# Chapter 5

# Conclusions

The use of internal resistive heating has proven a viable technique for matrix consolidation and composite rigidization. The results of this study progressed from initial resistive heating tests to the controlled rigidization a real structure. Specific accomplishments and contributions that have stemmed from this research are discussed below and followed by recommendations for continued work in this field.

## 5.1 Accomplishments and Contributions

- *Temperature-controlled resistive heating was established on thermoset resin-coated carbon fiber tow.* The work presented in Chapter 2 focused on using resistive heating to increase the temperature of a carbon fiber tow. Based on the foundations established by Ohm and Joule, electric current was passed through a segment of conductive, resistive carbon fiber tow in order to generate heat. Temperatures measured via thermocouples recorded proof that resistive heating in carbon fiber tow was plausible and significant. Predictive temperature control, which requires precise knowledge of material properties and other system variables, produced marginal temperature control results. Feedback temperature control, using a proportional-integral (PI) controller, avoided this issue and provided accurate temperature control. The control gains of this controller were developed through experimental tuning and found to accurate track a varying desired temperature signal. Work from this chapter preceded the use of internal resistive heating to cause material rigidization and was crucial in establishing a repeatable heating method for this purpose.

- *Curing schedules designed from thermal analysis were prescribed via internal resistive heating in order to cause matrix consolidation and composite rigidization.* In Chapter 3 the results of differential scanning calorimetry (DSC) and parallel plate rheology tests were used to design curing profiles for two different versions, 201A and 201B of U-Nyte Set thermosetting resin. This thermal analysis allowed for specific curing parameters such as cure temperature, curing time, heating rate, and flow regions to be intelligently selected. Desired temperature profiles were then created and prescribed to samples of carbon fiber tow coated with each resin. The cure completion and mechanical rigidity of the heated samples were then analyzed with DSC and an instrumented test fixture, respectively. The results indicated that with proper selection, the matrix resin underwent consolidation and complete curing during the heating schedule, producing a sample with as much as 20 times the original bending stiffness. This transformation required roughly 1W-hr of energy with 5W of peak power over the course of a 24-minute curing schedule.

- *The mechanical rigidity of the cured samples was correlated to cure parameters such as temperature, time, and heating rate.* Focusing in on just one of the thermosetting resins, U-Nyte Set 201B, work was performed to gauge the sensitivity of various cure parameters to cure completion and rigidity of the heated samples. These tests involved varying parameters such as the cure temperature, curing time, and heating rate in order to produce significant stiffening and complete curing with minimal electrical energy and process time. By combining thermal analysis with mechanical stiffness measurements, it was determined that structural rigidity and resin curing are not synonymous. A study in which samples were prescribed varying curing temperatures illustrated fully the idea that in order to achieve maximum stiffness, the resin must first melt and consolidate around the fibers. It is then that the formation of cross-linking bonds can adequately transfer load to the reinforcing fibers. It was also determined that the curing energy and time could be further reduced by varying the curing time and heating rate of a heating profile.

  The cure temperature study demonstrated again that bending stiffness values $18-24$ times that of the original material could be achieved by curing the material at $150^o$C and above. These samples, which consumed $1-1.4$W-hr of energy with $5-8$W of peak power, were held at their respective curing temperatures for 10 minutes (24-minute total heating schedule). The curing time study illustrated that samples cured at $150^o$C for even 1 minute experienced an equivalent increase in stiffening but only were partially cured. The reduced curing time required 50% less electrical energy and 37% less total time than for a 10-minute curing temperature dwell time. Energy-normalized stiffness values for both of these tests further emphasized the "cheapest" rigidization could be achieved in samples that were not fully cured. Material consolidation was also verified for various heating rates, with 20% savings in curing energy and time for samples heated at a rate of $120^o$C/min (compared with $30^o$C/min). Overall, this method requires roughly 8000W-hr/kg of energy to transform initially flexible composites into structurally stiff materials.

