THE USE OF GRAPHITE/EPOXY COMPOSITE STRUCTURES IN SPACE APPLICATIONS

Rudy Lukez
Morton Thiokol, Inc., Aerospace Group
Brigham City, Utah

ABSTRACT

Graphite/epoxy composite materials are being used increasingly for numerous space applications. Engineers are interested in these materials because of their favorable mechanical characteristic of high strength/high stiffness to weight ratio and potential for zero or near-zero coefficient of thermal expansion.

This paper presents an overview of graphite/epoxy composite use for space applications. The historical uses and environmental concerns of graphite/epoxy composites in the low earth orbit are reviewed. Detailed information on the design, fabrication and testing of struts for potential Space Station use is presented as an example of graphite/epoxy material usage for space applications.

INTRODUCTION

Vehicle and structure applications in space encounter a variety of design requirements which call for new and creative material applications. Problems associated with the space environment, such as radiation and atomic oxygen, physical demands based on size and weight and performance goals for longevity and functionality present a variety of challenges which call for new technologies.

Advances in materials during the past twenty years have solved many of the challenges found in the Space Program. One family of material systems, composites, has been used to meet many varied space requirements.

One material system of particular interest is graphite/epoxy composites. These materials have been used to meet a wide variety of design parameters ranging from minimal weight to high structural stiffness requirements. Because of their ability to meet many diverse design requirements simultaneously, the use of graphite/epoxy composites is expected to increase.

GRAPHITE/EPOXY COMPOSITE STRUCTURES WITH SPACE EXPERIENCE

Even though using graphite/epoxy structures for space applications appears to be a novel idea, there are a number of space vehicles which have successfully employed composites. Published papers contain numerous examples of these applications. A few spacecrafts which demonstrate the use of graphite/epoxy composites are:

1. Intelsat IV: This communications satellite was built by Ford Aerospace and Communications Corporation and is shown in Fig. 1. It used a hybrid horizontal cross arm made of graphite/epoxy tape and aluminum. This design was selected to meet requirement for small deflections and low weight. (Ref. 1)

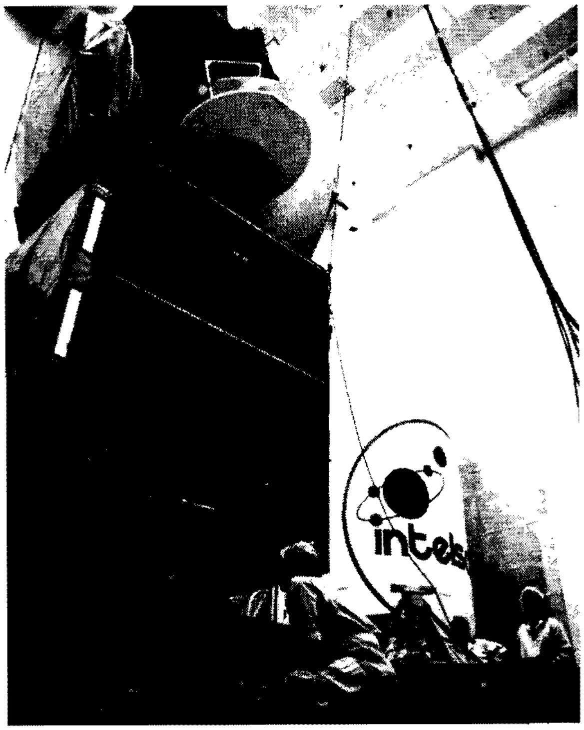

Figure 1. Intelsat Communications Satellite (NASA photo)

2. Anik: Anik, pictured in Fig. 2, is the Canadian communications satellite and was built by RCA Astro-Electronics. Anik's antenna structure is a 6 ft high elliptical parabola fabricated from graphite/epoxy skin/aluminum honeycomb core components. This material system was chosen to satisfy Anik's requirements for:
   1. controlling solar radiation effects,
   2. reducing thermal distortions and
   3. maintaining high structural stiffness. (Ref. 1)

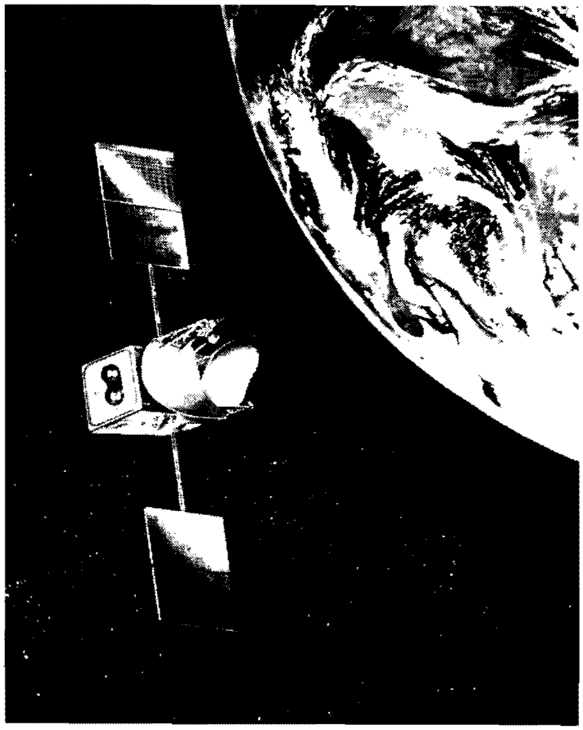

Figure 2. Anik, A Canadian Communications Satellite (NASA photo)

