Potential for On-Orbit Manufacture of Large Space Structures Using the Pultrusion Process

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Abstract

On-orbit manufacture of lightweight, high-strength, advanced-composite structures using the pultrusion process is proposed. This process is adaptable to a zero-gravity environment by using preimpregnated graphite-fiber reinforcement systems. The reinforcement material is preimpregnated with a high-performance thermoplastic resin at a ground station, is coiled on spools for compact storage, and is transported into Earth-orbit. A pultrusion machine is installed in the Shuttle cargo bay from which very long lengths of the desired structure are fabricated on-orbit. Potential structural profiles include rods, angles, channels, hat sections, tubes, honeycomb-cored panels, and T, H, and I beams. By manufacturing structures on-orbit in continuous lengths, the number of joints would be greatly reduced compared with structures manufactured at a ground station and assembled in space. Horizontal members are joined to vertical members by ultrasonic or conductive welding techniques. In this way, the structural materials can be transported to orbit at high packaging density for fabrication of very-low-density structure on-orbit. Tailored properties such as stiffness, tensile strength, and toughness are controlled by precise fiber orientations and selective combinations of matrix and fiber systems. Illustrations describing the pultruder and its arrangement in the Shuttle bay are presented. Properties of thermoplastic/graphite structures fabricated on-orbit are projected using pultrusion. This fabrication method has the potential for on-orbit manufacture of structural members for space platforms, large space antennas, and long tethers.

Introduction

The potential for on-orbit manufacture of large space structures using the pultrusion method is greatly enhanced by the development of high-temperature, high-strength thermoplastic polymers containing continuous graphite-fiber reinforcement. These composites are 35 percent lighter than aluminum alloys, and their strength values can be tailored to exceed those of conventional aluminum alloys by magnitudes of two to three. (See ref. 1.) At the present time, two such high-performance thermoplastic composites are commercially available in preimpregnated form: polyetheretherketone (PEEK) as Victrex1 PEEK carbon fiber and polyphenylene sulfide (PPS) as Ryton2 carbon. These composites, as well as a large selection of other thermoplastic resins, have characteristics which would be advantageous to on-orbit manufacture of long, lightweight structures. Several potential candidates for pultrusion and post-forming development and a comparison of some of their physical and mechanical properties are shown in table I. In the table, ULTEM3 6000 and ULTEM 1000, polyetherimides (PEI), and Torlon4, polyamide-imide (PAI) are amorphous; Victrex (PEEK) is crystalline in structure; and XYDAR5 is a liquid crystalline polymer (LCP). The table shows that Torlon has the highest tensile and flexural strength values and is slightly higher in specific gravity, but XYDAR has the highest heat resistance capability. Other desirable characteristics of these thermoplastics are their high solvent resistance, damage tolerance, and compressive strength. In addition to their potential for joining by welding and for post-forming by applying heat and pressure, these materials are likely candidates for on-orbit manufacturing. For example, coiled stock, having a solventless thermoplastic matrix, could be transferred to space in a very high storage density compared with that of finished structures. The coiled stock could then be post-fabricated into specific shapes by methods similar to those used in post-forming conventional metals such as aluminum and titanium alloys. In using solventless thermoplastic/graphite prepreg, toxic fumes would be eliminated during the on-orbit fabrication phase. (See ref. 2.) One of the purposes of this paper is to present a method for manufacturing large space structures on-orbit. In concept, coiled stock, with a very high storage density during transport, would be fabricated into very-low-density large space structures. Some of the concepts in the paper have not been developed and require a considerable amount of additional research and development; some concepts are presently being developed.

Proposed Manufacturing Method

The proposed manufacturing method consists of two phases. The first phase requires manufacturing and coiling stock material at a ground base using a pultrusion process. The second phase is on-orbit post-fabrication and is accomplished by rollforming or rolltruding the coiled stock into specific shapes or profiles. The ground-based pultrusion phase produces solventless double-ply prepreg. The prepreg could include communications wiring or this could be added during the on-orbit fabrication. Figure 1 is a schematic of a conventional pultrusion process. A machine designed to perform the functions of the

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1 Trademark of Imperial Chemical Industries.
2 Trademark of Phillips Petroleum Company.
3 Trademark of General Electric Company.
4 Trademark of Amoco Chemicals Corporation.
5 Trademark of Dartco Manufacturing, Inc.
Preliminary Materials Evaluation

