing profile, a cylindrical tube will be stiffened with U-Nyte Set 201B/carbon fiber composite tow.

The main objective of this chapter is to investigate the use of this particular rigidization technology on a small scale and simple approach to stiffening inflatable structures. The incorporation of the CFRP material into systems of other materials is considered and additional IR testing of these samples is used to show that changing the boundary conditions affects the thermal gradient near the resin/fiber composite. A miniature "inflatable, rigidizable boom" is constructed in order to demonstrate controlled rigidization through resistive heating. The boom is compared to its pre-hardened state and the change in material properties are quantified through the cantilevered bending stiffness of the boom. Lastly, the cost of rigidization is evaluated per amount of resin-coated fiber tow used.

4.1 Boom Construction and Experimental Setup

A miniature inflatable boom was chosen to represent the validity of this rigidization method due to its prominence in space structures. Inflatable booms, or tubes, can be combined to form bundled tubes and trusses [52], are used to support the Inflatable Sunshield In Space (ISIS) [53], and make up the supporting strut system of many inflatable antenna and solar concentrators [18]. In defining the success of such a demonstration, a boom was constructed such that it could be given shape via an internal inflation pressure, combined with the rigidizable fiber tow, and permanently rigidized via temperature-controlled internal resistive heating.

4.1.1 Materials

The fabrication of the boom began with the selection of a lightweight, flexible substrate that can be folded and inflated (i.e. airtight), that has a low thermal and electrical conductivity, and that is capable of withstanding the high-temperature curing environment of the resistive heating process. A polyimide film, Kapton 200HN (50-micron, 2-mil thickness) was chosen for this role. This space-durable material, which is popular in the fabrication of many inflatable space structures, is also used in circuit board, wire, and capacitor insulation.

Table 4.1: Material properties for Kapton [7] and CFRP [4, 5] components.

Kapton 200HN Polyimide Film		Toho Besfight G40-800 12k Carbon Fiber		U-Nyet Set 201B Reactive Epoxy Binder	
Density (g/mL)	1.42	Density (g/mL)	1.79	Viscosity (cP)	1200-2000
Yield Strength (MPa)	69	Fiber Count (dtex)	4200	Glass Transition Temperature (˚C)	62-65
Electrical Resistivity (W-cm)	1.50E+17	Ultimate Tensile Strength (GPa)	5.58	Cured Glass Transition Temperature (˚C)	108-110
Heat Capacity (J/g-˚C)	1.09	Tensile Modulus (GPa)	286	Onset of Cure (˚C)	100-120
Thermal Conductivity (W/m-K)	0.12	Elongation (%)	1.95	Peak Cure Temperature (˚C)	150
Maximum Service Temperature, Air (℃)	400	Electrical Resistivity (Ω-cm)	0.0014	Particle Size (μm)	~200
Minimum Service Temperature, Air (℃)	-269	Thermal Conductivity (W/mK)	10	Specific Gravity (g/mL)	1.2

The rigidizable material used on the boom is carbon fiber tow, Toho Besfight G40 − 800 12K, coated with Hydrosize's U-Nyte Set 201B thermoset epoxy resin. Extensive heating and stiffening studies on samples of this material were addressed in Chapters 2 and 3. As before, this material was prepared using a "pre-pregging" system developed at Virginia Tech.

4.1.2 Boom Fabrication

The inflatable boom was constructed using a 4-in by 7-in piece of Kapton, two 1-in PVC endcaps, one 1/8"-27 NPT pipe thread-to-3/16" tube nylon fitting, and 1/4-inch wide

Kapton tape. First, a 21/64-in hole was drilled through the end of one of the endcaps and then threaded by hand using a 1/8"-27 tap. The threads of the tube fitting were wrapped in 1/4-in poly(tetraflouroethylene) (PTFE or Teflon) tape for airtightness and the fitting was threaded into the PVC endcap. The Kapton was then taped to the outside of one endcap, wrapped completely around it (with the 7-in length of Kapton providing the length of the boom) and taped to itself (Figure 4.1). A 1/2-in overlap of Kapton resulted. The opposite end of the Kapton sheet was taped to the second endcap in a similar fashion. Lastly, a piece of Kapton tape was placed down the length of the boom to seal the overlapping Kapton seam and also used to seal the endcap/Kapton junctions at each end. The finished product measured 19.0cm ($7 - 1/2$in) long with a diameter of 2.54cm (1in) (Figure 4.2). Inflation of the structure was applied via a Whisper 800 aquarium pump that supplied roughly 1 psig to the internal chamber of the boom. Though not shown, this pressure provides shape-holding to the structure and can transform the boom from an initially compacted state (i.e. for space launch packaging) to its full geometry (upon deployment on orbit).

