

Chapter 1

Introduction

Inflatable, rigidizable space structure technology is an ever-increasing area of interest for scientists and engineers. The ability to minimize the packaging weight and volume of payloads being sent into space translates into substantial cost savings due to the fact that many commercial launch services charge as much as \$18,000/pound [11]. The development of inflatable structures also allows for multiple structures to be launched at one time, providing additional cost savings. As their name suggests, inflatable space structures are inflated with a pressurized gas from a compact launch volume to a fully-inflated state. These ultra-lightweight, flexible components are then “rigidized” in order to provide structural integrity and maintain geometric shape without a continued inflation pressure. Structures utilizing this concept include solar arrays, sunshields, and ultra-lightweight truss designs for optical satellites. Many techniques are currently being used to rigidize inflatable structures. The work presented in this document focuses on one rigidization method, internal resistive heating of carbon-fiber reinforced polymer composites, for use in inflatable spacecraft.

1.1 The History of Inflatable Space Structures

The concept of an inflatable space structure was proposed more than 40 years ago. One of the first “inflatable” designs, the Echo I Balloon, was launched on August 12, 1960 aboard a Delta unmanned rocket. NASA’s intent with this structure was to investigate the idea of large, high precision inflatable space structures to provide “passive, space based communications reflectors [12].” Developed by NASA Langley Research Center (LaRC), this 100 ft. diameter sphere balloon was made from a laminated gore of Mylar and vapor-

deposited aluminum and was rigidized through inflation pressure-induced, elastic strain-hardening. In all, the structure weighed only 136 lbs. and could be stowed in a 26 in. diameter spherical container. While the Echo I only lasted a few months in space [12], its existence validated inflatable structures and prompted many successive designs.

At about the same time (late 1950s through the early 1960s), Goodyear pioneered the inflatable search radar antenna, which was based on a rigidizable truss structure with a metallic mesh aperture. They are also credited with the development of a radar calibration sphere consisting of large hexagonal-shaped panels (like an over-sized soccer ball) to be used for high radio frequency (RF) reflectivity and as well as a toroidal-shaped structure called the “lenticular inflatable parabolic reflector” [12, 13].

America was not alone with its endeavors in inflatable, rigidizable space structures. Though lagging the United States by a few decades, the European Space Agency (ESA), in cooperation with Contraves Space Division in Switzerland, sponsored the development of reflector antenna [14] and sun shade structural concepts [15]. Their goal was to create an axisymmetric reflector for Very Large Baseline Interferometry (VLBI), as well as offset reflectors for mobile communications and sun shade support structures for telescopes and other sensors. Beginning in the 1970s and coming to fruition in the early '80s, the ESA projects combined innovative design and cutting-edge materials. Solar heating of the Kevlar-reinforce matrix material provided structural rigidization on orbit [12, 16].

With the growing success of inflatable space structures, the need for reliable rigidization techniques also emerged. In addition to providing structural stability and permanent shape-holding, rigidization allows the structure to maintain structural integrity without the need for a supply pressure. The quicker that rigidization can occur, the sooner the inflatable structure no longer requires support. Further, in the period of time between inflation and complete rigidization, the space structure exists in an extremely vulnerable state. Direct impact from space debris and meteoroids presents imminent danger to the structure [17]. The design of a stable structure must also account for ionizing radiation, UV and particle radiation, atomic oxygen, thermal cycling, and a high vacuum environment. In their study of rigidizable space structures, Han and Kim note:

Being exposed to the severe LEO space environment, the composite materials used in space structural components will undergo fatigue cracking caused by thermal cycling, surface erosion by AO attack, structural modification and mass loss

by outgassing, modification of material properties by UV radiation, delamination by collisions with micro-meteoroids and man-made debris with high velocities. Thus, in designing the space structures using composite materials, possible deterioration of mechanical properties caused by long-term exposure to the LEO space environment must be carefully considered.

1.1.1 Rigidization of Inflatable Space Structures

It is evident that inflatable space structures endure harsh environments and require stringent design criteria in order to successfully meet performance specifications. The rigidization techniques that have been developed strive to overcome these obstacles while providing uniform structural stability. These methods, however, are not devoid of their own flaws. A brief look into rigidizable materials as well as the various rigidization techniques for ultra-lightweight, inflatable space structures helps to better understand the design of these devices.

