Consolidation of U-Nyte® Epoxy-Coated Carbon-Fiber Composites via Temperature-Controlled Resistive Heating

STEPHEN A. SARLES AND DONALD J. LEO*
Center for Intelligent Material Systems and Structures (CIMSS), Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061, USA

ABSTRACT: Temperature-controlled internal resistive heating creates on-command rigidizable materials for structural consolidation of ultra-lightweight, inflatable space structures. A PAN-based carbon fiber tow coated with a novel, low cure-temperature thermosetting resin (Hydrosize U-Nyte® Set 201 epoxy binder) was investigated for consolidation through internal resistive heating. Precise, proportional-integral (PI) temperature tracking was achieved for controlled sample heating and used to prescribe intelligently-designed curing profiles to cause resin consolidation and curing. Rigidized samples were evaluated by measuring the increase in bending stiffness as well as verifying resin cure completion through DSC. The permanent strength gained through active rigidization via internal resistive heating was demonstrated on a small, inflatable structure.

KEY WORDS: internal resistive heating, phenoxy-toughened epoxy, U-Nyte® Set 201 resin, temperature control, inflatable rigidizable space structures.

INTRODUCTION

INFLATABLE RIGIDIZABLE STRUCTURES in solar arrays and other spacecraft can drastically reduce the weight, volume, and cost of launching payloads (a typical commercial launch service charges roughly $18,000/lb [1]). Inflatable components consist of ultra-lightweight, flexible materials that enable compact packaging prior to launch and require techniques for controlling structural shape and stiffness once rigidized on-orbit. To ensure on-orbit survivability, inflatable structure materials must be impervious to the environmental conditions in space – such as ionizing radiation, UV and particle radiation, atomic oxygen, and possible impacts from space debris and meteoroids. Further, they must also provide stable operation over a useful storage and mission life. Materials and methods for causing structural stiffening in inflatable, rigidizable space structures have been addressed in many ways [2–7]. Three types of materials are typically used in

*Author to whom correspondence should be addressed. E-mail: donleo@vt.edu
Figures 1–12 appear in color online: http://jcm.sagepub.com

0021-9983/08/24 2551–16 $10.00/0 DOI: 10.1177/0021998308097197

rigidization strategies: aluminum laminates, thermoplastic composites, and thermosetting composites. Thermal curing, passive cooling, UV curing, strain-hardening, inflation gas reaction, foam inflation, and solvent evaporation are examples of passive and active rigidization techniques. A brief comparison of the discussed techniques is shown in Table 1. Both the advantages and disadvantages, along with a short description and key literature references, are listed for each technique.

Allowing systems to rigidize passively in the space environment has the advantage of being inherently simpler than many active rigidization strategies. Passive techniques require little input, eliminating complex control strategies and bulky power supplies. On the other hand, because these methods initiate by exposure to a required environment, minimal input can translate into minimal control. Passively-rigidized structures can also exhibit weak spots caused from uneven consolidation and may require hours to achieve complete rigidization [2]. Prolonging the rigidization event leaves the structure in a vulnerable state prior to permanent stiffening. Additionally, longer transformation times require larger inflation gas supplies for both deployment and shape-holding before and during structural rigidization. Active rigidization methods provide alternative approaches that attempt to reduce the transformation time while providing a controlled, uniform stiffening effect.

Both active methods, such as using embedded resistive heaters [2], and passive techniques, for example UV solar curing [9,10], can be used to trigger the input (heat)–output (cured, consolidated polymer matrix) relationship inherent in thermosetting materials. Researchers at ILC Dover have used embedded resistive heating elements to cause material consolidation on a thermosetting resin cured at 120°C for 45 min [2]. Recent work by Naskar and Edie [11], focused on the active consolidation of a carbon-fiber tow coated in Ultem (GE Plastics) resin. Instead of using embedded heating elements, resistive (Joule) heating was performed by passing electric current through the resistive/conductive carbon fibers in order to heat the adjacent polymer resin. Their work validated internal resistive heating by showing that the Ultem resin, when heated to 380°C, underwent rapid rigidization. However, their resistive heating process lacked the ability to precisely control material temperature and the power requirements were excessive (300 W) due to the large cure temperature required. Additionally, the authors suggested that, 'a temperature feedback power controller will be required for an in-space consolidation system' [11].

In this study we use PI-based feedback temperature control to create an electrically-controlled, thermally-activated composite. This study investigates the use of internal resistive heating to induce matrix consolidation and curing in thermoset-coated carbon fiber tows for the application of rigidizing flexible, inflatable spacecraft. Feedback-temperature control is implemented to provide control over the consolidation process such that the rigidized composites can be evaluated with respect to heating parameters such as curing temperature and time. The rigidization is quantified in terms of the increase in composite bending stiffness as well the completion of the resin cure. Methods for shortening the rigidization process and reducing the electrical energy consumed are related to curing profile parameters. Lastly, the use of this technique as a method for causing structural stiffening is demonstrated on a simple, inflatable boom structure.

COMPOSITE MATERIAL SELECTION AND EVALUATION

The initial selection of the composite materials as well as thermal identification of the thermosetting resins precluded rigidization testing. The results of the thermal analysis

Table 1. Summary of current rigidization techniques.

Method	Description	Advantages	Disadvantages	References
Thermal curing via embedded heaters	Electric current passed through the wires of the embedded heaters result in heating.	Controllable heating process, active	Thermosets can only be activated once. Complex wiring and larger power requirements.	Cadogan (2001)
UV light (thermal) curing	Absorbed UV light thermally cures the thermoset resin used in the composite.	Simple, passive, thoroughly-tested	Passive; lack of control and longer curing times.	Schwartz (1963); Allred (2004)
Sub-T_g cooling	A pre-heated thermoplastic composite hardens as it cools below its glasstransition temperature T_g.	Simple, reversible process, unlimited shelflife	Power supplies and heaters are sometimes required to pre-heat and soften the matrix prior to deployment.	Cadogan et al. 1998; Guidanean and Lichodziejewski, 2002
Aluminum laminates	An aluminum/polymeric film laminate is strain hardened using inflation pressure.	Most-experienced method, simple activation	Large inflation pressures are required and generate signficant hoop stresses.	Cadogan, 1998; Guidanean, 2003; Lichodziejewski, 2002
Inflation gas reaction	The inflatant gas reacts with a permeable substrate, causing chemical rigidization.	Simple, active/passive	Non-uniform curing can occur.	Cadogan (1998)
Foam inflation	An expanding foam inflates the structure and then hardens as it dries.	Simple, passive	Inability to inject/distribute the foam before swelling/drying.	Tinker et al. (2002)
Hydrogel evaporation	A flexible fabric hardens as the impregnated water-soluble resin evaporates.	Simple, passive, fullyreversible, evaporation rate can be controlled	The hydrated material must be kept in high humidity/pressure environment prior to solvent 'boiloff,' shrinking and geometric instability can result from mass loss due to outgassing.	Guidanean and Williams (2002)
Internal resistive heating	Electric current is passed through reinforcing conductive/resistive fibers in order to generate heat and cure the surrounding matrix resin.	Controllable, active technique, shorter cure times	Large power requirements for resins with high curing temperatures.	Naskar (2005)