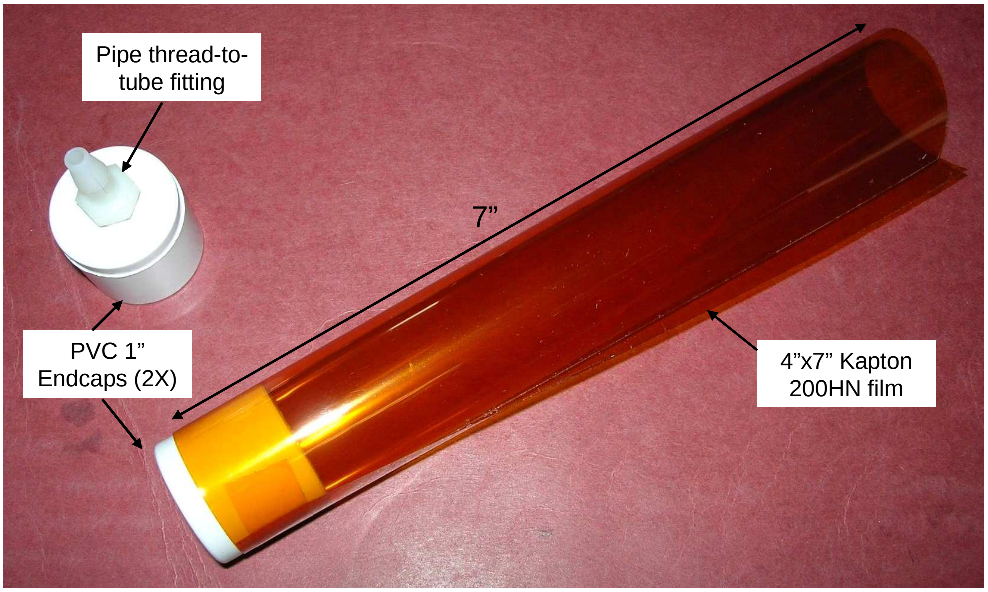

Figure 4.1: The inflatable structure shown partially completed.

The resin-coated fiber tow must also be incorporated onto the boom in order for this structure to be rigidizable. Many current structures that benefit from carbon fiber reinforcement take advantage of woven carbon fiber fabrics [54]. These fabrics provide carbon fiber strength in many directions and their patterns include both biaxial and triaxial weaves. However, due to the unavailability of such a weave, the issue of applying a resin-

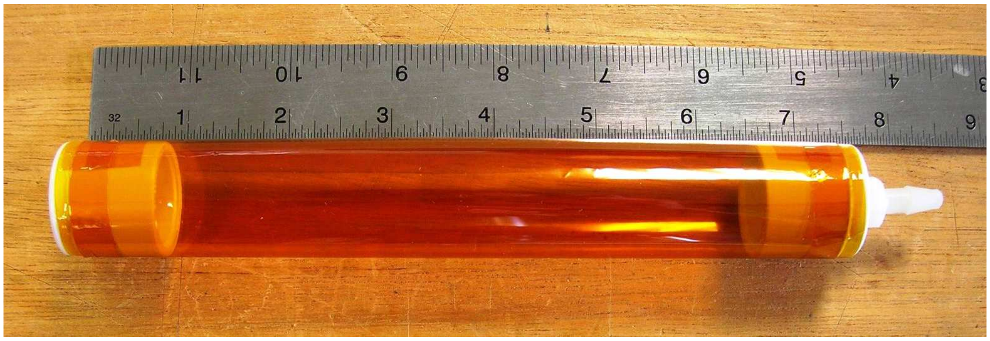

Figure 4.2: The completed "inflatable" boom before applying rigidizable CFRP material.

coated fiber tow was investigated. Specifically, a method of applying such a material to the boom in order to give it strength through the resistive heating process is required. Since the rigidity of the material was previously measured (Chapter 3) by the increased bending stiffness of the samples, the strength of the boom will also be quantified with respect to its change in bending stiffness. The orientation of the applied tow must be such that it strengthens the underlying structure in this direction.