In a paper entitled “Rigidizable Materials for use in Gossamer Space Inflatable Structures,” Cadogan and Scarborough compile an extensive review of the materials and methods employed for rigidization [18]. In their work, the authors define rigidizable materials as “*materials that are initially flexible to facilitate inflation or deployment, and become rigid when exposed to an external influence.*” Generally, the three types of rigidizable materials can be categorized as thermosetting composites, thermoplastic composites, and aluminum/polymer laminates. The rigidization techniques, greatly dependent on the type of material used in the construction of the structure, must account for the inherent differences in these material types.

Rigidizable Materials

Thermosetting materials require heat to permanently set, or cure, the plastic. Once set, these materials cannot be remelted and reformed; thus, their use is limited to “one-time only” applications. This property stems from the chemical reaction that forms a network molecular structure of primary covalent bonds, called cross-linking, during application of heat and/or pressure [3]. Stated differently, “*a thermosetting plastic is a polymer that can be caused to undergo cross-linking to produce a network polymer*” [19]. In general, thermosetting plastics offer high thermal stability, rigidity, dimensional stability, resistance

to creep, they are lightweight, and have excellent electrical and thermal insulating properties [3].

On the other hand, many inflatable space structures utilize thermoplastic composites. These materials soften and harden reversibly with changing temperature. Typically, thermoplastic materials are softened and made to flow for applications such as injection molding, extrusion molding, and blowing [19]. The ability to heat, mold, cool, and set the material gives this type of plastic the advantage of being reused. Examples of these materials include thermoplastic polyester (PE), polysulfone (PS), polyphenylene sulfide (PPS) and polyetherimide (PEI).

Lastly, aluminum/polymer laminates have been used extensively in the construction of inflatable spacecraft. As mentioned previously, the Echo I Balloon was made from a gore containing mylar (a high-strength polyester film) and aluminum thin film. Popular for fabricating thin shell structures (i.e. spheres and tubes), this type of material was also used on Echo II, and later spherical balloon satellites, Explorer IX and XIX. The laminates are constructed with two layers of polymeric film laminated to a layer of aluminum (typically Aluminum 1100 – 0 or 3003 – 0 in its softest condition) [18]. Further, the total aluminum thickness is kept less than 0.1mm to avoid laminate degradation from folding.

Rigidization Techniques

Many methods exist to cause permanent rigidization in inflatable space structures. Passive rigidization occurs when exposure to the space environment provides the necessary influence, such as UV light or temperature, to cause structural stiffening. Conversely, active methods require deliberate control over the external influence, like heat or pressure, used to initiate the rigidization process. Thermal heating, passive cooling, UV exposure, inflation gas reaction, thin wall aluminum, foam inflation, and hydrogel evaporation are popular passive and active methods for material rigidization on orbit [20, 12].

Thermally cured composites are rigidizable materials hardened through the application of heat. The heating source, magnitude, and duration is dependent on the material being cured. Two main types of thermal curing exist: resistive heating (active) with embedded heating elements and UV curing (passive) from sunlight. ILC Dover, Inc. was one of the first to develop thermal curing via resistive heating elements [18]. In this procedure, heating elements are encapsulated within layers of polymeric film and the composite ma-

terial. Electric current is then passed through wires embedded in the elements and heat is generated. One obvious advantage for using this kind of rigidization technique is that the heating process can be controlled by the amount of electrical current supplied. However, this method is limited by the power required to cure the thermosetting material as well as the inability to remelt and reform the material multiple times.

Passive cooling, or sub- T_g cooling, causes material hardening through exposure to the cold space environment. With this technique, thermoplastic composites that are flexible at room temperature become structurally stiff once inflated and deployed on orbit [20]. Guidanean and Lichodziejewski, of L'Garde, Inc., investigated this type of rigidization technique on aromatic-rich polyurethane resins with controllable glass transition temperature, T_g , values [21]. They discovered that these materials possessed excellent ionizing radiation resistance and unlimited storage life, in addition to the process being reversible (ideal for ground testing). One weakness of this rigidization method, however, is that a power supply and heaters are sometimes required to preheat the material prior to deployment.

Solar heating, or UV curing, generates material stiffening when ultra-violet light warms the resin system. This passive technique has long been established as a method of *in-situ* rigidization and was specifically used by the Hughes Aircraft Company in the early 1960s [22]. Schwartz et al researched the feasibility of curing a UV activated polyester resin for use in inflatable space structures. More recently, researchers at Adherent Technologies, Inc. et al again studied the use of light-curing resins to rigidize an inflatable wing for space applications [23]. Through their endeavors, they demonstrated packaging and deployment of an inflatable wing design and, more importantly, rigidization through solar curing.