were later used to prepare curing schedules implemented through temperate-controlled resistive heating.

Composite Materials

The composite materials used for this study are a PAN-based carbon-fiber tow coated with one of two thermosetting polymer resins. A high-tensile strength tow, Toho Besfight G40-800 (12k), provides reinforcement to the composite and is the medium to which the polymer matrix adheres. Using the inherent electrical resistivity present in the carbon-fiber tow, electric current passing through the material results in Joule heating, which increases the temperature of the composite. The adjacent thermosetting resin cross-links, forming a highly-branched polymer network, when the polymer is heated to a temperature above its cure onset temperature [8]. Embedding the carbon fibers in a more compliant, yet tougher resin matrix allows for transverse loads imparted onto the composite element to be transmitted through shear stress along the length of the fibers [12]. By controlling when cross-linking occurs and in prescribing how long it takes, internal resistive heating actively induces matrix consolidation for rigidization purposes.

Two thermosetting resins, U-Nyte® Set 201A and 201B epoxy binders, are employed for consolidation testing via resistive heating. Both are novel thermosetting resins developed by Hydrosize, Inc. and exhibit low cure-onset temperatures in the range from 100 to 150°C. These materials feature high glass transition temperatures, thermal stability, high cohesive and adhesive properties, and good solvent resistance [13]. The first resin, U-Nyte® Set 201B, is a bisphenol A toughened epoxy containing Amicure AMI-2 (a cure accelerator). U-Nyte® Set 201A lacks the Amicure curing agent, which postpones the onset of curing, and was developed in order to lower the melt viscosity for improved processing. Researchers at Clemson [11] used Ultem poly(etherimide) (PEI) thermosetting resin developed at GE Plastics. Comparatively, Ultem resin offers many of the same advantages (high T_g, excellent thermal stability, and chemical resistance [14]) as the U-Nyte® Set but requires a much higher curing temperature (380°C).

The carbon fiber tow was coated with the resin using a dry powder 'prepregging' system (DPPS) [11]. It was determined that the resin mass fraction of the coated tow ranged from 40–60%. A typical sample used in this study was a 15–20 cm (6–8 in) length of the resin-coated fiber tow.

Preliminary Resin Analysis

Differential scanning calorimetry (DSC) was performed to experimentally measure the glass transition temperature and cure temperature for each U-Nyte® resin. A TA Instruments Q1000 DSC at a heating rate of 5°C/min was used to study the key thermal events of these materials. This type of thermal analysis provided a method for verifying the curing behavior of the U-Nyte® Set 201B as stated by Hydrosize and also obtaining similar data for the U-Nyte® Set 201A resin. The DSC thermograms were later used to design successful curing profiles for the resin-coated tow composites. Parallel plate rheometry, using a TA Instruments AR1000, was also performed in order to measure the melt viscosities of the resins prior to curing. The temperature was increased in 5°C increments every 3 min throughout these tests.

Table 2. Key U-Nyte® Set epoxy resin properties.

Resin type	Melting	Key temperatures (°C) Cure onset	Key temperatures (°C) Peak curing exotherm	Advantages	Disadvantages
201A	50–60	167	197	More fluid-like in the melt	Has higher curing temperatures
201B	60–75	100	150	Lower curing temperature	Does not 'flow' well in the melt

The thermal analysis obtained through DSC provided information about key thermal events in the heating of the resins (Table 2). Though similar in shape, the temperatures at which melting and especially curing are different. The U-Nyte® Set 201B resin experienced melting as the temperature increased from 70–90°C, with an endothermic peak located at 75°C. Cure onset for this material occurred at 100°C and the curing exotherm peaked at 150°C. The U-Nyte® Set 201A resin experienced a much later cure onset temperature at 167°C. Rheology testing on 201A resin indicated that with an increased temperature window prior to cure onset, a minimum viscosity of 14 Pa-s was measured at 170°C. Compared with the U-Nyte® Set 201B resin, which did not flow well and ultimately cured, the 201A resin trades a lower cure temperature for better rheological properties. The ability of this material to melt, flow, and wet the fibers adequately prior to cure onset increases the strength and effectiveness of the rigidized composite [12].

Cure Schedule Design

The goal for rigidization is to transform the material from an initially flexible state to a rigid one. In effective composite rigidization, the resin particles consolidate around the reinforcing fibers creating a continuous resin matrix. Loads imparted onto cured composites are directed through the polymer and transferred to fibers along their axial direction [12]. The respective curing profiles were designed using the results of the thermal analysis of each resins (Table 2) and were selected so as to induce resin particle softening and consolidation prior to the gel point [19].

Curing temperatures of 200 and 150°C were chosen for the 201A and 201B resins, respectively, by selecting the peak curing exotherm locations from the DSC results. Intermediate *flow* regions (located between the melting and cure onset temperatures for both resins) of 85°C for 5 min were included in the heating schedules to facilitate resin consolidation prior to cure onset. Previous experiments with these materials demonstrated that if the cure temperature was achieved too quickly, the resin particles would cure before consolidating. Samples cured in this manner were inherently weaker as the cured resin particles could not transfer load effectively to the reinforcing fibers. A constant heating (and cooling) rate of 30°C/min was selected for increasing (and decreasing) sample temperature throughout the test. A representative curing profile along with the actual heating schedules prescribed to the two types of samples in this study are illustrated in Figure 1.