4.1.3 Experimental Procedure

In order to provide increased structural rigidity and strength, the resin-coated fiber tow must be physically adhered to the inflatable boom. Possible solutions included wrapping the boom with the tow, taping a piece or pieces of the tow to the boom, or laminating the tow between layers of Kapton. The effects of this change of boundary conditions was considered prior to attempting boom rigidization. Coupon testing on small samples of both the fiber tow and Kapton was performed in order to evaluate the ability for the CFRP material to rigidize in different environments and configurations. Infrared (IR) imaging was also used to look at the thermal effects of changed boundary conditions during internal resistive heating schedules.

Considering that the resin-coated fiber tow would be either taped down to the Kapton or laminated between pieces of Kapton, samples representing each configuration were prepared. As before, the rigidizable material was 15 – 20cm (6 – 8in) of U-Nyte Set 201B resin-coated carbon fiber. These samples were pulled tight (slightly), twisted, and fixed on each end. Two 36-gauge J-type thermocouples were used to measure the sample temperature at separate locations. The temperature-control system, as discussed in Chapter 2, consisted of a proportional-integral (PI) temperature feedback controller. The samples were prescribed a curing schedule that included a constant heating rate of 30^{o}C/min, 5 minutes at a flow temperature of 85^{o}C, and 10 minutes of curing at 150^{o}C. Knowing that this curing profile previously resulted in fully-cured, rigidized samples, it was selected for this study as well. The configurations of interest for this test included a laminated sample, one that was taped to the surface of Kapton, and a longer piece of coated tow arranged in more-complex zig-zag pattern.

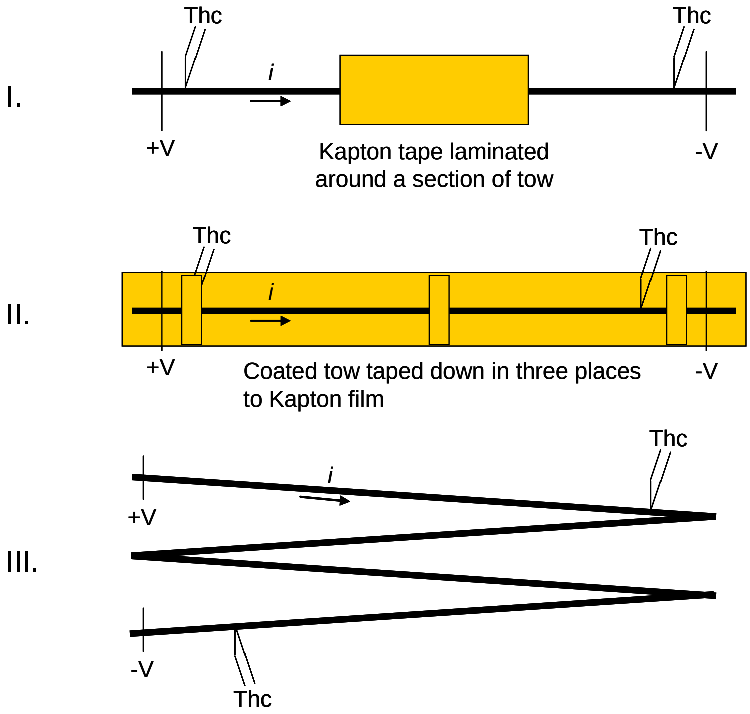

Figure 4.3: Three test configurations were used to evaluate possible techniques for incorporating rigidizable materials onto the boom.

These samples were evaluated in two ways: During their respective curing schedules, thermographic imaging with a Flir ThermaCAM EX320 infrared camera was used to look at thermal effects of various boundary conditions. Then, each rigidized sample was judged on evenness of resin consolidation and the resulting sample stiffness (qualitative). Observations for each sample test were noted with respect to their possible use on the inflatable boom.

