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News Release
Research Communications Office
Georgia Institute of Technology
Atlanta, Georgia 30332
(404) 894-3444

CONTACT: John Toon/Ginger Pinholster
(404) 894-3444

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Colton
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SOLAR HEAT, NATURAL VACUUM AND SPACE BALLOONS MAY ALLOW MANUFACTURE OF COMPOSITE PARTS IN ORBIT

Composite parts for future U.S. space structures could be manufactured in orbit using an ingenious system of inflatable balloons, containment bags, heat from the sun -- and the natural vacuum of space.

The system, proposed by researchers from the Georgia Institute of Technology in the current issue of SAMPE Quarterly, could also be modified to make three-dimensional composite parts on earth without the need for solid dies.

The technology would use a flexible resin-impregnated carbon fiber pre-preg material produced by an electrostatic deposition process under development at Georgia Tech.

Manufacturing the parts in orbit would increase by up to 70 percent the packing density of construction materials shipped into space, reducing the number of Space Shuttle trips needed. In ground-based applications, it could improve the quality and lower the cost of making three-dimensional composite parts.

"It's really a new kind of dieless forming that uses air pressure to replace the die," said Dr. Jon Colton, assistant professor of Mechanical Engineering at Georgia Tech. "We could form almost any size or shape of structure by weaving it properly, providing the appropriate constraints around the outside, and inflating it for consolidation."

Space Station components could be built from tubes of composite pre-preg material that would be woven on earth around a special air bladder similar to a balloon. The tubes would be collapsed and wound onto spools or stored in boxes for placement aboard the Shuttle.

Once in orbit, the tubes would be removed from the boxes, or cut to desired lengths from the spool. The air bladder would be inflated, pressing the tubes against a containment material which would control outside diameter and provide a protective outer shell. The tubes would then be placed into a solar oven which would concentrate sunlight to generate heat for consolidating the composite material. The natural vacuum of space would draw off the gases, Colton explained.

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Composite materials are cured inside a vacuum chamber on earth to eliminate small voids or gas bubbles which could weaken the structure. Colton believes the high vacuum of space would help improve the quality by better eliminating those voids.

But he concedes the existence of some technical challenges in obtaining consistent heating -- and weaving the shapes required.

Calculations show that a system of mirrors would provide enough heat to cure all areas of the tube, he said, though some areas would receive more heat than others. The tubes would be cooled by removing the mirrors and letting heat dissipate into space.

Producing three-dimensional shapes is another challenge. Current technology uses incremental heating and bending to gradually form thermoplastic composites into the desired shape. This technique is time-consuming and limited in the shapes that can be produced.

The flexibility of the composite pre-preg developed at Georgia Tech permits weaving operations which could produce a three dimensional structure ready for consolidation.

The pre-preg material, carbon fiber with PEEK resin, is produced using an electrostatic fluidized bed to coat the fiber tow with powdered resin. The tow is then heated to flow the resin, leaving a flexible fiber.

"Textile engineers can do an amazing job of weaving different shapes," said Colton. "By using the fiber structure itself to provide the shape, we could eliminate the need to make metal dies now used for forming composite parts."

Since air pressure within the balloon would expand to fill the entire structure, quality might also be improved.

"Pressure gets everywhere, so that should give a higher quality process," he said. "You would probably get a higher level of consolidation because metal dies are sometimes mismatched or not closed properly, allowing variations in thickness or producing areas not cured uniformly."

Previous proposals for producing composites in space use a process called pultrusion, which involves forcing composite material through a heated die in the shape of the final part. I-beams and other structure members can be fabricated in this way.

Colton would like to pursue more fundamental research into the structure of fiber and how the resin flows around it. From there, he will pursue refinements of the dieless processing techniques and produce prototypes for testing.

# # #

On-Orbit Fabrication of Space Station Structures

Dr. Jonathan Colton, Jed Lyons, Bob Lukasik, John Mayer,
Stefan Witte, and Dr. John Muzzy
Georgia Institute of Technology
Composites Processing Laboratory and
George W. Woodruff School of Mechanical Engineering
Atlanta, Georgia 30332-0405

Introduction

The Space Station is a critical component in many of the leadership initiatives of America's civilian space program. Planned to be operational by the end of 1990's, it will provide a platform from which to study and characterize the earth, maintain facilities to store large quantities of propellant, and assemble large inter-space vehicles.[1] The current baseline configuration for the Space Station consists of a truss network on which a power system, experiments, and pressurized modules are attached.[2] An erectable truss design was selected over a deployable design because the former is capable of growth in all three dimensions and can accommodate changes in operational needs.[3] Consequently, a major consideration in the design of the Space Station is on-orbit construction.