RIGIDIZATION THROUGH RESISTIVE HEATING

Methods for establishing temperature-controlled resistive heating and quantifying the change in the composite materials subjected to resistive heating curing schedules were

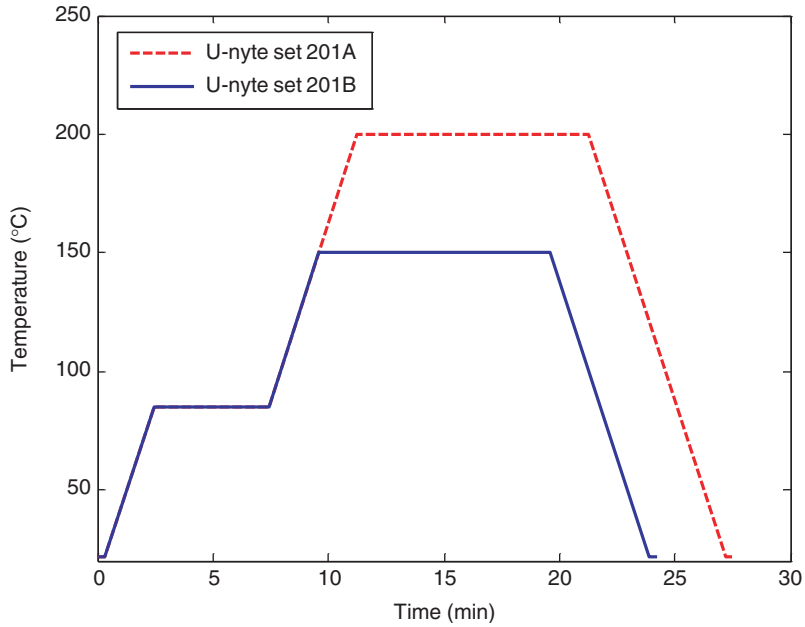

Figure 1. *Resistive heating temperature profiles were designed from DSC results on the U-Nyte® epoxy resins investigated in this study.*

first developed. The results and discussions of material rigidization through temperature-controlled resistive heating then follow.

Controlled Resistive Heating

Feedback control, using a proportional-integral (PI control algorithm, was selected to administer control over) the resistive heating process. This method, which relies on comparing a measured variable (i.e., temperature) to a desired value, eliminates the need for precise system modeling and can even minimize the effects of external disturbances. It has been previously shown that feedback temperature control allows for tailored curing schedules to be prescribed for composite consolidation [18,19].

Experiments in temperature-controlled resistive heating were performed by fixing a 15–20 cm (6–8 in) long sample of resin-coated tow at each end (Figures 2 and 3). Omega J-type (iron–constantan) thermocouples (36-gage, 0.13 mm) placed at two separate locations along the sample measured temperature. An additional thermocouple was also used to record ambient air temperature. Three signal conditioners (Omega #CCT-22-0/400C) with ranges of 0–400°C provided cold-junction reference points for each thermocouple and produced 0–10 V voltage signals proportional to each measured temperature. These voltage signals were then input into dSpace and converted into temperature values in Simulink. A proportional-integral (PI) control algorithm compared the maximum of the measured temperatures (in efforts prevent overheating the sample) with the desired temperature and produced a voltage signal designed to minimize this difference. This voltage (generated in Simulink/dSpace and amplified by a Xantrex XHR 300V-3.5A DC Power Supply/Amplifier) was applied across the length of the sample,

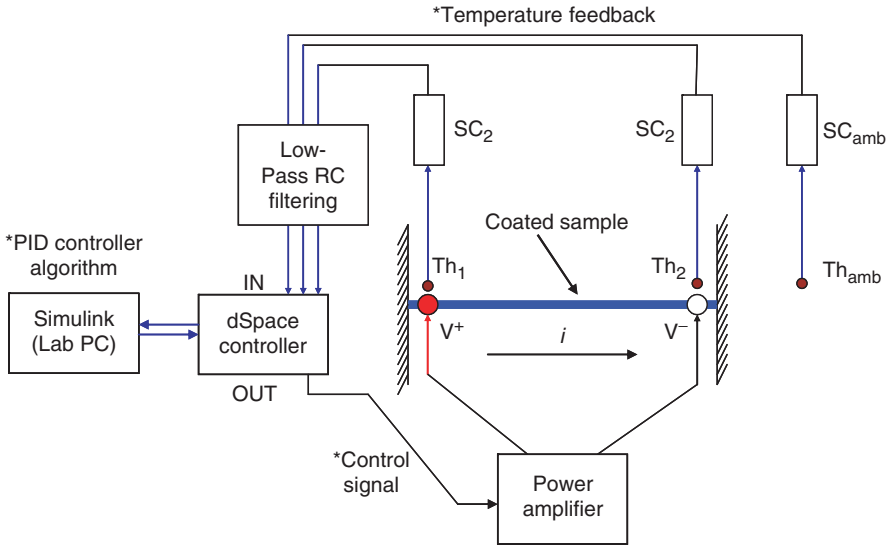

Figure 2. *The experimental setup used for feedback temperature control relied on measured temperature and comparing it to a desired value.*

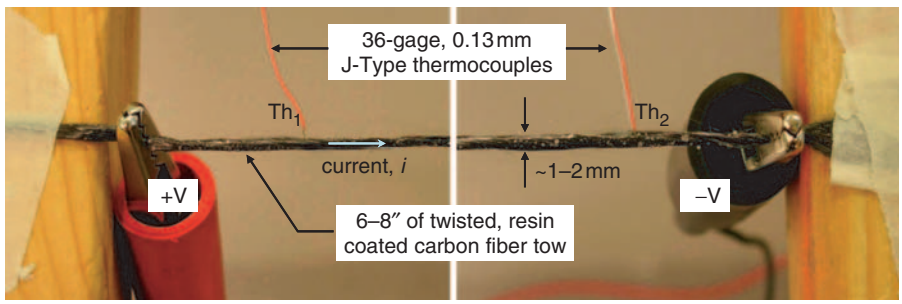

Figure 3. *Samples were fixed on each end and alligator clips were used to send electric current through the material. Note that only the ends of the entire sample are shown.*

resulting in current flow through the material. The temperature change due to heating from this current signal was then measured in subsequent sampling events. The described process repeated each time a new sample temperature was taken (a sampling rate of 5 Hz was used for this study).