Results of these experiments led to the application and rigidization of the inflatable boom. Evaluating the stiffened structure was then carried out by fixing the boom in a cantilevered configuration and measuring the maximum tip load that could be successfully carried by the rigidized boom without buckling. A clamp was used to fix one end of the

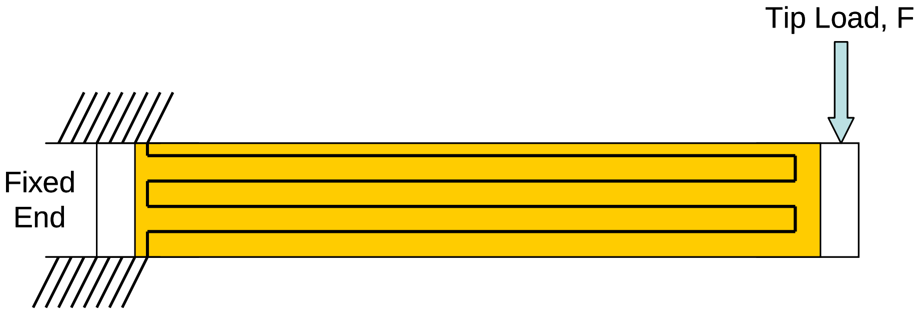

Figure 4.4: The boom's resistance to bending/buckling was measured in a cantilevered configuration.

boom at the endcap location. Then, a string of known weights were hung from the free end of the boom. The stiffness of the structure was measured with the CFRP tow applied both before and after rigidization. Since rigidization is designed to give the boom permanent shape/strength, the inflation pressure is no longer required. Similarly, the strength of the boom was measured without the aide of internal air pressure. In this test, the increase in load bearing capacity due to rigidization was quantified. The energy expense of this process was also quantified per amount of material rigidized and per increase in strength.

4.2 Experimental Results and Discussion

Coupon testing, which was designed to test methods for incorporating resin-coated fiber tow on to the boom, was performed on three different configurations (Figure 4.3). Infrared testing and qualitative analysis of these samples were used to gather evidence of successful rigidization. From these results, the inflatable boom was rigidized using internal resistive heating and curing profiles developed for samples of U-Nyte Set 201B resin-coated fiber tow. The added strength due to this rigidization process was deduced through simple measurements of the load bearing capacity of the boom in a cantilevered configuration.

4.2.1 Coupon Testing Results

Each of the three sample configurations that were attempted produced rigid materials. In the first case, a section of the coated tow was "laminated" with a piece of Kapton tape. The Kapton tape, though it has a small thermal conductivity (0.12 W/m-K, compared with 177 W/m-K for aluminum), conducted heat from the fiber tow during rigidization. Infrared imaging of this sample produced noticeable differences in thermal gradient at the location of the Kapton tape. However, the sample rigidized successfully, even in the laminated region.

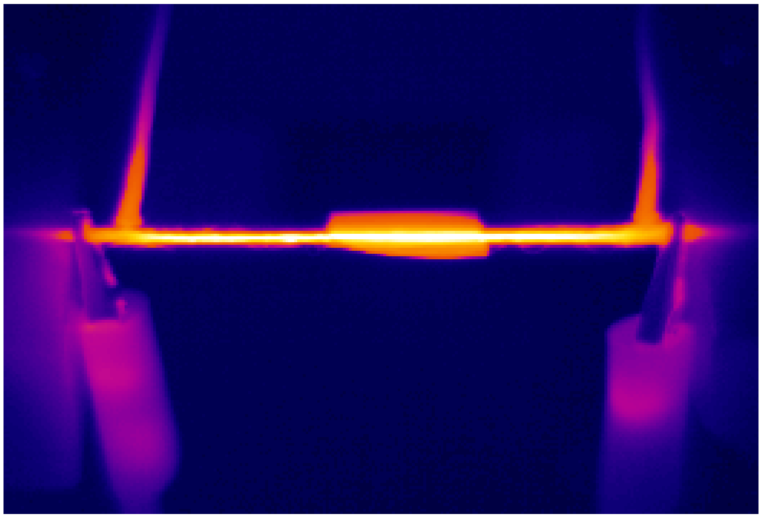

Figure 4.5: Thermal imaging of a coated fiber tow sample with Kapton laminate.

It was noticed that the resin powder consolidated during the resistive heating schedule and that the material was much stiffer than before. In the taped area, the Kapton cause the fiber tow to be smashed slightly, changing its cross-sectional area. Because of the flattening effect, the sample seemed to be less resistant to bending in this region.

The second sample (Figure 4.6), one in which a length of coated tow was taped with Kapton tape to an underlying piece of Kapton film, also rigidized well. The resin again consolidated during the cure schedule, producing a stiff composite sample. The Kapton tape, due to its high service temperature resisted delamination and visually seemed unaffected. Excess resin from the fiber tow provided additional adherence to the Kapton film. Further, because the taped areas were smaller than the laminated area in the first configuration, changes to the composites cured strength were less noticeable.