Of the current rigidization techniques, aluminum laminates are probably the most mature [20]. The Echo balloons in the 1960s used this form of rigidization to smooth wrinkles and provide structural stability in their shapes. The technique consists of inflating a laminate of aluminum and some polymeric film (say, Kapton or Mylar) to a point slightly beyond the elastic strain limit for aluminum. Aluminum laminate continues to be a popular rigidization method and was used in L'Garde's Orbital Calibration Sphere in 2000 [24]. Further, researchers at L'Garde just recently improved aluminum laminate rigidization by using a spiral wrapping technique in order to reduce the hoop stresses incurred on the structure during rigidization. They observed that with spiral wrapping, the hoop stress is reduced, which increases the burst strength of the structure, and higher rigidization

pressures can now be used, which increases the geometric precision and stability [25].

Though lesser known, inflation gas reaction and foam inflation can also be employed to rigidize an inflatable structure. The first method relies on the pressurized inflation gas to not only give shape to the structure, but react with and harden the surrounding laminate [20]. Foam inflation is similar in that the inflation gas is used to chemically harden the structure. Specifically, an expanding foam is injected into the inflatable and allowed to swell and dry. Tinker, et al developed a manufacturing method for foam-rigidization of thin-film booms. One question prompted by this research regarded the ability to evenly inject or distribute the foam prior to full expansion and drying [26].

A final method used to rigidize space structures is called hydrogel evaporation. In this scenario, the flexible fabric is impregnated with a water soluble resin that hardens as the water evaporates. Again, this technique like many of the others is truly passive and requires no additional process support. Prior to rigidization, however, the material must be kept in an environment—usually high humidity and pressure—that prohibits curing (evaporation). The hydrated material can also be sandwiched between laminate layers to control the rate of evaporation. Much of the work addressing this form of rigidization occurred in the 1960’s, though L’Garde recently worked with NASA Jet Propulsion Laboratory (JPL) in developing gelatin beam structures [27]. Rigidization through solvent “boil-off” is a relatively simple and fully reversible process well-suited for inflatable structures. The biggest limitation of the method is the high mass loss due to outgassing in space, resulting in significant shrinking and decreased geometric accuracy.

A brief comparison of the discussed techniques is shown in Table 1.1. Both the advantages and disadvantages, along with a brief description and key literature references, are listed for each technique.

1.2 Literature Review

Previously published work in the areas of composites, polymer science, resistive heating, and composites testing has been reviewed. Past accomplishments provide a solid foundation from which to build from for future research. While these topics are only briefly addressed, the key aspects of each subject and their respective authors are recognized.

Table 1.1: Summary of current rigidization techniques

Method	Description	Advantages	Disadvantages
Thermal Curing via Embedded Heaters [18]	Electric current passed through the wires of the embedded heaters result in heating.	Controllable heating process	Thermosets can only be activated once. Complex wiring and larger power requirements.
Sub-Tg Cooling [20, 21]	A pre-heated thermoplastic composite hardens as it cools below its glass-transition temperature, T _g .	Simple, reversible process, unlimited shelf-life	Power supplies and heaters are sometimes required to pre-heat and soften the matrix prior to deployment.
UV Light (Thermal) Curing [22, 23]	Absorbed UV light thermally cures the thermoset resin in the composite.	Simple, passive, thoroughly-tested	Passive; lack of control and longer curing times
Aluminum Laminate [20, 24, 25]	An aluminum/polymeric film laminate is strain-hardened using inflation pressure.	Most-experienced method, simple activation	Large inflation pressures are required and generate significant hoop stresses.
Inflation Gas Reaction [20]	The inflation gas reacts with a permeable substrate, causing chemical rigidization.	Simple, active and passive	Non-uniform curing can occur
Foam Inflation [26]	An expanding foam inflates the structure and then hardens as it dries.	Simple, passive	Inability to inject/distribute the foam before swelling/drying
Hydrogel Evaporation [27]	A flexible fabric hardens as the impregnated water-soluble resin evaporates.	Simple, passive, fully-reversible, evaporation rate can be controlled	The hydrated material must be kept in high humidity/pressure environment prior to solvent "boil-off;" shrinking and geometric instability can result from mass loss due to outgassing

1.2.1 Fiber-Reinforced Polymeric Composites: An Overview

Composite materials have received much attention in recent years due to their enhanced mechanical properties. Fiber reinforced materials especially have been given increased focus because of their high strength-to-weight ratios. These materials are being used readily in fields such as aircraft, ballistics, space, naval vessels, tooling, automotive, and sports equipment [1]. Since the composites field is so large, only the basic mechanics concepts and material behaviors are discussed. Further, fiber-reinforced polymer composites are specifically addressed for their relation to this work. Basic information on fiber-reinforced composites can be found in any one of a number of textbooks on the subject [1, 2, 8].