Space Truss Construction

On-orbit construction methods must overcome the difficulties presented by the space environment. Without a strong gravity field or a firm base on which to attach, some mechanisms which operate well on earth would send the machine and its operator spinning out into space. Consequently, moving masses must be counterbalanced. Components must function under extreme temperature variations, as they are alternately exposed to the sun's radiation and shielded in the shadows of the earth and of other components. The absence of a breathable atmosphere limits the amount of time that an astronaut has to perform extra-vehicular activities (EVA), and his pressurized suit affects the types of tasks that can be performed by restricting his movements. Automated processes are therefore preferred.

A key consideration for on-orbit fabrication of space structures is the cost of delivering materials and machines to the construction site. This will be performed by the Space Shuttles, which can deliver only what will fit into their 4.5 meter diameter cargo bay.[3] Hence, materials and machines must be packaged efficiently so that a minimum number of Shuttle missions are required.

NASA has conducted detailed studies on various approaches for constructing the Space Station on-orbit[2,3,4] and has chosen an erectable structure approach. Individual struts and connecting nodes are completely fabricated on earth and shipped into space. The Station is then erected strut by strut in orbit by the astronauts. The concept was proven feasible by the success of the ACCESS demonstration. In this experiment, a 10-bay truss was erected on an assembly fixture which was attached to the Space Shuttle. The assembly time for the 96 member truss was only 25 minutes, indicating the practicality and economy of on-orbit erected trusses.[5] A major disadvantage of this approach is the low packaging density of the prefabricated struts during transport.

A pultrusion process has also been proposed to fabricate the Station.[6] In concept, coiled stock material consisting of thermoplastic/graphite fiber prepreg is manufactured on earth. On-orbit manufacture of the structure is performed by pultrusion, using the coiled stock material. The finished pultruded sections are then cut to length and ultrasonically welded together to form the completed truss. This process has the advantage that the prepreg material would have a high storage density during transport. However, pultruded parts are limited in size and shape by the pulling force which results from the frictional forces developed in the die. Furthermore, a welded design prohibits replacement of truss members which are damaged by meteorites or accidental overloads. Repair procedures would require additional astronaut training and EVA time.

Abstract

A novel mold-less processing technique has been developed which uses gas pressure and bladders to produce tubular structural members out of which one can construct space truss structures. A woven or braided prepreg preform is produced on Earth and brought into orbit. Integral to the preform is an inner bladder which contains the gas pressure used in consolidation, and an outer layer which produces the counter-force needed for consolidation. Solar heating is used in conjunction with the gas to process the preforms into the final parts. This technique allows for the most efficient use of resources while providing for the flexible production of a wide size range of structures.

Proposed Preform Approach

A novel processing technique which forms unconsolidated earth-manufactured preforms into tubular space station truss members is described herein. The design calculations for this process can be found in reference 7.

As the material is not consolidated during transportation to orbit, 70% increases in storage density can be attained. The preform has three layers: an inner vacuum bag bladder, a woven or braided comingled thermoplastic and carbon fiber tube, and an outer bag to provide diameter control during consolidation. The outer layer could also provide protection from solar radiation.

The on-orbit consolidation process is essentially vacuum bag molding. The unconsolidated preform is gripped by inflation chucks which are inserted into the free ends. Gas is then injected into the inner bladder of the preform, which supplies the pressure necessary for consolidation. Focused solar energy is used to melt the thermoplastic and process the preform into the final shape. The composite is then sheilded from the sun and is quenched by radiation cooling to black space.

Upon consolidation, end connector fittings are attached. The connectors allow the Space Station to be constructed strut by strut; therefore, the design is compatible with existing NASA plans. Structural design changes are easily accommodated because the struts can be removed and/or replaced with the same techniques used to erect the truss.

The Preform

The consolidation process is essentially vacuum bag molding, with the vacuum on the outside and pressure applied internally. The unique design of the preform results in self-consolidating tubular composite structures.

Materials and Fabrication

Carbon fiber reinforced polyetheretherketone (PEEK) composites were introduced several years ago by ICI, Ltd.[8] The thermoplastic PEEK matrix has an indefinite shelf life and can be rapidly formed under pressures as low as 70 kPa.[9] The structural layer of the preform is an arrangement of woven or braided comingled thermoplastic fibers and carbon fibers.

The fabrication process, shown in Figure 1, begins with a mandrel upon which the inner bladder is placed. The first ply is woven or braided around the bladder. Multiple layers are then braided on top of each other, and stitched together as needed. The preform is then enclosed in the outer bag.