Lastly, the serpentine, or zig-zag, sample rigidized evenly on each segment of its path. It was noticed for this sample that the bends in the sample also caused changes in stiffness. The resin consolidated fully in these areas, but because the sample was wrapped around insulated posts, the local geometry was affected much like in the laminated case. Otherwise, this configuration produced a successfully rigidized, cured sample.

The curing energy densities of these configurations were compared to that of a typical sample with no Kapton present. The second configuration required only 7000W-hr/kg to

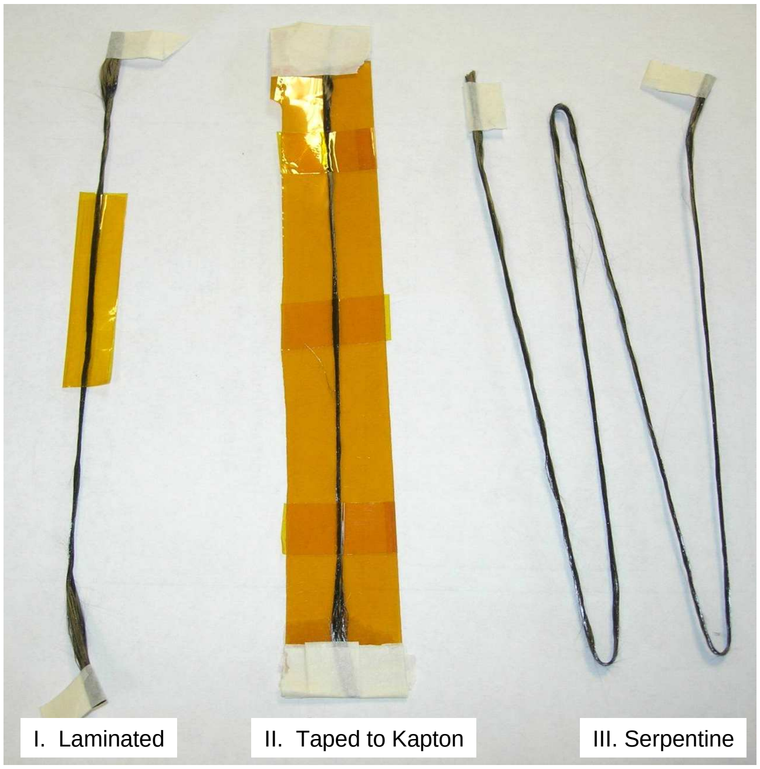

Figure 4.6: Successful matrix consolidation and material rigidization occurred in all three configurations.

Table 4.2: Boundary Condition Effects on Energy Consumed

Configuration	Fully exposed to the air	Taped to Kapton in three places with Kapton tape	Serpentine path, exposed to air
Length of Coated (cm)	16.5	16.5	55.9
Mass of Sample (g)	0.133	0.133	0.45
Total Time (sec)	1452	1452	1452
Ppeak (W)	5.3	4.18	17.22
Energy (W-hr)	1.03	0.93	3.65
Energy Density (W-hr/kg)	7800	7000	8100

prescribe the same curing profile as the exposed samples (which required roughly 8000W-hr). This reduction in curing energy required can be attributed to the presence of the insulating Kapton substrate. This material lowers the amount of heat lost to convection, thereby requiring less electrical energy to increase the temperature of the material.

4.2.2 Boom Wrapping and Rigidization

Using a path similar to that shown in the third coupon test configuration, coated fiber tow was taped to one end of the boom. The tow was pulled taut, twisted a few times, and then fixed to the opposite end with Kapton tape. Using tape as a pivot point, the direction was then reversed and the coated tow was pulled back toward the first end of the boom. This process was repeated around the circumference of the boom, creating seven individual segments of rigidizable tow affixed to the boom. The midpoints of each segment were then taped to the Kapton substrate to increase adherence to the structure.