Pultruded composite structure with a high performance thermoplastic has been reported by only one researcher (ref. 5). The pultrusion of polyphenylene sulfide with reinforcement materials of both fiberglass and graphite fiber was reported in reference 5. Because of the early development stages of pultrusion processes using high-performance thermoplastics, data are not available to evaluate properties of materials produced by this method. However, approximations of some of the mechanical properties can be derived by using equations such as the Halpin-Tsai equations. (See ref. 6.) The equation for the Halpin-Tsai rule of mixtures was used to estimate the probable moduli of graphite-reinforced pultrusions; each of the thermoplastics listed in table II were used as matrices and polyacrylonitrile (PAN)-base graphite fiber (Hercules AS4). The equation form is

\[ E_{11} = E_f V_f + E_m V_m \]

where \( E_{11} \) is the modulus of the composite, \( E_f \) and \( E_m \) are the moduli of the graphite reinforcement and matrix, respectively, and \( V_f \) and \( V_m \) are the volume fractions of the reinforcement and matrix, respectively. The values for tensile moduli and specific tensile moduli are shown in table II. These values are comparable to values reported for graphite/epoxy composite systems using conventional fabrication technology. (See ref. 7.) These values are shown graphically in figure 9 to illustrate that the high-modulus XYDAR caused the only significant increase in tensile properties.

On-Orbit Fabrication of Large Space Structures

A polyetherimide/graphite (Hercules AS4) rolltruded channel structure with a density of 0.057 lb/in\(^3\) is presented as a model for determining the mass properties of a large space structure. The structure would consist of 600 sections welded together to form a structure 300 ft wide by 25 ft high by 5000 ft long. A typical section is shown in figure 10. The structure would require channels of three varied widths to simplify assembly. Figure 11 illustrates the versatility of a channel design. The channels are constant in cross-sectional dimensions, and each would have flange widths of 1.5 in. and wall thicknesses of 0.080 in. The channels have dimensions across the webs of 3.0 in., 2.8 in., and 2.6 in., respectively. Some of the advantages of using channel structure are (1) the ease of rolltruding a simple shape; (2) the
elimination of mechanical fasteners for assembly; and
(3) the versatility of combining channels to form
other shapes such as H, T, cross, or closed-box beams
for vertical and diagonal stiffeners. The proposed
design requires only three varied size channels and
provides flat surfaces for attaching modules such as
living, storage, and work areas. Structures fabri-
cated from polyetherimide/graphite could be joined
by bonding, welding, or mechanical methods.

Several thermoplastic joining techniques have
been investigated. (See refs. 8 through 12.) The
most promising technique is the “Plastic Welder”
(ref. 9), which was developed at Langley Research
Center. This technique uses an induction heating
toroid gun to produce fusion welds in thermoplastics.
The technique could conceivably be modified to use
a solar power source for on-orbit use. (See fig. 12.)
Figure 13 is an artist’s rendition of on-orbit manu-
facture and construction of a large space platform.
The concept envisions a rectangular shape. In the
figure, channel structure is being produced by roll-
trusion machines located in the three attached mod-
ules. By using on-orbit manufacturing, the longitudi-
nal stiffeners could be produced in continuous 5000-ft
lengths or longer. A spider crane robot is used for
assembling the structure. A compilation of channel
lengths, weights, and volumes for ground-based man-
facture and on-orbit assembly is shown in table III.
The total delivered weight is 106 200 lb, and the vol-
ume is 5161 ft$^3$. The weight and volume compilation
for on-orbit manufacture of the same structure using
ground-based pultruded coiled stock is shown in ta-
ble IV. This method of manufacture would require
an ETO lift capability of 110 200 lb or an increase of
4000 lb because of the added empty weight of the
spools. The storage volume, however, would be re-
duced by 2900 ft$^3$. A comparison of ETO delivered
densities of ground-based versus on-orbit manufac-
ture of the same structure is given in table V. The
delivered density using the on-orbit method is 2.3
times greater than that of the ground-based method.
Based on these calculations, the on-orbit-fabricated
structure would require only 43.7 percent of the ETO
volume required by the ground-based-manufactured
structure.

The environmental difficulties involved in space
manufacturing and construction are not addressed in
this paper; however, many of these problems would
be overcome by the use of high-tech robotic assem-
bly. A potential robot assistant, a spider crane, is
shown in figure 14. The spider would be operated
in a telepresence mode; that is, there would be com-
bined voice commands and computer-program con-
trol by an observing astronaut located in a mobile

Concluding Remarks

On-orbit manufacturing concepts for large
space structures using lightweight, high-strength,
advanced-composite materials and advanced high-
tech fabrication methodology are presented. A po-
tential pultrudable thermoplastic/graphite compo-
site material is presented as a model for determining
the effect on Earth-to-orbit package density of on-
orbit manufacture of large space structures. The re-
results indicate that by using pultruded coiled stock
and on-orbit manufacture, the package density is in-
creased by 132 percent and the payload volume re-
quirement is decreased by 56.3 percent. This re-
prestents a substantial decrease in payload volume
requirements for the transport of structures to orbit.