The underlying intent with composite materials is to tailor the overall material properties by creating the proper balance of the individual component strengths and weaknesses. For example, a high strength, low ductility component can be combined with a

tough, corrosion-resistant material to produce a strong, durable composite. Advanced composite materials, as defined by Pilato [1], consist of both a high strength reinforcing agent and a high performance matrix resin. The matrix surrounds the fiber and offers many advantages over using only a high strength fiber. Specifically, the matrix has two primary roles: load distribution and increasing fracture toughness. When a load is applied to a reinforced composite material, the matrix (softer, more ductile) transfers the load to fibers (less ductile, much stronger). The matrix, because of its polymeric behavior, also increases the fracture toughness of the material by absorbing energy and reducing stress concentrations [1]. Additional qualities such as corrosion and chemical resistance and thermal and electrical properties can be tailored through the selection of the individual composites.

Carbon Fiber Basics

The majority of carbon fibers produced for composite materials are made from one of three precursors: rayon, poly(acrylonitrile) or PAN, and mesophase pitch. Rayon-based carbon fibers are thermally treated under special conditions in order to produce low modulus carbon fibers (≤ 50 GPa). This type of carbon fiber is typically found in rocket nozzle designs and missile technology since it can provide lightweight, structural materials resistant to heat degradation and moisture absorption. Petroleum pitch-based carbon fibers benefit from having a very high tensile modulus (up to 900 GPa), high thermal and electrical conductivity, and adequate tensile properties. Pitch-based fibers are therefore choice candidates for many space hardware and aircraft applications. However, pitch-based carbon fibers suffer from decreased compressive strength and poor ductility. PAN-based fibers offer superior tensile strength and stiffness as compared to the rayon and pitch-based types. The process of forming carbon fibers from PAN involves first polymerizing acrylonitrile with other comonomers and then heat treating (cross-linking) the PAN fiber in order to carbonize it [1]. The three types of fibers provide a variety of performance attributes and serve many applications.

Carbon fibers typically have very small diameters ($5 - 12\mu\text{m}$) [2], and, as a result, the strength of one fiber is insufficient in reinforcing a given material. Most carbon fibers are produced and used in loose, untwisted bundles of filaments called tows. The fiber tows can also be braided or woven in order to make fiber weaves that increase dimensional stability and strength in multiple directions. Carbon fibers are also anisotropic, with physical

Table 1.2: Physical properties of various carbon fibers produced by Amoco Performance Products, Inc [1, 2].

Trade Name	Thornel VCK 8HS	Thornel P-100	Thornel T650-35
Precursor Type	rayon	pitch	PAN
Unit Amount	yarn bundle	fiber	fiber
Axial Tensile Strength (GPa)	0.69	2.24	4.55
Axial Tensile Modulus (GPa)	41.4	690	248
Density (kg/m ³)		2160	1770
Filament Diameter (μm)			6.8
Elongation at break (%)		0.9 ^a	1.75
Surface Area (m ² /g)			0.5
Axial Thermal Conductivity (W/mK)	3.7	530	14
Electrical Resistivity, (μ Ω-m)	59	250 ^a	14.9
Fibers/Yarn Bundle	980	n/a	n/a

^a source: *Engineers' Guide to Composite Materials*

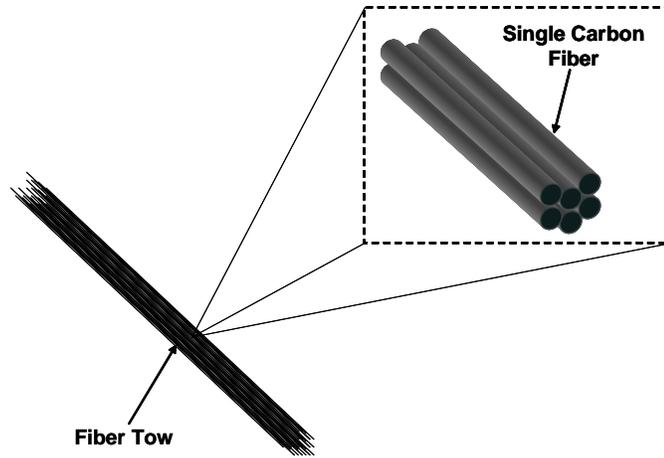


Figure 1.1: Carbon fiber tows consist of thousands of individual fiber filaments.

properties differing greatly between the axial and transverse directions. This quality results in highly orientation-specific behavior in the final composite material. For most purposes, the fibers exhibit higher strength and conductivity along their lengths.