A representative heating cycle and measured sample temperature is shown in Figure 4. Accurate temperature tracking (1.1°C RMS or 3.3% error) was achieved with a proportional-integral (PI) feedback controller [20] (additional experimental details on tuning the feedback control system can be found in this reference). The curing profile chosen in this case was arbitrary, though it demonstrates that feedback temperature control allows resistive heating to provide material-specific curing profiles of nearly any form. The ability to minimize temperature overshoot also ensures that this process can heat samples to desired temperatures without overstepping the mark. In cases where sub-cure onset temperatures are required, this measure prevents unwanted resin curing.

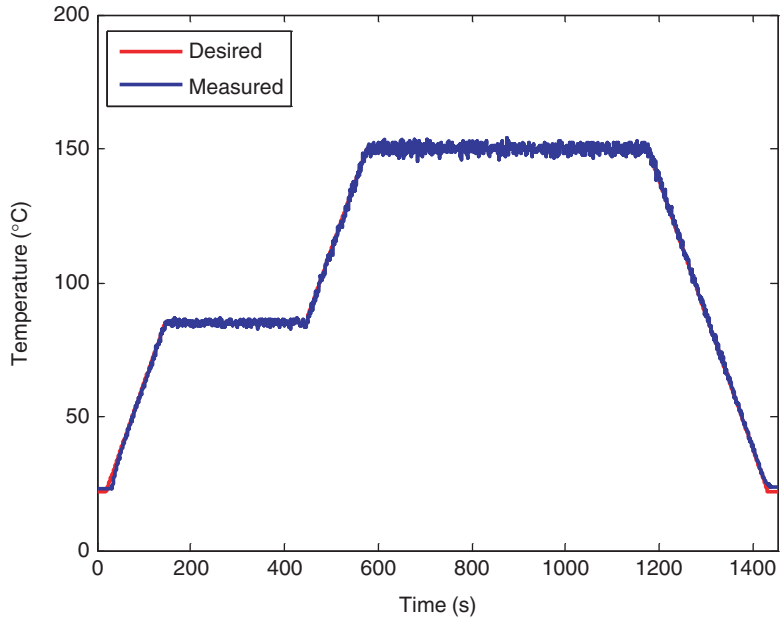

Figure 4. *Feedback control provides accurate temperature tracking and was used to realize a desired heating routine.*

The risk of overheating the sample and causing degradation at extreme temperatures is also eliminated.

Rigidization Quantification

An instrumented bending strength test fixture was designed to quantify the increase in composite strength gained through resistive heating. In this experiment, a sample fixed at each end was deflected at its midpoint. A 100 g load cell (Transducer Techniques GSO-100) measured the deflection force while a laser vibrometer (Polytec OFV 303 Sensor and OFV 3001 Controller) focused on the load cell (Figure 5) recorded displacement data. The slope of a given force vs. deflection curve was obtained and used to quantify the resistance to bending acquired through matrix consolidation. This bending stiffness was measured as the instantaneous slope of the force vs. deflection curve at 90% of the maximum deflection. Uneven loading effects as well as local material deformation were deemed possible reasons for the observed non-linearity. However, the relationship became more linear at higher deflections. Stress and strain were not used in this test as inconsistencies in material composition resulted in imprecise calculations.

A TA Instrument Q1000 DSC was again used for post-resistive heating thermal analysis on hardened samples to qualitatively verify resin curing. Fully-cured composite samples were expected to exhibit a cured glass transition temperature near 110°C with no cure exotherm [13]. Quantitative cure completion was not evaluated as these tests were performed on composite samples that included both fiber and resin. Without knowing precise mass fractions of each component, the total amount of heat released during a cure exotherm could not be compared with that of the initially-uncured material. DSC testing was merely used to categorize the samples as either partially or fully cured.

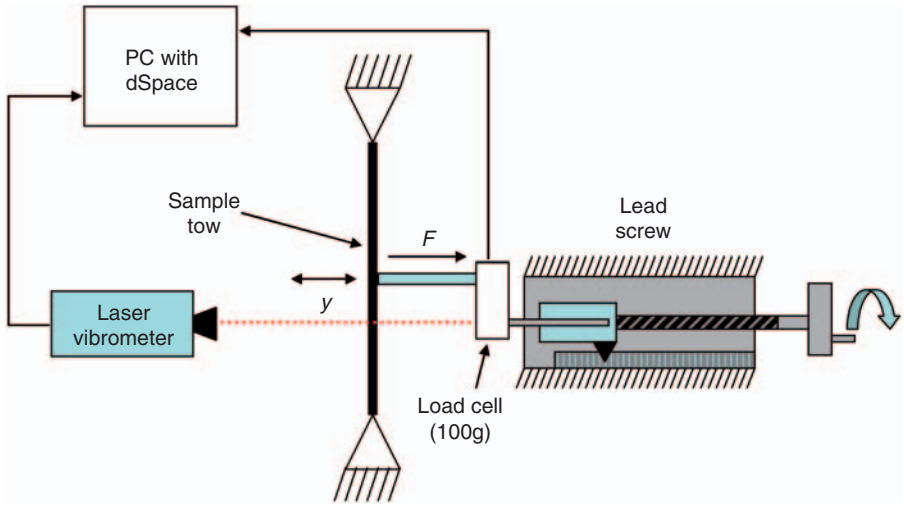

Figure 5. *The test fixture for measuring sample bending strength determined stiffness by recording the force required to induce a known deflection.*

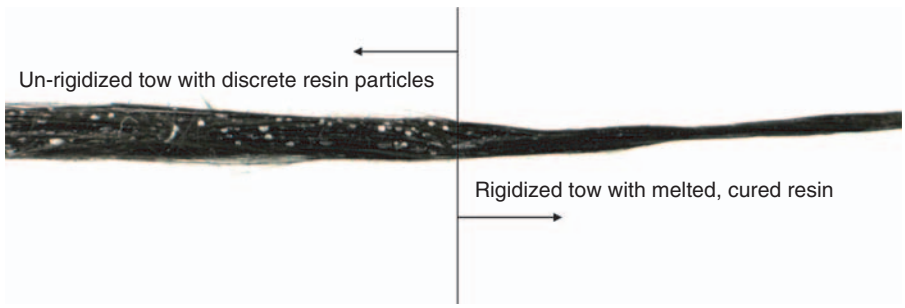

Figure 6. *Incorporating a flow region into the temperature profile caused the U-Nyte® Set resin particles to consolidate fully during their curing cycles.*