The inner bag is a polyimide film, such as is used in vacuum bag forming. When internally pressurized on-orbit, this bladder becomes an expanding die during consolidation of the preform. The outer bag provides the shape and outer diameter control for the tube as the composite is consolidated. Therefore, it must be strong enough to contain internal pressures up to 620 kPa, while being heated to the processing temperature of 380°C.

A recent study[10] showed that the orbital temperature variations in tubular space structures can be reduced from 111°C to 22°C by protecting the exterior tube surface with a low solar absorbance, low infrared emitting layer. The surface of the outer layer could be tailored to protect the load-bearing composite from radiation damage. Alternately, a radiation shield could be attached to the tube after consolidation.

Packaging

As the preform is not consolidated until it reaches the orbital construction site, it remains flexible, and is collapsed after it is woven. This saves precious space in the Shuttle cargo bay. The volume savings over the same amount of solid tubes increases with decreased preform stiffness. This is illustrated using the notation on Figure 2. If the 51 mm diameter preform is compressed so that the wall is bent to a 12 mm bend radius, then a space savings of 40% is realized. A preform wall bend radius of 6 mm radius yields a 70% savings.

Preforms can be packaged in continuous lengths rolled onto spools, or in discrete lengths pressed into boxes. Both of these methods are illustrated in Figure 3. The spooled preform has an end connector attached to the free end, which is preconsolidated. This assists in the on-orbit consolidation processes described later.

The canister with the collapsed preforms has an opening through which the preforms are grabbed. In the bottom of the canister is a springback that pushes the preforms against the opening as the top one is removed. The grommets attached to the inside edge of the ends are manufactured of a spring material, which ensure that the preform ends can be grabbed by the deployment and consolidation machinery.

Deployment

Preform deployment is the first process which is performed on-orbit. Before the preform can be consolidated, it must be removed from its packaging. The processing equipmment and the preform packing are combined in order to develop automatic deployment equip-