NASA Langley Research Center
Hampton, Virginia 23665-5225
October 30, 1987
References

Table I. Properties of Potential Pultrusion Thermoplastic Resins

<table>
<thead>
<tr>
<th>Property</th>
<th>ULTEM 6000 (PEI)</th>
<th>ULTEM 1000 (PEI)</th>
<th>Torlon 4203 (PAI)</th>
<th>Victrex (PEEK)</th>
<th>XYDAR SRT-300 (LCP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt temperature, °F</td>
<td>435</td>
<td>420</td>
<td>528</td>
<td>633</td>
<td>680</td>
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<tr>
<td>Specific gravity</td>
<td>1.27</td>
<td>1.27</td>
<td>1.38</td>
<td>1.32</td>
<td>1.35</td>
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<tr>
<td>Tensile strength, psi</td>
<td>15 000</td>
<td>15 200</td>
<td>27 800</td>
<td>15 000</td>
<td>20 000</td>
</tr>
<tr>
<td>Flexural strength, psi</td>
<td>21 000</td>
<td>22 000</td>
<td>34 900</td>
<td>16 000</td>
<td>19 000</td>
</tr>
<tr>
<td>Deflection temperature under load, °F at 264 psi</td>
<td>420</td>
<td>392</td>
<td>500-525</td>
<td>320</td>
<td>671</td>
</tr>
<tr>
<td>Flexural modulus, psi</td>
<td>$440 \times 10^3$</td>
<td>$480 \times 10^3$</td>
<td>$520-665 \times 10^3$</td>
<td>$560 \times 10^3$</td>
<td>$2000 \times 10^3$</td>
</tr>
</tbody>
</table>

Table II. Properties of Potential Thermoplastic/Graphite Pultrusion

<table>
<thead>
<tr>
<th>Property</th>
<th>ULTEM 6000 (PEI)</th>
<th>ULTEM 1000 (PEI)</th>
<th>Torlon 4203 (PAI)</th>
<th>Victrex (PEEK)</th>
<th>XYDAR SRT-300 (LCP)</th>
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<td>Fiber orientation</td>
<td>$[0^\circ]$</td>
<td>$[0^\circ]$</td>
<td>$[0^\circ]$</td>
<td>$[0^\circ]$</td>
<td>$[0^\circ]$</td>
</tr>
<tr>
<td>Fiber volume, %</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Density, lb/in$^3$</td>
<td>.058</td>
<td>.058</td>
<td>.059</td>
<td>.058</td>
<td>.059</td>
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<tr>
<td>Tensile modulus, b psi</td>
<td>$20.6 \times 10^6$</td>
<td>$20.6 \times 10^6$</td>
<td>$20.7 \times 10^6$</td>
<td>$20.6 \times 10^6$</td>
<td>$21.4 \times 10^6$</td>
</tr>
<tr>
<td>Specific tensile modulus, psi</td>
<td>$355 \times 10^6$</td>
<td>$355 \times 10^6$</td>
<td>$351 \times 10^6$</td>
<td>$349 \times 10^6$</td>
<td>$362 \times 10^6$</td>
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*aHercules AS4 graphite.*

*bCalculated values based on Halpin-Tsai equation.*
Table III. Ground-Based Manufacture of Thermoplastic/Graphite Channel for Space Platform
[300 ft by 25 ft by 5000 ft]

<table>
<thead>
<tr>
<th>Channel stiffener, in.</th>
<th>Length required, ft</th>
<th>Number of pieces required</th>
<th>Total length, ft</th>
<th>On-board weight, lb</th>
<th>On-board volume, ft³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 by 3.0 by 1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>50.00</td>
<td>1400</td>
<td>70 000</td>
<td>22 500</td>
<td>1123</td>
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<tr>
<td>Diagonal</td>
<td>49.75</td>
<td>1212</td>
<td>60 300</td>
<td>19 400</td>
<td>1019</td>
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<tr>
<td>1.5 by 2.8 by 1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>24.75</td>
<td>998</td>
<td>24 700</td>
<td>7700</td>
<td>371</td>
</tr>
<tr>
<td>Diagonal</td>
<td>25.00</td>
<td>1198</td>
<td>30 000</td>
<td>9300</td>
<td>449</td>
</tr>
<tr>
<td>1.5 by 2.6 by 1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>70.70</td>
<td>1200</td>
<td>84 800</td>
<td>25 500</td>
<td>1184</td>
</tr>
<tr>
<td>Diagonal</td>
<td>55.90</td>
<td>1300</td>
<td>72 700</td>
<td>21 800</td>
<td>1015</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>106 200</td>
<td>5161</td>
<td></td>
</tr>
</tbody>
</table>