Rigidization Testing

Rigidization through controlled resistive heating was first tested on carbon fiber tow samples coated with U-Nyte® Set 201A and 201B, respectively. It was noticed that the resistive heating process produced a visible change in the appearance of the coated tow. In regions subjected to resistive heating (i.e., in the current flow path), the initially-discrete resin particles melted, consolidating around the carbon fibers. A comparison image of the unaffected, flexible material and consolidated composite is shown (Figure 6). Mechanical stiffness values and DSC analysis for the two resin types demonstrated that both resistive heating schedules caused matrix consolidation and resin curing (Figure 7). The cured samples were 14–21 times stiffer than the flexible, uncured material and exhibited little if no additional curing exotherms during DSC. The two heating routines required roughly 1.60 and 1.10 W-hr of electrical energy (during 27 and 24 min of heating, respectively) for the tows coated with 201A and 201B resins, respectively. Normalizing the electrical energy per unit lenth of the sample, this transformation required 0.08–0.11 W-hr/cm of rigidizable

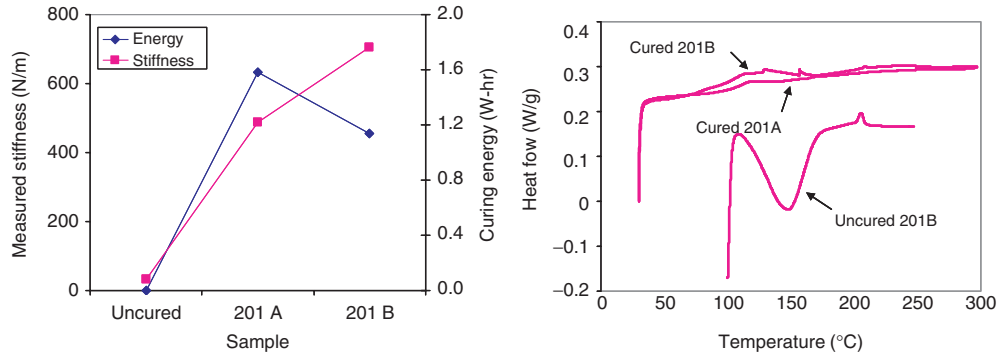

Figure 7. *Measured mechanical stiffness (left) and cure completion via DSC analysis (right) for U-Nyte® Set 201A and 201B composite samples.*

material for the tested schedules. Peak electrical power, corresponding to the maximum temperature attained in each cure profile, ranged from 5–8 W.

The rigidization of these materials was performed in a manner to both compare the different thermosetting resins as well as demonstrate effective rigidization with the newly developed resistive heating scheme. Samples coated in the U-Nyte® Set 201B measured larger stiffness values, though composites containing this resin are not necessarily stronger. This resin was finely ground with mortar and pestle prior to fiber coating in order to increase its melting capability before curing. A smaller particle size, which increases how well the resin adheres to the fiber tow during the pre-pregging process, and a heavier resin distribution have probably influenced the rigidity of these specific samples. This test also illustrated that the U-Nyte® Set 201A resin required more energy to achieve a full cure. Though it benefits from better rheological (flow) properties in the melt, the lack of Amicure curing agent shifted its cure onset temperature from 100 to 150°C. A higher curing temperature translates into larger supplied electrical energy. The two resins that were tested are not equal, and their individual attributes necessitate different curing profiles. The primary strength of this study was to demonstrate that resistive heating can be used to cause full matrix consolidation and complete curing for effective composite rigidization.

Comparing to previous work on Ultem resin [11], which required more than 340 W of peak power, U-Nyte® Set 201-coated tow samples fully cured and rigidized with the application of 5–8 W of peak power and 1.10–1.60 W-hr of total electrical energy. Though the amount of material and test configuration were not equal, the reduction in curing temperature from 380°C for the Ultem to 150°C for the U-Nyte® Set is listed as a major factor in reducing the energy supplied to the material.

Intelligent Cure Schedule Design

Further testing on samples of resin-coated fiber tow was performed to identify ways to shorten the heating time and reduce the required amount of energy while still achieving substantial stiffening and complete resin curing. Specifically, the relationship between the prescribed curing temperature and curing time was investigated. The results of the first study on samples containing U-Nyte® Set 201A and 201B resins (Figure 7) confirmed that complete curing was achieved at curing temperatures of 200 and 150°C, respectively,

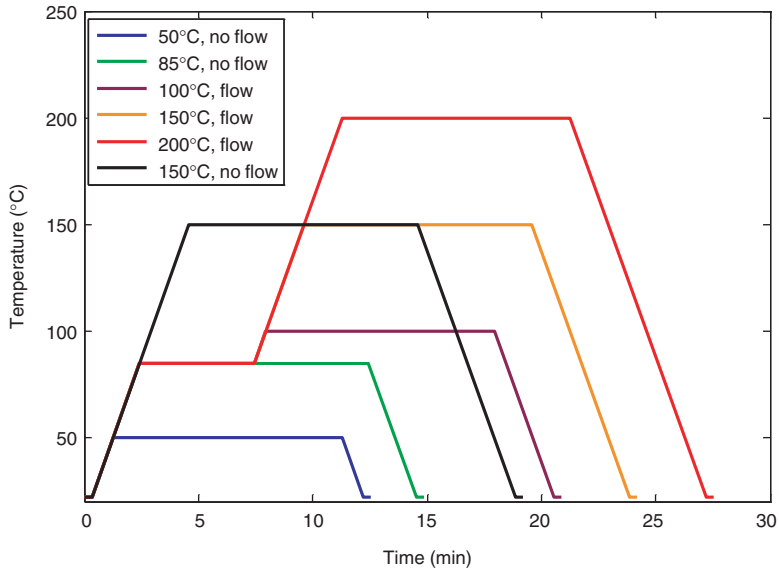

Figure 8. *The curing temperature was varied between 50 and 200°C in order to relate this design parameter to the resulting rigidization.*

in 10 min. However, does this requirement change at different curing temperatures and is this the minimal amount of time required to produce fully-cured samples? Two studies, one in which the curing temperature was varied and one where the curing time (dwell time at the curing temperature) was varied, outline the relationship between temperature and time. These tests were performed on U-Nyte® Set 201B-coated tow as this material demonstrated significant rigidization at a lower temperature and reduced energy level. The DSC results of this resin identified cure-onset to occur at roughly 100°C, with the peak curing exothermic reaction located near 150°C.