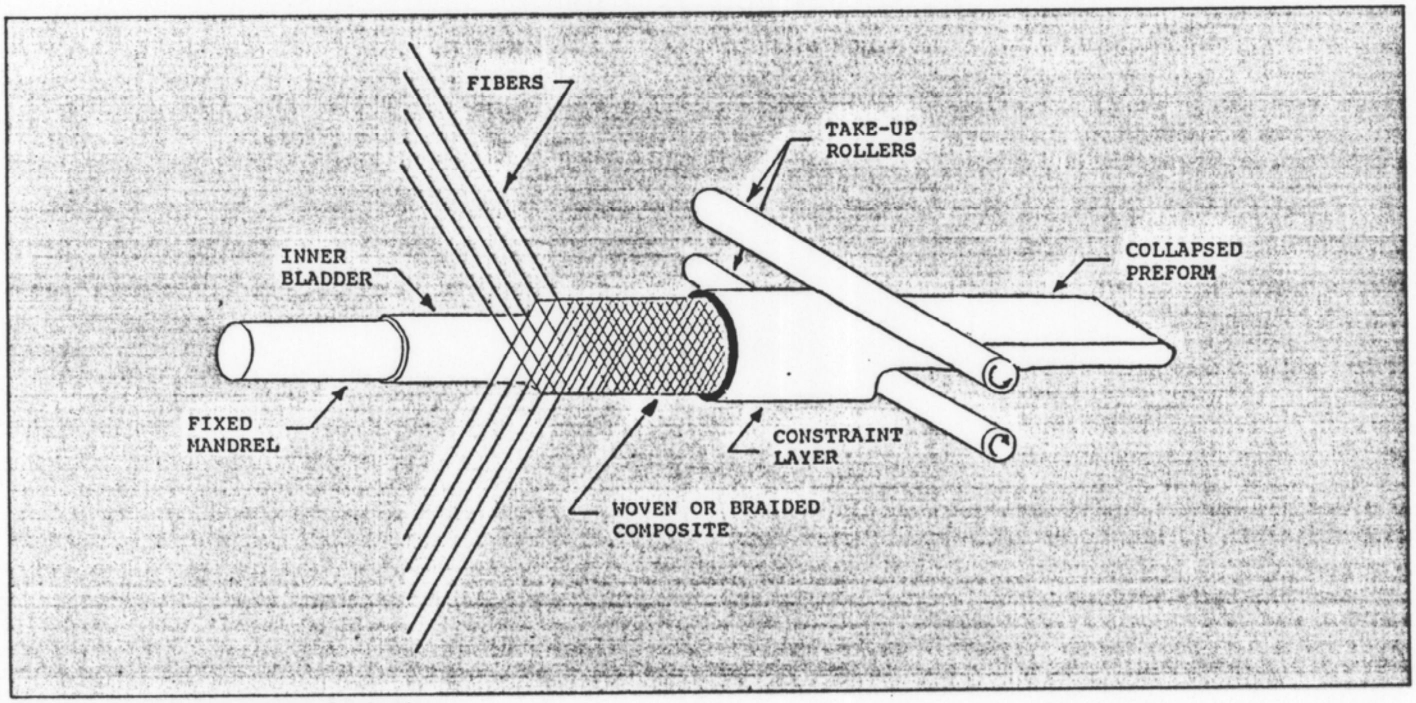

Figure 1. Earth-based preform fabrication

ment. The overall machine configuration is shown in Figures 4 and 5. The entire system can be collasped flat, and telescoped towards the preform containers, for ease of transport into space. This configuration also provides for ease of deployment once the system is in space. All of the telescoping members lock into place with spring loaded ball-locks, as the members reach their final positions.

Semi-Continuous Process

The spooled preform package is desirable if it is necessary to make consolidated struts of any length. The preform is deployed in a semi-continuous manner. First, a tube conveyor attaches to the existing end connector and pulls the preform off the spool. The tube conveyor pulls the end of the tube to the inflation chuck. At this point, the motor moving the conveyors stops and the spool is stopped by a damper. The inflation chuck is constructed such that it expands as the middle section is retracted. The expansion creates a seal between the chuck and the inner bag of the preform tube. The center section of the chuck is simply a hollow steel tube used to inject the gas into the tube. This is also used to release the gas after consolidation. The movement of the inflation chuck is accomplished using ball screws fitted with counterbalances to counteract the torque effects. The ball screws are turned by electric motors.

Simultaneously with the injection of the inflation chuck into the front end of the tube, a pinch mechanism constricts the aft end of the tube. This pinch mechanism provides for the seal of the inner bag at the aft end. The pinch mechanism works by using two oppositely threaded screws between flat plates which squeeze down on the preformed tubes.

Discrete Process

The exact size and shape of each part of any space station truss will be designed long before the astronauts get into space. This fact makes the deployment and consolidation of precut lengths of the preform more feasible. Figure 5 illustrates how the precut lengths of the preform material would be consolidated on orbit. Cartridges which contain collapsed preforms are plugged into the chucking assembly. The cartridges are designed so that the next preform pops up into position as each one is removed.