Table IV. On-Orbit Manufacture of Thermoplastic/Graphite Channel for Space Platform Using Ground-Based Fabricated Prepreg
[300 ft by 25 ft by 5000 ft]

<table>
<thead>
<tr>
<th>Prepreg width, in.</th>
<th>Length, ft</th>
<th>Spools required</th>
<th>On-board weight, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>Spools</td>
<td>Prepreg</td>
</tr>
<tr>
<td>5.84 (for 3-in. channel)</td>
<td>521 000</td>
<td>102</td>
<td>41 900</td>
</tr>
<tr>
<td>5.64 (for 2.8-in. channel)</td>
<td>220 000</td>
<td>43</td>
<td>17 100</td>
</tr>
<tr>
<td>5.44 (for 2.6-in. channel)</td>
<td>632 000</td>
<td>124</td>
<td>47 300</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>110 200</td>
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Table V. Comparison of Earth-To-Orbit Storage Densities of Ground-Based Versus On-Orbit Manufacture of Space Platform Using Pultrusion/Rolltrusion Method

[300 ft by 25 ft by 5000 ft]

<table>
<thead>
<tr>
<th>Channel stiffener, in.</th>
<th>Total length, ft</th>
<th>Ground-based-manufactured delivered density, lb/ft$^3$</th>
<th>On-orbit-manufactured delivered density, lb/ft$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 by 3.0 by 1.5</td>
<td>130 300</td>
<td>19.6</td>
<td>48.7</td>
</tr>
<tr>
<td>Vertical stiffness</td>
<td>55 000</td>
<td>21.0</td>
<td>48.9</td>
</tr>
<tr>
<td>1.5 by 2.6 by 1.5</td>
<td>158 000</td>
<td>22.3</td>
<td>48.9</td>
</tr>
<tr>
<td>Average</td>
<td>21.0</td>
<td>48.8</td>
<td></td>
</tr>
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Figure 1. Schematic of pultrusion process.

Figure 2. Pultrusion machine.
Figure 3. Multidirectional fiber creel.

Figure 4. Pultruding T-beam.
Figure 5. Continuous-length pultrusion.

Figure 6. Thermoplastic pultrusion.
Figure 7. Thermoplastic rolltrusion.

Figure 8. On-orbit rolltrusion.
Figure 9. Thermoplastic/graphite moduli. 1 Msi = 1 \times 10^6 psi.

Figure 10. Channel structure.
Figure 11. Channel concepts.

Figure 12. Schematic of toroid gun.
Figure 13. On-orbit manufacturing.

Figure 14. Space spider robot.
Figure 15. Archimedean spiral concept.

Figure 16. Robotic fabrication.
Figure 17. Continuous spiral.

Figure 18. Structural concepts.
On-orbit manufacture of lightweight, high-strength, advanced-composite structures using the pultrusion process is proposed. This process is adaptable to a zero-gravity environment by using preimpregnated graphite-fiber reinforcement systems. The reinforcement material is preimpregnated with a high-performance thermoplastic resin at a ground station, is coiled on spools for compact storage, and is transported into Earth-orbit. A pultrusion machine is installed in the Shuttle cargo bay from which very long lengths of the desired structure is fabricated on-orbit. Potential structural profiles include rods, angles, channels, hat sections, tubes, honeycomb-cored panels, and T, H, and I beams. A potential pultrudable thermoplastic/graphite composite material is presented as a model for determining the effect on Earth-to-orbit package density of on-orbit manufacture of large space structures. The results indicate that by using pultruded coiled stock and on-orbit manufacture, the package density is increased by 132 percent, and payload volume requirement is decreased by 56.3 percent. This fabrication method has the potential for on-orbit manufacture of structural members for space platforms, large space antennas, and long tethers.

### Key Words
- Pultrusion
- Graphite-reinforced thermoplastic
- On-orbit manufacturing
- Large space structures

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