In varying the maximum (curing) temperature, a dependence on temperature for both the strengthening effect due to consolidation and resin curing (crosslinking) was gained. The various heating routines prescribed during this study (Figure 8) ranged between 50 and 200°C and include *flow* regions for some samples. The results of this study verified that while stiffening (consolidation) occurred in samples heated above the melting point, full curing in 10 min happened only for the samples heated to temperatures above 100°C. The last sample, '150, no flow' in Figure 9 was heated to 150°C but not given a distinct flow region. Full-curing and a large increase in stiffness over the unheated material were still seen as the resin consolidated during the heating process prior to curing. Because the overall process for this cycle was shorter, less energy was consumed. However, a sufficiently slow heating rate (30°C/min) and additional resin grinding for the U-Nyte® Set 201B material provided test-specific conditions that promoted effective consolidation without the additional flow period.

Curing time was also considered as the rate of polymerization increases with increasing temperature [8]. The previous test demonstrated that 10 min of curing at 150°C resulted in fully-cured materials, while samples heated to only 100°C resulted in partial curing. By allowing the samples to cure longer at a temperature of 100°C, cure completion is expected. Conversely, a cure temperature of 150°C may permit shorter curing times

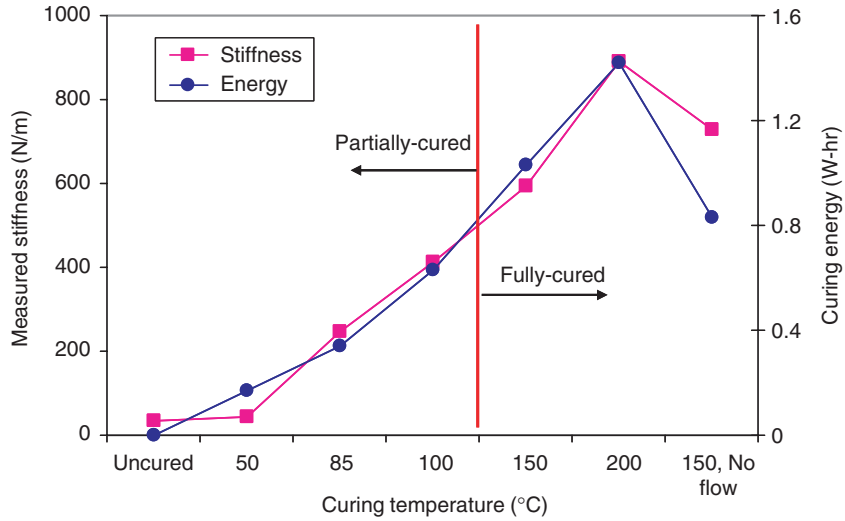

Figure 9. *The resistance to bending and the required energy increased with increasing curing temperature. Samples heated to 150°C or higher demonstrated no additional curing exotherms in the DSC thermograms.*

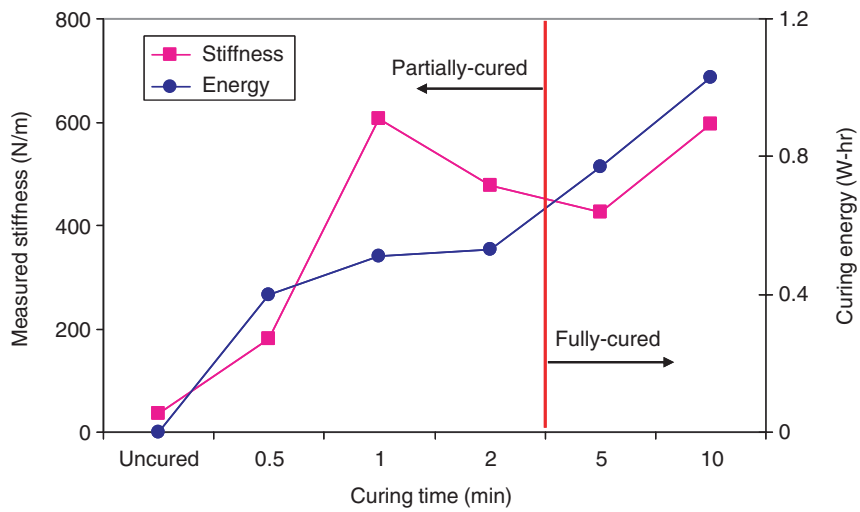

Figure 10. *Increasing the time at which the material was held at a curing temperature of 150°C resulted in increasing stiffness and required more energy. Samples cured for less than 5 min exhibited only partial resin cross-linking.*

and still produce complete curing. An experiment in which the curing time was decreased from 10 min down to 30 s illustrated this concept. The results of this study show that for a curing temperature of 150°C, 5 min of dwell time is required to achieve full resin curing (Figure 10). However, samples cured at this temperature for a less amount of time still demonstrated significant stiffening. Variations in resin/fiber composition between samples may explain the unexpectedly high stiffness for 1 min of curing. Compared to the base

curing profile, which included 10 min at 150°C, this test asserts that curing the sample for half the time (5 min) produces roughly the same amount of stiffening and a fully-cured resin matrix. The resistive heating process has been shortened and the total electrical energy was reduced from 1.0 to 0.8 W-hr, a 20% savings in both time and energy.

This discussion is meant to clarify that prescribing rigidization through resistive heating allows for the curing schedule to be intelligently chosen. Variations in the curing temperature as well as curing time affect both the mechanical stiffening as well as the long-term stability of the polymer composite. Further, these routines should be selected in order to minimize the cost of rigidization – both in the amount of energy to be supplied as well as the time that it takes to transform the material from a vulnerable state to one that is permanently robust. It should also be emphasized that consolidation and curing can be triggered independently, and the increase in stiffness alone does not provide the long-term chemical stability characterized by fully-crosslinked materials [8].