Inflation chucks move inside both of

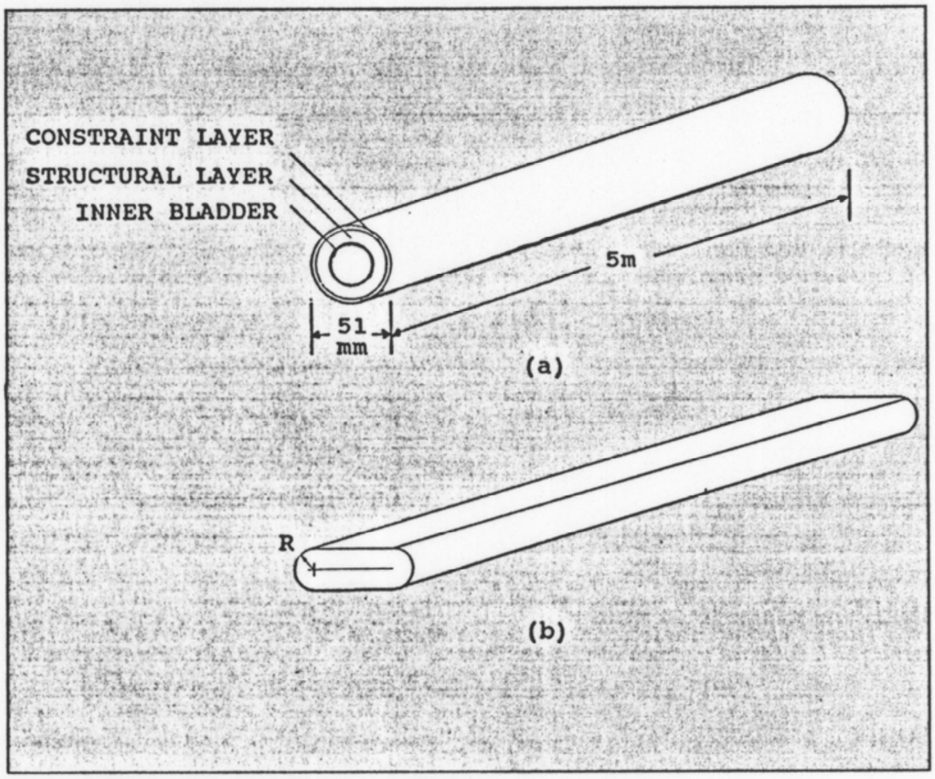

Figure 2. The preform: a) inflated, b) collapsed

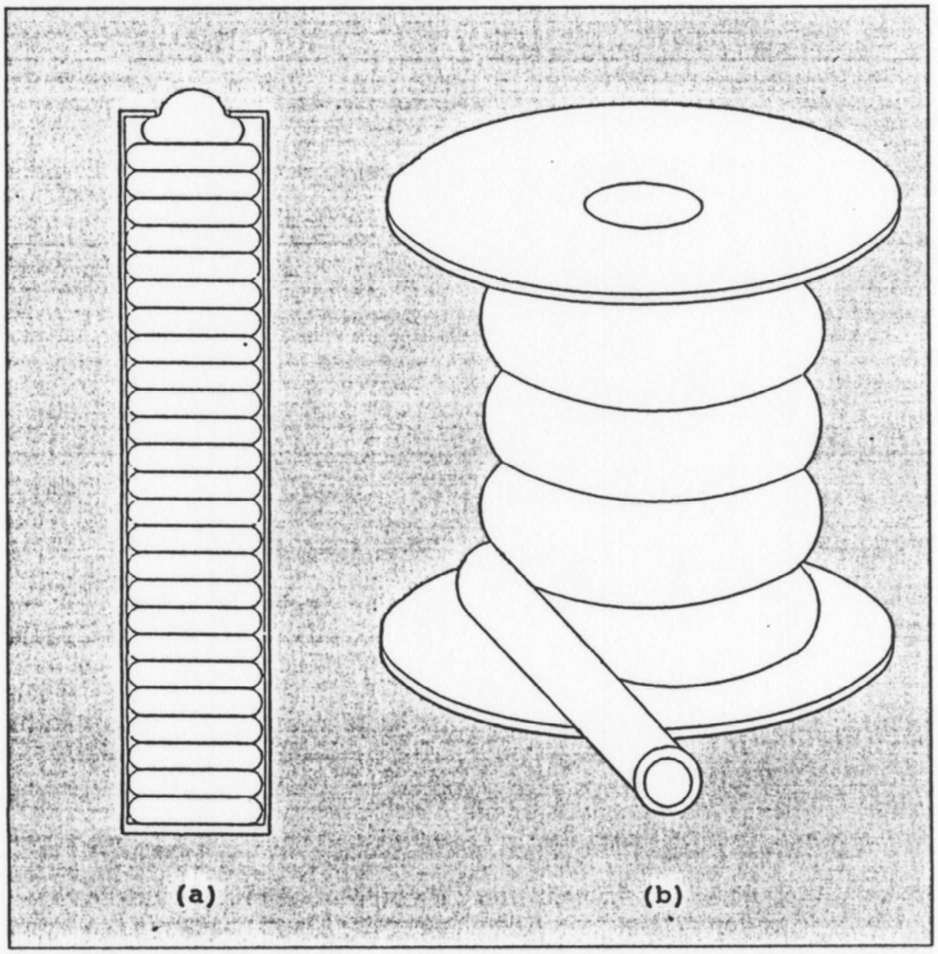

Figure 3. Packaged collapsed preforms: a) cartridge containing discrete lengths b) roll holding a continuous length