Polymer Matrices

The choice of the matrix phase also greatly influences the nature and consolidation of the composite. Whether the material is metallic, ceramic, or polymeric, the matrix must serve the basic purposes of distributing load to the reinforcing agent and increasing the general toughness of the composite. Polymeric materials typically fall into two different groups: thermoplastics and thermosets. Thermoplastic materials soften when heated and harden when cooled, allowing them to be used in passive cooling rigidization methods [21]. Thermosets cross-link when heated, resulting in a networked structure that has higher

rigidity, dimensional stability, and resistance to heat and chemicals. These materials, unlike thermoplasts, are not reversible, have a limited storage life prior to deployment, and require heat in order to cure. Even though each of these types of polymeric materials can be further categorized, a general appreciation for their major inherent differences is noted.

Table 1.3: Physical properties of some common thermoplastic and thermosetting resins [1].

Property	Thermoplastic			Thermoset		
	Polyaryl ethers (PEEK)	Polyimides (PEI)	Polyaryl sulfide (PPS)	Epoxy (III)	Phenolic (PF)	Polymide (CPI)
T_g (°C)	143	220	85	262	127	330
T_m (°C)	343		285			
Fracture Strength (MPa)	103	110	65	138	80-100	86
Fracture Modulus (GPa)	3.8	3.3	3.8	3.9	5-7	3.1
Elongation (%)				5	5.1	7.5

Two important features of polymers that greatly affect their use are their glass transition temperature and melting temperature. When a polymer is kept below its glass transition temperature, T_g , it behaves as a high modulus solid. But as the temperature rises, an increase in thermal energy allows chains to move freely within the solid and the polymer becomes a rubbery, viscous liquid [19]. The melting temperature, T_m , defines the upper service temperature for the polymer and marks the onset of sharp decreases in viscosity. For semi-crystalline materials that have both a T_g and T_m , the polymer is generally heated to a temperature between these transitions for molding/shaping processes. Further, in composites manufacturing the ability to soften and form the polymer matrix around the fiber bed results in a more even product. While factors such as molecular weight also affects the values of T_g and T_m , a basic knowledge of what these temperatures mean and at what temperatures the polymer can be processed is highly beneficial.

Fiber-Matrix Interphase

The interaction between the fiber and matrix phase is crucial to the performance of the composite material. Up until now, it has only been said that the matrix serves to transfer load to the fiber and provide toughness to the composite. A more detailed look at this interfacial behavior further solidifies this concept.

Since fibers are anisotropic, having direction-dependent properties, their are typically aligned parallel to each other (in a direction that experiences the highest load) and embedded within the matrix (Figure 1.2). The axial direction marks the “strongest” direc-

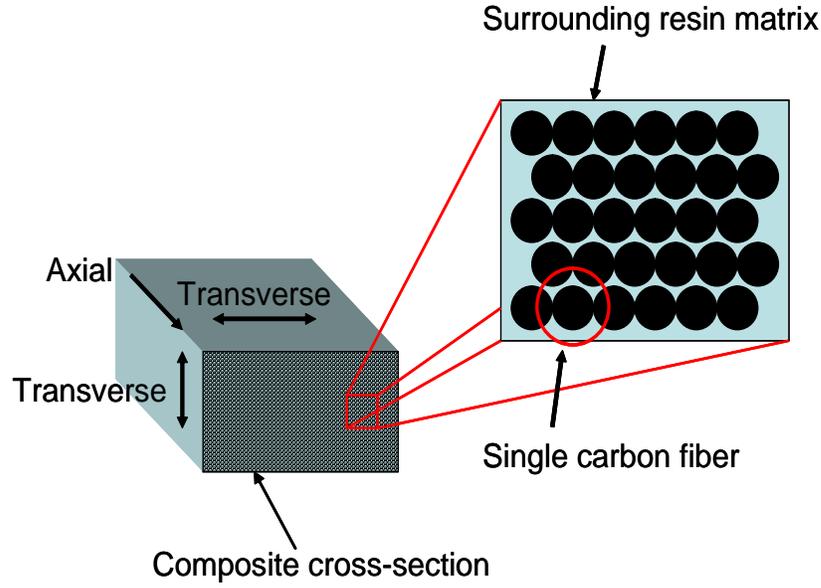


Figure 1.2: Finite composite element that shows typical polymer matrix/fiber orientation.