Rigidization of a Simple Structure

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 [15], are used to support the Inflatable Sunshield In-Space (ISIS) [16], and make up the supporting strut system of many inflatable antenna and solar concentrators [2]. In defining the success of such a demonstration, a composite boom was constructed such that it could be given shape via an internal air pressure and then permanently rigidized via temperature-controlled resistive heating. 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. Kapton 200HN (50 μm, 2 mm thickness) polyimide film was chosen for this role. This space-durable material, used widely in the fabrication of many inflatable space structures, is also used in circuit board, wire, and capacitor insulations.

Temperature-controlled resistive heating was used to consolidate the rigidizable material incorporated onto the boom structure. The method of applying the rigidizable materials to the boom created a single path for current flow through the composite. As a result, the same resistive heating experimental set-up (Figure 2), using two voltage leads to apply a voltage potential across the length of the coated tow, was used here. Measuring the strength of stiffened structure was then carried out by fixing the boom in a cantilevered configuration and recording the maximum tip load that could be successfully carried by the boom (both before and after resistive heating) without buckling. The boom was tested without any inflation supply as inflatable structures are evacuated after rigidization concludes.

The rigidizable material (U-Nyte® Set 201B resin-coated carbon fiber tow) was applied to the boom in a serpentine path (Figure 11). The resistive heating cure schedule prescribed consisted of curing the boom at 150°C for 10 min, following a 5 min resin-softening period at 85°C. This curing schedule, identical to that for U-Nyte® Set 201B-coated tow in Figure 1, was selected for its effective matrix consolidation (for strength) and complete resin curing (for durability). Rigidizing the boom, which incorporated nearly 127 cm of rigidizable material, required more energy than previous tests on short samples. The described curing profile demanded 4.8W-hr of energy with roughly 20–25W of power

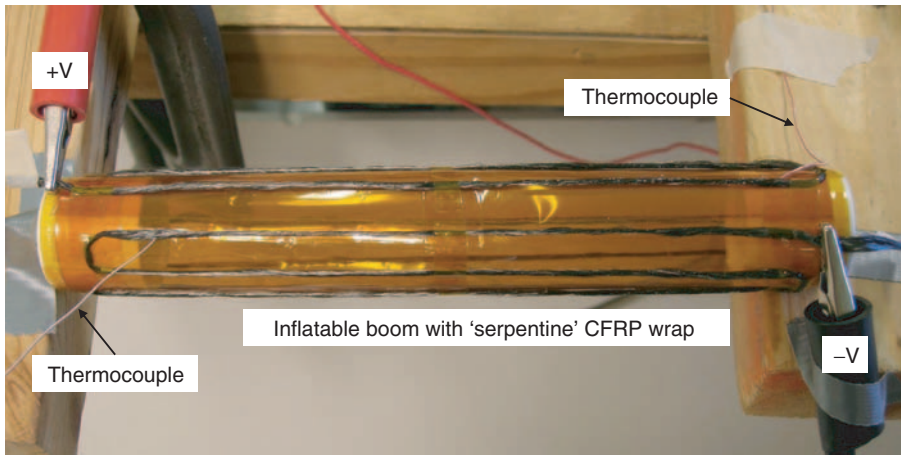

Figure 11. *Boom rigidization was accomplished by taping U-Nyte® Set 201 B coated-tow to the Kapton substrate and then curing this material through temparature-controlled resistive heating.*

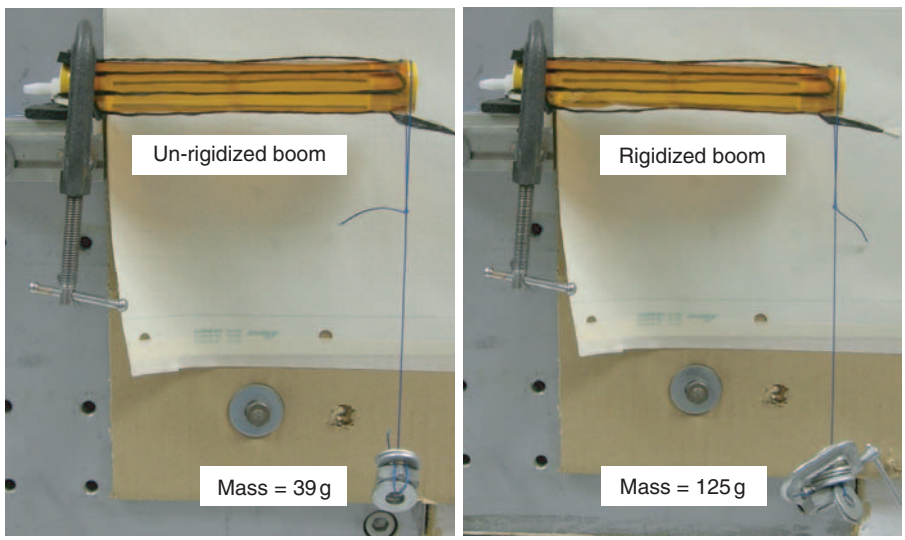

Figure 12. *Cantilevered boom testing demonstrated the increased strength gained in the CFRP material through the prescribed resistive heating schedule.*

at required at the curing temperature. Due to the selection of the same heating profile, the overall process time remained at 24 min. The un-rigidized boom withstood a tip load of 39 g, though it failed when loaded with 47 g. The rigidization process increased this capacity for the boom. Post-rigidization, the boom held a load of 125 g and eventually failed at roughly 127 g. The inflatable boom carried three times as much load after curing the material via temperature-controlled internal resistive heating. Roughly 127 cm (50 in) of material was used in order to provide the strengthening of the boom.

The application of this rigidization technique demonstrated that temperature-controlled resistive heating of thermoset-coated carbon fiber tow can be used to

strengthen structures. In addition, the supplied electrical energy per amount of rigidizable material was found to be less than that for the consolidation and curing of short samples. The heating routine for the boom consumed 4800 W-hr of energy per kilogram of coated tow, a 40% decrease from the 8000 W-hr/kg requirement of individual U-Nyte® Set 201B-coated tow samples. This decrease in energy is likely attributed to the presence of the Kapton substrate in close proximity to the rigidizable material. Heat lost to convection is reduced as the Kapton, an electrically and thermally isolative material, limits heat loss. For real space structures, the rigidizable material may be incorporated within a multi-layered composite structure, laminated between layers of substrate. A configuration like this is expected to further reduce the energy requirement for heating the CFRP while providing additional strength through shear lamination. It should also be noted that the tests discussed in this article were performed in the ambient environment and heat lost was primary due to convection. Radiative heat loss is expected to dominate in-space and the design of such a structure should account for this occurrence.