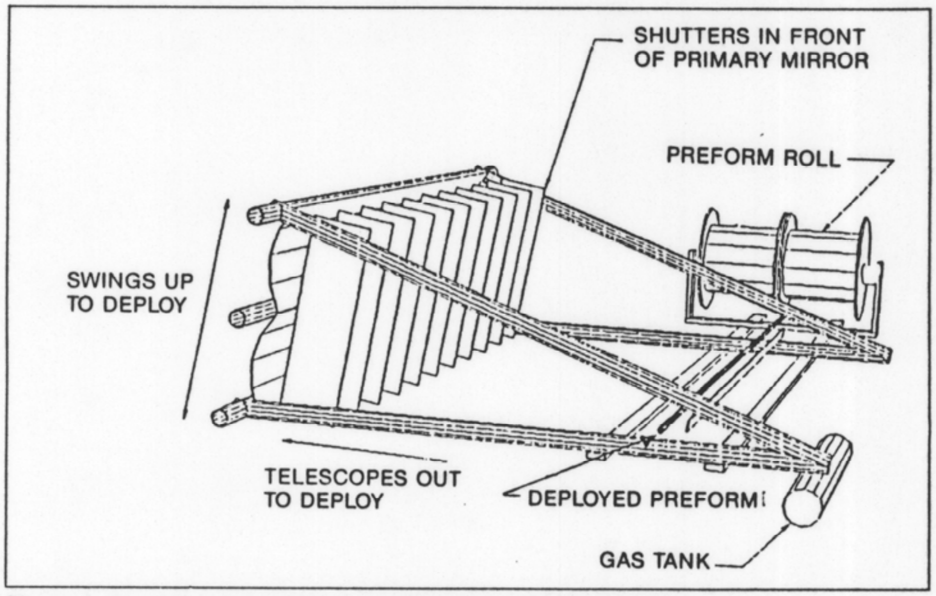

Figure 4. On-orbit semi-continuous preform consolidation device

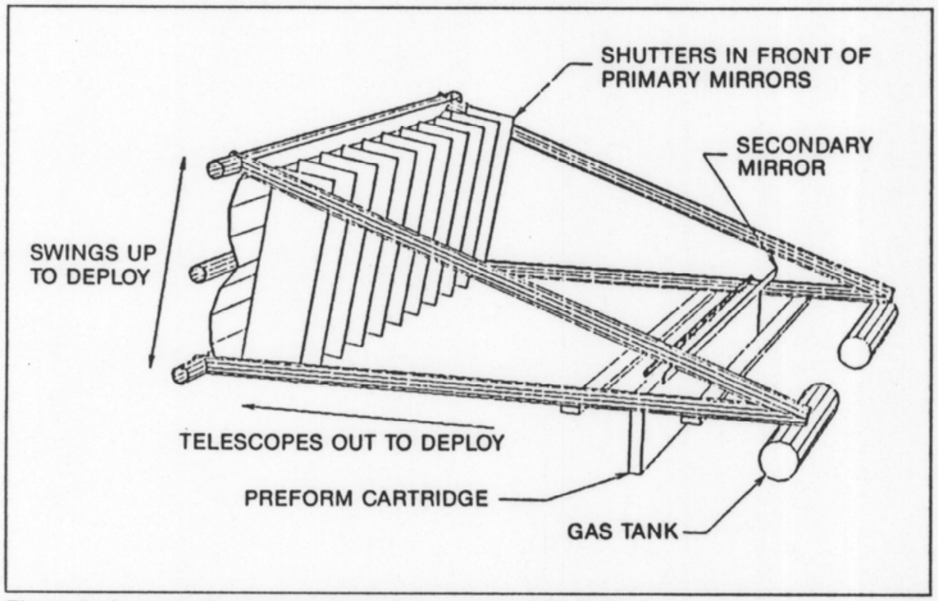

Figure 5. On-orbit discrete-length preform consolidation device

the opened ends, gripping the preform, as decribed above. A mechanism then removes the gripped preform and translates it to the consolidation position, which is directly above the preform cartridge.

Consolidation

Consolidation is the use of elevated temperatures and pressures to melt the resin and densify the different layers of the preform into a void-free tube. This process determines the quality of the product. The three major processing areas requiring control are as follows:

1. pressure application
2. consolidation heating
3. component cooling.

Pressure Application

Structural foams, gases, and fluids all have the potential to provide the internal pressure necessary for consolidation of the composite tubes. A liquid pressurizing media would be essentially incompressible, requiring a storage volume equal to the volume needed for processing. One of the advantages of using a gas media is its shipping economy. The evaporation of a liquified gas is accompanied by a large increase in volume for the pressure ranges under consideration. An effectively large processing volume could be transported into space as a compact, bottled liquid.

Gas Selection

The choice of which particular gas to use is influenced by factors such as economy, compatibility with the process, and availability. Another factor to be considered is the possible reuse of the media in other parts of the system, such as maneuvering jets or environmental supply. Nitrogen is an inert gas and is readily available in liquid form at a moderate cost. Another possibility is liquid oxygen. A problem with oxygen use which could occur at the elevated process temperatures is the formation of explosive mixtures or a reaction with the composite. These could preclude oxygen as a choice. As a result, nitrogen was chosen as the model gas for the calculations.

Pressurizing Media

The equipment necessary to employ gas in the manner needed for processing requires no new technology. The media is simply allowed to escape from the containment bottle through a pressure regulator. The correct mass of gas for processing is indicated by a flow meter. The amount of gas is chosen so that the internal pressure is maintained below the rupture strength of the constraining layer, over the range of process temperatures. Once the consolidation has progressed to the point at which the internal pressure is unnecessary, the gas is allowed to discharge to a holding reservoir.

From here the gas could be discharged through jets for attitude correction, or recovered with a pump for another process run. For the preform shown in Figure 2, approximately 21 grams of nitrogen per tube would provide a consolidation pressure of 550 kPa at a processing temperature of 425°C. With this amount of gas, an internal tube pressure of 390 kPa would be retained through the composite's solidification temperature of 200°C. These calculations show that a large enough pressure can be maintained to assure complete consolidation of the preform.