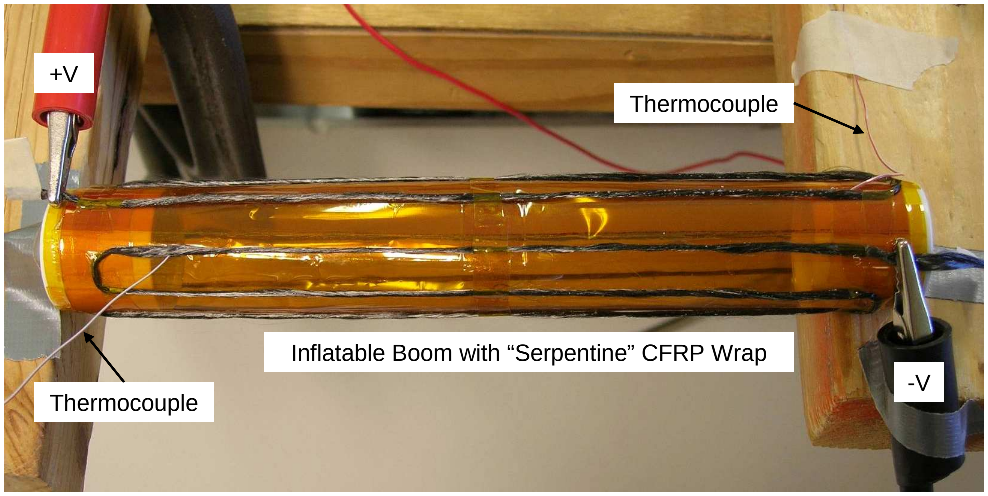

Figure 4.7: Internal resistive heating of the inflatable, rigidizable boom.

The resistive heating cure schedule prescribed consisted of curing the boom at 150^{o}C for 10 minutes, following an initial 5-minute resin melting period at 85^{o}C. This schedule was first evaluated in Chapter 3 on smaller samples that exhibited both significant increases in rigidity and complete cure. Since more material was used, rigidizing the boom required more energy. This specific curing profile demanded 4.8W-hr of energy with roughly $20 - 25$W of power at required at the curing temperature.

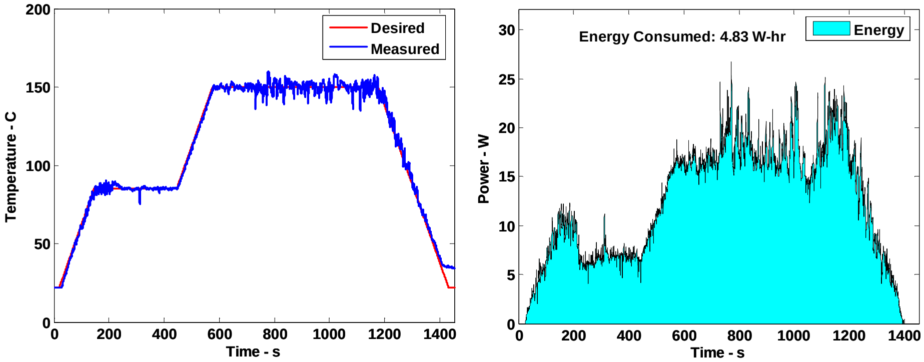

Figure 4.8: The resistive heating schedule selected was based on successful results from previous sample tests.

4.2.3 Increased Boom Strength

Prior to rigidizing the inflatable boom, its strength was quantified as the maximum tip load that the structure could carry when placed in a cantilevered configuration. Using a string of known weights, the load was increased until the boom buckled. Since this test was performed without supplying an internal air pressure to the boom, its inherent strength was due the Kapton holding its cylindrical shape. It should be noted that with an internal pressure, the boom was expected to carry more weight. However, since these structures are typically rigidized and their inflation pressures are then removed, the strength of the boom before and after rigidization was compared without using any air pressure.