The testing and methodology presented in this study 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 qualified internal resistive heating as a method for strengthening thermosetting-composite structures. In the event of using a woven carbon fiber fabric [17], both the energy required (due to a much higher electrical resistance) and the strength gained through rigidization are expected to increase substantially.

CONCLUSIONS

Temperature-controlled internal resistive heating was established for the active rigidization of flexible, thermoset-coated carbon fiber composites. This study investigated temperature-control via a proportional-integral (PI) feedback control strategy in order to prescribe and maintain accurate resistive heating schedules. Results of preliminary thermal analysis on the thermosetting materials were used to develop resin-specific curing profiles. Mechanical strength testing and post-resistive heating DSC were employed to evaluate the stiffness and cure completion of materials heating in this fashion. Active rigidization was demonstrated on a small, 'inflatable' boom structure for the purpose of causing increased strength and load-carrying capacity. Direct application to inflatable, rigidizable space structures is envisioned, though additional attention to methods of reducing electrical energy consumption, lowering the curing temperature of the resin, and introducing woven carbon fiber are needed to scale-up this technology.

ACKNOWLEDGMENTS

The authors of this study would like to acknowledge Dr. Judy Riffle, Mark Flynn, and Thompson Mefford for their assistance in obtaining and testing the thermosetting resins. Andy Brink of Hydrosize, Inc. was instrumental in allowing this research to happen by providing the novel U-Nyte® Set thermosetting materials. Financial support provided by an IGERT Fellowship from the National Science Foundation is also recognized.

REFERENCES

1. Koelle, D. (2003). Specific Transportation Costs to GEO – Past, Present and Future, *Acta Astronautica*, **53**: 797–803.
2. Cadogan, D. and Scarborough, S. (2001). Rigidizable Materials for use in Gossamer Space Inflatable Structures, In: 42*nd AIAA SDM Conference Proceedings*, AIAA-2001-1417.
3. Cadogan, D., Grahne, M. and Mikulas, M. (1998). Inflatable Space Structures: A New Paradigm for Space Structure Design, In: *49th International Astronautical Congress Proceedings*, No. IAF-98-I.5.01.
4. Freeland, R. et al. (1998). Inflatable Deployable Space Structures Technology Summary, In: 49*th Congress of International Astronautical Federation Proceedings*, No. IAF-98-I.5.01.
5. Lichodziejewski, D., Veal, G. and Derbès, B. (2002). Spiral Wrapped Aluminum Laminate Rigidization Technology, In: 43*rd AIAA SDM Conference Proceedings*, No. AIAA-2002-1701.
6. Guidanean, K. and Veal, G. (2003). An Inflatable Rigidizable Calibration Optical Sphere, In: 44*th AIAA SDM Conference Proceedings*, No. AIAA-2003-1899.
7. Guidanean, K. and Lichodziejewski, D. (2002). An Inflatable Rigidizable Truss Structure Based on New Sub-T_g Polyurethane Composites, In: 43*rd AIAA SDM Conference Proceedings*, No. AIAA-02-1593.
8. Chanda, M. (2000). Chapter 1: Introductory Concepts and Definitions, *Advanced Polymer Chemistry*: *A Problem Solving Guide*, p. 27, Marcel Dekker, Inc., New York, NY.
9. Allred, R., Hoyt, A. and Harrah, L. (2004). Light Curing Rigidizable Inflatable Wing, In: *45th AIAA SDM Conference Proceedings*, No. AIAA-2004-1809.
10. Schwartz, S., Jones, R. and Keller, L. (1963). Ultraviolet and Heat Rigidization of Inflatable Space Structures, *Aerospace Expandable Structures Conference Transactions*, pp. 369–380.
11. Naskar, A. and Edie, D. (2005). Consolidation of Reactive ULTEM Powder Coated Carbon Fiber Tow for Space Structure Composites by Resistive Heating, *Journal of Composite Materials*, **40**: 1871–1883.
12. Hyer, M. (1998). Chapter 1: Fiber-Reinforced Composite Materials, *Stress Analysis of Fiber-Reinforced Composite Materials*, pp. 4, McGraw-Hill Companies, Inc., United States.
13. U-Nyte® Set 201 Reactive Epoxy Binder, Hydrosize Technologies, Inc., http://www.hydrosize.com/products/binders/set-201/index.html
14. Ultem PEI Resin Product Guide, GE Plastics, http://www.geplastics.com/gep/Plastics/en/ProductsAndServices/ProductLine/ultem.html
15. Derbès, B. (1999). Case Studies in Inflatable Rigidizable Structural Concepts for Space Power, 37*th AIAA Aerospace Sciences Meeting*, No. AIAA-99-1089.
16. Sandy, C.R. (2000). Next Generation Space Telescope Inflatable Sunshield Development, 2000 *IEEE Aerospace Conference Proceedings*, **6**: 505–519.
17. Tsunoda, H. and Senbokuya, Y. (2002). Rigidizable Membranes for Space Inflatable Structures, In: 43*rd AIAA Structural Dynamics and Materials Conference*, No. AIAA-2002-1367.
18. Sarles, S.A., Bullions, T., Mefford, T., Riffle, J. and Leo, D. (2006). Carbon Fiber Reinforced Rigidizable Space Structures, *Materials and Devices for Smart Systems II*, Yasubumi Furuya, Ji Su, Ichiro Takeuchi, Vijay K. Varadan and John Ulicny (eds), (*Mater. Res. Soc. Symp. Proc.* **888**, Warrendale, PA, 2006), 0888-V02-06.
19. Sarles, S.A. and Leo, D.J. (2006). Active Rigidization of Carbon-fiber Reinforced Polymer Composites for Ultra-lightweight Space Structures, *Smart Structures and Materials 2006*: *Smart Structures and Integrated Systems*; Yuji Matsuzaki (ed.), (Proc. SPIE Vol. **6173**, pp. 363–374).
20. Sarles, S.A. (2006). Active Rigidization of Carbon Fiber Reinforced Composites via Internal Resistive Heating, M.S. Thesis, *Virginia Polytechnic and State University*, Blacksburg, VA.