Also important is the effect of the gas on the cooling rate of the compacted preform. Here, the thermal mass of the nitrogen would be 0.2% of that of the tube, so the effect on composite heating and cooling rates is negligible.

Consolidation Heating

The largest energy requirement for the process is the heating of the preform to the consolidation temperature. Heating alternatives include the following:

(1) The use of radiating electrical resistance elements.

(2) Direct electrical resistance heating using the carbon fibers in the preform as the heating elements.

(3) Focused solar radiation.

While panels of solar cells can easily be used to power other devices on the space station when the process machinery is not in use, the conversion of solar radiation to electricity and then back to radiation heat is inefficient. Direct electrical resistance heating was ruled out because of non-uniform heating and of the fact that hot-spots might develop, resulting in a poor product. The use of focused incident solar radiation eliminates losses associated with conversion to other forms of energy.

HEATING PROCESS DESCRIPTION

Figure 6 shows how solar radiation could be focused on the preform. The primary collection mirror is a curved trough the same length as the strut being processed. It is constructed of a reflective fabric stretched over a telescoping framework, facilitating ease of machine deployment. A secondary mirror provides for the uniform heating of all sides of the preform. The position, size and shape of the focusing surfaces can be readily changed to process different sizes of struts.

RADIATION REQUIREMENTS

The required energy density for the focused radiation is dictated by the radiative power of the heated composite member. For the preform described, approximately 12,250 W/m^2 of energy must be focused onto the tube to counterbalance the maximum radiative heat loss. Using a coefficient of thermal absorption of 0.9, and taking into account the fact that the surface of the tube is round and that the input radiation is parallel, this requirement increases to 21,400 W/m^2.

A final increase in the size of the collection mirror is needed to account for the degree of reflectivity of the mirror surface. The final magnification factor is approximately 16:1 (mirror area:focal spot size). For a 51 mm diameter tube, the required mirror diameter is approximately 970 mm.

Component Cooling

Cooling of the consolidated composite is one of the stages that most greatly affects the overall system design. The material being processed imposes restrictions on the allowable cooling rate. Poor material properties can result from heat removal rates that fall outside of the range 10°C/min. to 700°C/min. This restriction, coupled with the desire for an economical solution, directs the choice of cooling methods. Heat can be removed from the members by three different means: radiation, conduction, or convection to a fluid. Of these three methods, direct radiation to black space requires no additional equipment.

To determine the feasibility of radiative cooling, an analysis of the heat removal rate was performed. Modeling the heat transfer process required the determination of the cooling mode. The considered preform has a Biot modulus of 0.52. As this is less than one, the cooling rate analysis is based on the assumption of Newtonian cooling. By equating the rate of change of internal energy of the strut to the rate of radiative transport