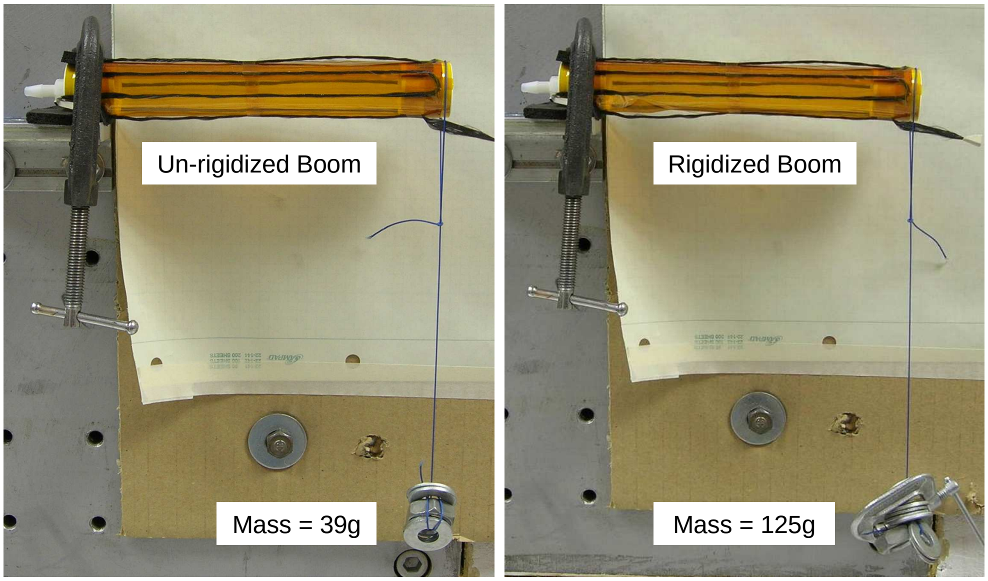

Figure 4.9: The rigidization process drastically increased the load bearing capacity of the boom.

The un-rigidized boom withstood a tip load of 39g, though it failed when loaded with 47g. The rigidization process increased this capacity for the boom. Post-rigidization, the boom held a load of 125g and eventually failed at roughly 127g. Using internal resistive heating and the described curing schedule, the inflatable boom was able to carry three times as much load. The cost of this increase came at the expense of roughly 127cm (50in) of coated fiber tow. The electrical resistance for this conductive path measured 76.2Ω prior to heating. As shown in Figure 4.7, 4.83W-hr of energy was used over a total curing time of approximately 24 minutes.

In contrast to the required energy-density value reported in Chapter 3, the rigidiza-

Table 4.3: Boom Rigidization Evaluation

Maximum carried load (un-rigidized state)	40	g
Maximum carried load (rigidized state)	125	g
Percent Increase	213%	g
Curing Energy Expended	4.8	W-hr
Peak Power	~25	W
Length of Rigidizable Material	127	cm
Mass of Rigidizable Material	1.02	g
Volume of Rigidizable Material	375	mL

tion of this boom consumed less energy per mass of rigidizable material. The values in Table 4.3 indicate that 127cm of rigidizable material consumed roughly 4800W-hr/kg, compared with 8000W-hr/kg for the shorter, $15-20$cm samples. The presence of the Kapton substrate, an insulating material, could be influencing the energy requirement of the heating process. If more heat is held close to composite and less is lost through convection to the air, then possibly lower amounts of energy are required to heat and maintain the necessary temperatures. This specific trait is seen in Figure 4.7, where the power supplied to the material decreases to maintain a temperature of 85^oC within the composite. Furthermore, infrared testing of a sample laminated with Kapton demonstrated a more-gradual temperature gradient at the boundary of the composite tow than for the exposed portion of the sample. Since heat loss from the composite is proportional to the magnitude of the gradient, Figure 4.5 and Table 4.2 demonstrate that the Kapton reduces heat loss during the heating cycle.

4.3 Conclusions

This chapter investigated the use of internal resistive heating to cause permanent shape holding and structural rigidity in a real structure. A small scale (2.54cm (1in) in diameter, 19.0cm (7.5in) in length) cylindrical boom was constructed from Kapton film, PVC endcaps, and U-Nyte Set 201B resin-coated fiber tow. Knowing that the rigidizable material must be physically applied to the inflatable structure, several Kapton/CFRP tow configurations were evaluated with coupon testing. From these results, a method for adhering this material to the boom was developed. Using roughly 127cm (50in) of the coated tow, a single conductive path of material was taped in a back-and-forth pattern down the length of the boom. The rigidization of the boom, through temperature-controlled resistive heating, produced a structure that was three times as resistant to bending in a cantilevered configuration. In addition, it was seen that this rigidization process required 40% less energy per amount of rigidizable material (4800W-hr/kg) than for individual samples of the coated fiber tow (8000W-hr/kg). This decrease in required energy density may in fact be attributed to the change in boundary conditions near the composite. The presence of an insulating material, such as Kapton, increases the amount of heat retained in the material and requires less energy to maintain a desired temperature. It is further speculated that creating a fully-laminated, mulilayered composite structure could reduce the curing energy even more.

The testing and methodology presented in this chapter took a simple approach to creating an "inflatable, rigidizable" structure. Though crude in its fabrication, selection of materials, and method for applying the rigidizable material to the boom, this study succeeded in demonstrating that internal resistive heating can be used to strengthen structures. In the event of using a woven carbon fiber fabric, both the energy required (due to a much higher electrical resistance) and the strength gained through rigidization are expected to increase substantially.