tion in the composite, while the two transverse directions suffer from reduced properties. As a load is applied to the composite (Figure 1.3), the polymer matrix transmits the load through a shear stress on the fiber surface. This transfer results in a tensile (or compressive) stress within the fiber. At the end of the fiber, the shear stress is high and the tensile stress is low. But, as the distance from the end of the fiber increases, the tensile strength reaches a maximum and carries nearly the entire load [8]. This distance, referred to as the characteristic length, should be much smaller than the length of the fiber in order for the fiber to fully function.

The extent to which the matrix bonds to the fibers and to itself smears the individual component properties and creates an overall composite homogeneity. The Rule of Mixtures can be used to describe many mechanical properties of composites in terms of the properties and proportions of each component[2]. The tensile strength for a composite, σ_c , can be written as

$$\sigma_c = \sigma_f V_f + \sigma_m V_m \quad (1.1)$$

where, σ_f and σ_m are the fiber and matrix tensile strengths, and V_f and V_m are the respective volume fractions. The same form can also be used to calculate the composite's modulus of elasticity, Poisson's ratio, density, etc [2]. This calculation assumes uniform fiber/matrix distribution, perfect bonding, mutual insolubility between fiber and matrix, and fibers of

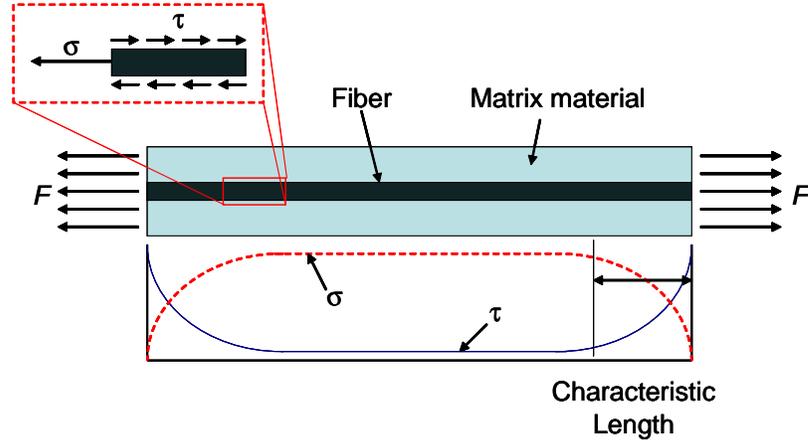


Figure 1.3: The polymer matrix distributes shear stress along the fiber surface, creating an axial tensile stress within the fiber [8].

length much greater than the characteristic length.

1.2.2 Rigidization by Resistive Heating

Resistive heating used to cure carbon-fiber reinforced polymer composites is not a brand new technology, though it is still relatively young. In fact, this method has been shown to be a successful consolidation method for thermosetting-matrix composites and some key papers have been published in its regard.

Much of the interest in resistive heating as a curing method began as an attempt to increase the strength of the polymer matrix/reinforcing fiber interphase. In 1993, Sancaktar, et al proposed that the interphase in carbon fiber-epoxy composites could be improved through supplemental resistive heating [28]. As a conductive element in the composite, the authors believed that current flowing through the fibers would generate a thermal field and cause increased “elastic modulus, toughness, and/or strength distribution” in the nearby matrix. To test this idea, the authors embedded single carbon fibers into resin molds and cured them in a convection oven. Specifically, the composite consisted of $7\mu\text{m}$ Celion *G30* – 500 fiber finished with EP03 and embedded into Shall Epon 815 epoxy resin along with DETA (Diethylenetriamine) and Armocure 100 curing agents. Then, a DC current was passed through the fiber to induce post-cure heating. The post-cured samples were then evaluated through single fiber tensile testing and it was determined that resistive heating post-cure schedules improved the material properties of the composites. Their

results showed increased adhesion and crack initiation/propagation prevention.