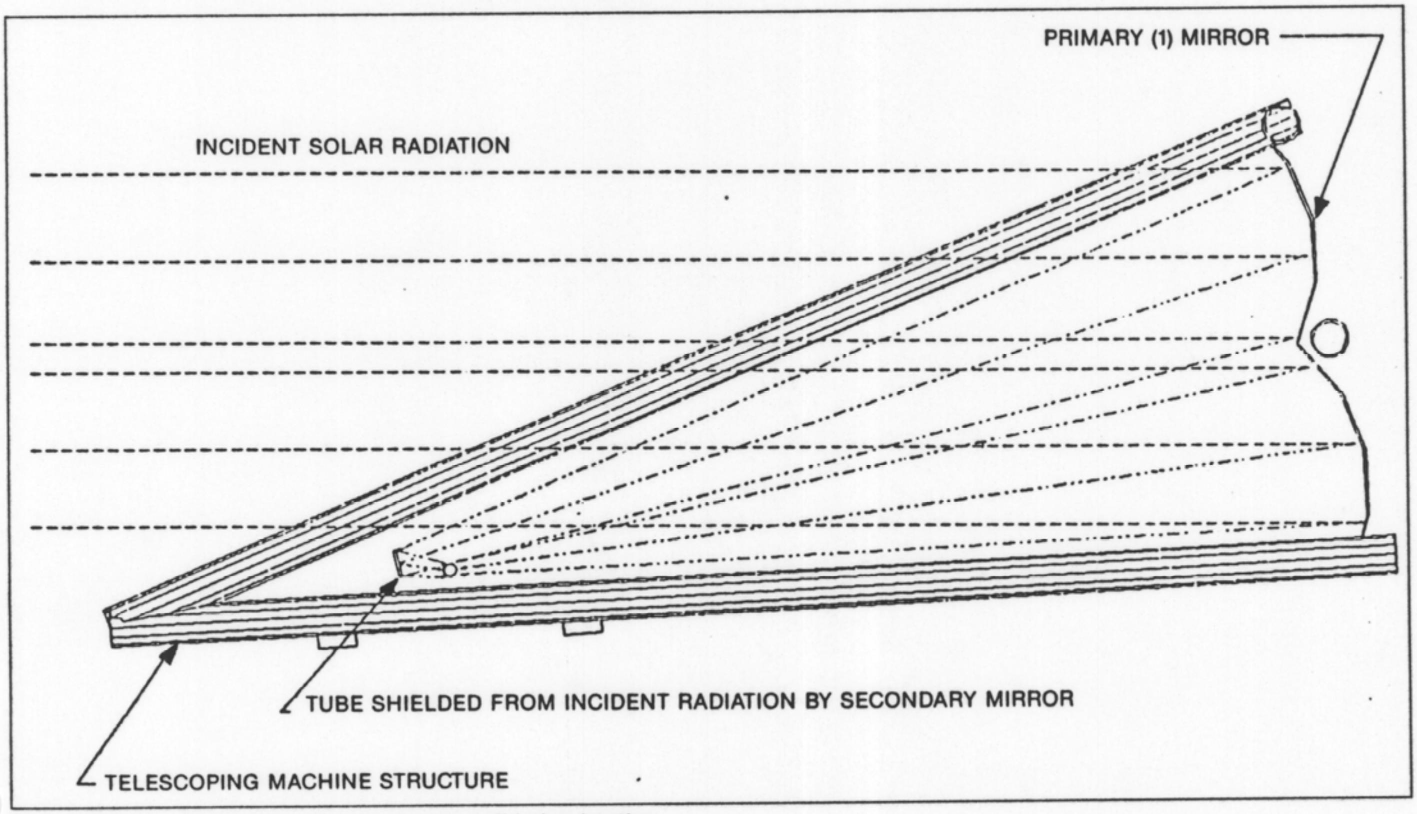

Figure 6. Solar radiation ray diagram for consolidation heating

to black space, the following cooling rate equations are derived:

$$p c V dT/d\tau = A \varepsilon \sigma T^4 \tag{1}$$

$$d\tau = p c V/A \varepsilon \sigma * dT/T^4 \tag{2}$$

$$\tau = -1/3T^3 * p c V/A \varepsilon \sigma \text{ from } T_{LOW} \text{ to } T_{HIGH} \tag{3}$$

where:

p = mass density of strut (1600 kg/m^3)

c = specific heat (1750 J/kgK)

V = material volume (0.00302 m^3)

A = surface area (0.817 m^2)

T = material temperature (K)

τ = cooling time (sec)

ε = emissivity (0.9)

σ = Stephan-Boltzman constant

An investigation of the thermal system indicates that radiative cooling is feasible. For the preform of Figure 2, the above equation and data predicts a cooling rate of 35°C/min which will lead to an appropriate amount of crystallization of the PEEK matrix.

Conclusions and Recommendations

A potential process has been designed for the on-orbit fabrication of the structural members of the Space Station from braided thermoplastic composite preforms. The consolidation process developed is similar to autoclave and vacuum-bag moldings. Integral outer and inner temperature resistant membrane layers serve as vacuum bags when the preform is internally pressurized. The process uses focused solar radiation to supply the heat for the consolidation of the composite. Heat transfer analysis results show that the composite can be effectively quenched by radiative cooling to black space.

Two methods were developed which deploy the required length of preform material to the consolidation position. The semi-continuous approach uses rolls of continuously braided preform. Discrete lengths are consolidated and then cut off from the roll. The collapsed preform packages occupy less volume than an equivalent number of preconsolidated tubes. The second approach processes preforms which are cut to length on earth and collapsed into a cartridge box. Preform deployment is less complicated in the semi-continuous method, with an equivalent volume savings.

There are several areas of the proposed process which would benefit from additional research. An experimental, earth-based apparatus should be constructed which consolidates braided preforms. This would demonstrate the feasibility of the process as well as provide materials for the determination of the strut's mechanical properties.

Alternative pressurizing media should be investigated further. A high temperature structural foam which expands during consolidation might provide sufficient pressure. The foam could also be added after consolidation for additional strut stiffness.

The attachment of the radiation protection sheath could be eliminated if a material was developed which possessed a high emissivity (for fast radiative cooling) and a low absorption (for environmental protection). Such a material could be included as part of the earth-manufactured preform, simplifying on-orbit consolidation.

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