- *Rigidization via this technique was demonstrated and quantified on a small, scale inflatable boom.* Chapter 4 investigated the application of resistive heating to cause mechanical stiffening of a real structure. U-Nyte Set 201B resin-coated tow was applied to the outside of a 19.0cm (7.5in) inflatable boom made from Kapton 200H polyimide film and PVC endcaps. The strength of the boom was quantified as the maximum tip load that it could bear without buckling when fixed in a cantilevered configuration. Prior to rigidization the boom withstood a 40g-load. In contrast, the rigidized structure was able to carry three times as much, successfully supporting 125g. A comparison of the energy consumed per mass of rigidizable material illustrated that insulating boundary conditions retain heat and reduce the energy required to follow a prescribed curing schedule. The energy density required by the boom was substantially (40%) less than that required to rigidize a sample fully exposed to air. Though crude in fabrication, the boom illustrated that the *in situ* strengthening of a real structure can be attained with even a small amount of rigidizable material.

## 5.2 Recommendations for Continued Work

- *Apply internal resistive heating to woven carbon fiber fabrics.* Extending the concepts of this research to a more useful method would require the ability to use a woven carbon fiber fabric. In describing one of the weaknesses of the boom testing in Chapter 4, it was noted that a woven fabric would provide increased material strength in more than one dimension. This fabric could be incorporated into the design of an inflatable, rigidizable structure either as an exterior material or laminated between layers of either Kapton or Mylar. The change in going from one-dimensional segments of coated tow to a two-dimensional fabric, however, may require additional study of the heating process itself as well as how best to apply temperature control. Feedback temperature control, as was used through this work, would still provide an active approach to rigidization, though applying the control signal (i.e. the physical connection) and the temperature measurement method may need more attention.

- *Modify the "pre-pregging" system in order to improve powder-coating consistency and increase resin concentration on the fibers.* The ability to accurate control the distribution (i.e. amount and evenness) of the thermosetting resin in these composites provides an additional tool for optimizing this method. One of the unavoidable inconsistencies experienced through this research has been that of the fiber tow "pre-pregging," or resin-coating, process. The system developed at Virginia Tech, which can be described as an *art* more than a *science*, included hand-sprinkling the resin powder onto the fiber tow. As a result, the coated tow depended on the ability of the "coater" to evenly distribute the resin. Additionally, as it was seen in comparing the U-Nyte Set 201A and 201B resins, particle size affected how much of the resin stuck to the tow as well as how well the particles melted and flowed during matrix consolidation. A consistent and small particle size may offer a solution to more repeatable rigidization. Other powder-coating techniques, such as electrostatic charging, may provide a more-even resin distribution. Powder Coating Composites from Israel, offers the ability to electro-statically "powder-preg" carbon fiber tows and fabrics. Their patented process can coat one or both sides of the material, with one or two different resin powders, and of varying concentration ($2 - 95\%$).

- *Optimize the material properties of both the matrix resin and the carbon fiber reinforcement.* A different approach to making rigidization through resistive heating more applicable is to focus on the individual composite components. Tailoring the carbon fiber reinforcement and the thermosetting resin can add an additional perspective in improving this method. The carbon fiber, in addition to its reinforcing role, provides the resistive/conductive path for current flow during heating. For control systems and power supplies that are current limited, decreasing the resistive nature of the fibers would result in more heat generation per applied volt. On the other hand, voltage limited systems (such as solar-powered battery packs that store current at a certain voltage) would benefit from an increased fiber resistivity to maximize heat generation. The resin's material properties, namely its glass transition and curing temperatures introduce additional factors into the design of a system that rigidizes via thermal heating. The resin used in this study, U-Nyte Set 201B offers cure onset at a temperature of 100$^o$C. Research on composites containing ULTEM resin [31] illustrated the power requirements required to heat the material to 380$^o$C. For a method that requires electrical energy to induce a temperature increase, lowering the melting and curing temperatures of the resin (without sacrificing chemical resistance, shelf-life, durability, etc.) even further offers the ability to design a system that rigidizes at a lower temperature, in less time, and with less energy.

- *Perform space-environment testing and develop a temperature control system for in-space application.* The cold, vacuum environment in-space provides for more realistic evaluations of this rigidization technique. The extreme cold and lack of air introduce new considerations into the design of a complete rigidization system. Specifically, the amount of power required to heat the material from an initially lower temperature to the cure temperature should be gauged. In addition, the lack of air eliminates convective cooling affects. In its place, radiation effects are expected to play a larger role in this process and may require additional changes to the temperature control system. Incorporating these effects into resistive heating experimentation would not necessarily require deployment on orbit. An altitude simulator, or temperature-controllable vacuum chamber, provides the capability to vary both the pressure and temperature of the testing environment.