Seven years later in 2000, Ramakrishnan, Zhu, and Pitchumani investigated resistive heating as an option for improving resin transfer molding of composites [29]. Their efforts concentrated on using resistive heating to cure conductive fibers embedded into composite laminates in order to improve temperature distribution and reduce cure times. The primary experimental procedure involved placing “resistive heating mats” between layers of fiber-resin preform in a resin transfer mold (where pressure is applied). DC power between 0 and 20V was then supplied to the resistive mats connected in parallel and temperatures were measured using thermocouples inserted between layers. A PID controller in LabVIEW was then used to control an auxiliary surface heater at the base of the setup. The authors noted that the use of resistive heating is viable technique for reducing temperature gradients in the through-thickness of thick composites and for shortening the cure process time.

Chugh and Chung refined their focus in resistive heating to the evaluation of flexible graphite as a heating element [30]. Using a resistance heater and a temperature controller, samples of varying thickness were heated by passing a fixed DC current ranging from 2A to 10A through them. During the heating process, resistance of the sample between the electrical contacts was measured with a multimeter and a K-type thermocouple measured temperature at a point on the top surface of the sample. In addition to verifying that the resistance decreases with increasing temperature, the authors noted the maximum temperatures attained as well as the energy to required to raise the temperature by 1°C, called the specific heat. With the application of 94W of power, a maximum temperature of 981°C was obtained in only 4 seconds. The feasibility of using flexible graphite as heating elements was demonstrated in their simple resistive heating experiments.

While the entire list of papers concerning resistive heating of thermosetting-matrix composites cannot be addressed here, the emergence of this technique to consolidate composites is evident. Researchers at Clemson, however, have taken this principal and just recently applied it to the consolidation of materials for use in inflatable space structures [31]. Naskar and Edie used internal resistive heating to cure PAN-based carbon fiber tows coated with Ultem powder. Using uncontrolled resistive heating, an electrical current was passed through the material and the resulting temperature increase was recorded with one thermocouple. In addition, a simple heating model was developed in order to predict power requirements, temperature-modulated differential scanning calorimetry (TDSC) was used

to measuring the melting temperature and calculate the specific heat for the Ultem resin, and tensile testing was used to evaluate the strength of the hardened composite. Though internal resistive heating was shown to be a successful method for inducing thermoset cure, the authors noted having trouble in regulating the cure temperature and suggested that, “*a temperature feedback power controller will be required for an in-space consolidation system.*” Naskar and Edie have only started to address resistive heating as proven rigidization technique, though their contributions provide encouraging results to this field.

1.3 Motivation

Several of the described techniques for rigidizing inflatable structures benefit from a passive approach. Thermoplastic cooling, UV curing, and solvent evaporation are all triggered by the space environment conditions. Curing materials in a passive manner has the obvious advantage of requiring no additional control effort. But are these techniques devoid of limitations? No, the benefits of each method are offset by unwanted disadvantages. Passive cooling often requires preheating the material, demanding a power source and heating elements. UV curing is easy, but the same solar radiation that sets the material can also cause long term degradation and structural weakening. Hydrogel evaporation requires that the materials must be kept in a specific environment prior to deployment so as to avoid premature curing. Further, mass loss due to outgassing can also be significant for this method. Even active techniques such as thermal heating, aluminum laminate, inflation gas reaction, and foam inflation have limitations. With higher controllability comes increased control effort. As a result, these methods often require large amounts of power or pressure, are complicated by intricate electrical wiring, and may experience non-uniform cure distributions. Evaluating these methods incurs much responsibility on the designer to properly weigh the advantages with the restrictions when choosing a form of rigidization. Increased knowledge and even creative tailoring of the available materials should also be considered.

In this light, the rigidization of a new material through the use of internal resistive heating is proposed. Instead of using embedded resistive heaters in the rigidizable composite material, the inherent resistivity of the material itself acts as the heating element. The heat generated through Joule heating will then be used to cure an adjacent thermosetting resin matrix. By using a novel, high-strength thermoset resin, another innovation of this

concept, the cure temperature can be reduced and thus the energy required to induce heating can be lowered. Resistive heating, as in the previous discussion of thermally-cured composites, provides direct control of the curing process through current management. Further, with precise control and reduced curing temperatures, rigidization through internal resistive heating of the composite reinforcement offers uniform structural stiffening and reduced cure times. As a result, the inflatable structure spends less time in a vulnerable, pre-hardened state. Internal resistive heating to induce rigidization of inflatable space structures provides yet another tool in the design of these ultra-lightweight spacecraft and its study deserves equal attention.

1.4 Research Objectives

The proposed research investigates the use of internal resistive heating as a viable mechanism for the consolidation and curing of carbon-fiber reinforced polymeric materials. Pertaining to the field of inflatable space structures, the work is tailored to evaluate the feasibility of this being a successful *in-situ* rigidization technique. The primary objectives of this research are:

- *Establish temperature-controlled resistive heating through feedback temperature monitoring.* Temperature control via both open-loop and closed-loop control schemes are investigated for prescribing the desired curing schedule.
- *Demonstrate consolidation of a novel thermoset through resistive heating.* Electrical current will be applied to samples of the carbon-fiber tow coated in the U-Nyte Set 201 thermoset resin to see if the material can be rigidized. The mechanical stiffness of the hardened samples will be compared to the uncured material.
- *Relate temperature control of the curing process to measured, post-cured mechanical stiffness.* A relationship between mechanical strength and the prescribed curing profile will be established through stiffness measurements and cure completion data on the rigidized samples.
- *Demonstrate structural stiffening via resistive heating on an inflatable structure.* The concept of applying this rigidization method to inflatable structures is evaluated on

a miniature, inflatable boom. The successful inflation and curing requirements are measured along with the resulting increase in strength.

1.5 Contributions

The major contributions of this work solidify resistive heating as a viable technique for actively rigidizing space structures. The specific achievements of this research include:

- *Feedback temperature-controlled resistive heating was established on carbon fiber tows.* A tuned proportional-integral controller was shown to provide accurate tracking of a desired temperature profile.
- *The bending stiffness was measured for the rigidized samples and the cure completion of the composite material was verified with differential scanning calorimetry (DSC).* A test fixture designed to measure bending stiffness and post-cure DSC analysis provided useful insight in differentiating the effects of various curing profiles.
- *Complete consolidation and cure through prescribed resistive heating schedules was achieved for carbon fiber tow coated with a novel, thermoset resin.* Carbon fiber tow coated with one of two thermosetting resins (U-Nyte Set 201A and 201B) were rigidized from cure schedules based on previous thermal analysis. These materials exhibited increases in strength of 14 – 21 times that of the uncured composite.
- *Rigidization and cure completion of the composite material was related to the prescribed curing schedule in terms of the cure temperature, curing time, and heating rate.* Samples of U-Nyte Set 201B-coated tow rigidized exhibited full curing and significant stiffening in only 5 minutes of curing at 150°C. The curing time and temperature were shown to be closely linked, while the heating rate allowed for further reductions in rigidization time and electrical energy.
- *The rigidization of an inflatable structure was demonstrated and the increase in strength and energy cost of rigidization were both quantified.* A small inflatable boom in a cantilevered configuration was shown to be three times as strong as the pre-cured state. This test also highlighted the reduction in curing energy due to a change of boundary conditions.

1.6 Overview

Temperature-controlled rigidization of polymer composites is addressed in several steps: establishing temperature control on internal resistive heating of carbon fiber reinforced material, demonstrating consolidation and curing for the purpose of rigidization, and applying this form of active rigidization to strengthen an inflatable structure.

In Chapter 2, internal resistive heating is investigated two different ways. First, the feasibility of Joule heating to cause melting in the polymer resin and the ability to measure the temperature of the sample is evaluated. Open-loop and closed-loop control methods are then examined for providing accurate temperature control. Specifically, feedback temperature control based on a PID control algorithm is experimentally tuned. These experiments result in an accurate, robust temperature control strategy for prescribing internal resistive heating.

Chapter 3 switches focus and concentrates on using temperature-controlled resistive heating to effectively rigidize samples of thermoset resin-coated carbon fiber tow. Two thermosetting resins, U-Nyte Set 201A and 201B, are prescribed curing profiles based on previous thermal analysis of each resin. The mechanical stiffness and cure completion of the “cured” samples are measured and used to judge the respective curing profiles. Additional testing on samples coated with U-Nyte Set 201B resin is performed to investigate the influences of cure temperature and curing time on rigidization. These results establish working cure profiles for the materials and also quantify both the increase in stiffness and power required by resistive heating.

This work culminates in Chapter 4, where active rigidization through temperature-controlled resistive heating is applied to cause strengthening in an inflatable structure. A miniature, inflatable boom is constructed from Kapton and plastic endcaps. Thermoset-coated carbon fiber tow is then applied to this structure such that it can be stiffened by resistive heating. The issues associated with combining the rigidizable material with the Kapton substrate are illustrated in small-scale coupon testing. The strength of the rigidized boom is then compared with its pre-cured state and the energy supplied to the structure to cause this transformation is quantified.