3. Viking: The Viking spacecraft, which was used in the late 1970s for the exploration of Mars, employed graphite/epoxy parts built by Ford Motor Company's Philco Division. As with Anik, a 5 ft diameter antenna using graphite/epoxy skins over an aluminum honeycomb was designed for the lander (see Fig. 3) and satellite (see Fig. 4). Composites were selected to meet requirements for
   1. low thermal response,
   2. high structural stiffness and
   3. low weight. (Ref. 1)

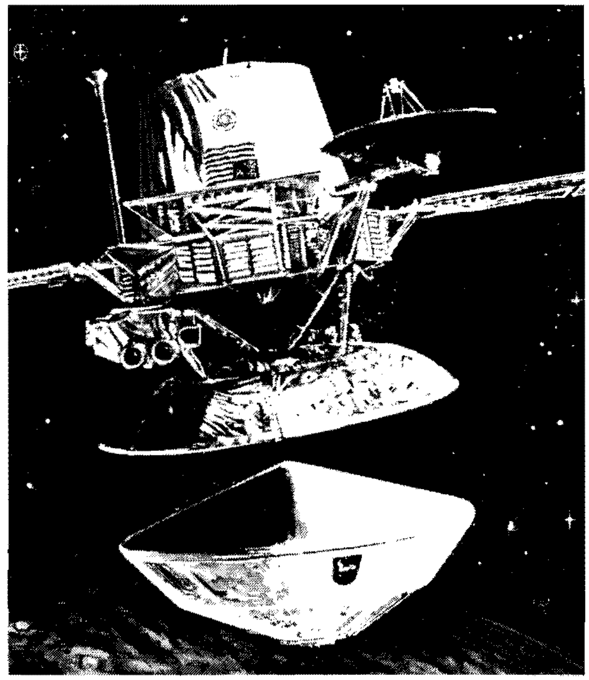

Figure 4. Viking Satellite Above Mars Deploying Viking Lander (NASA photo)

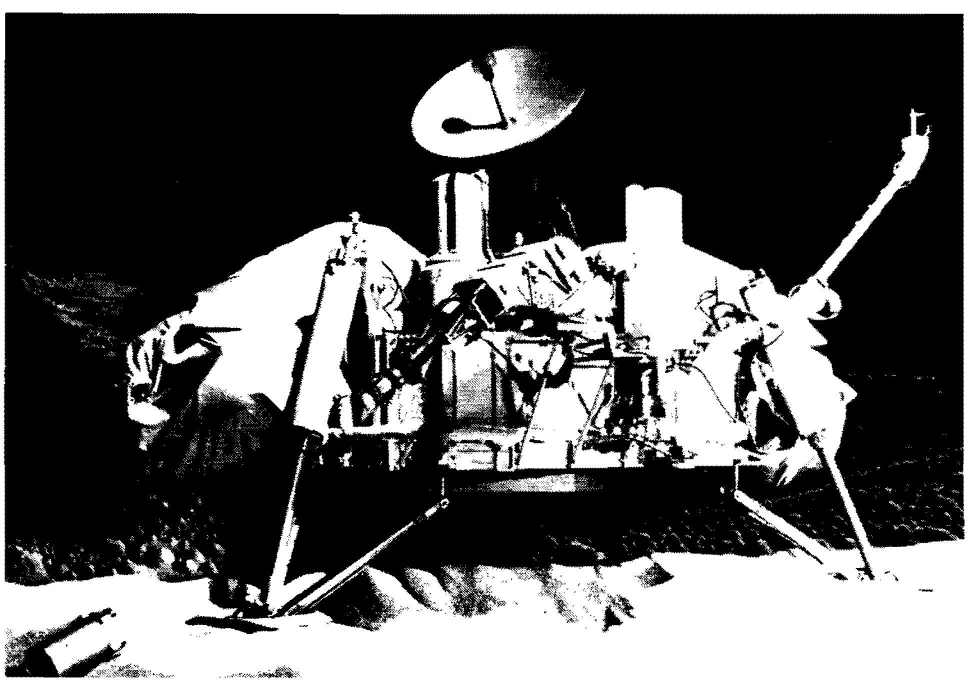

Figure 3. Viking Lander Spacecraft on the Surface of Mars (NASA photo)

4. DSCS III: Another space vehicle which uses graphite/epoxy composites is the third Defense Satellite Communication System (DSCS III) satellite shown in Fig. 5. This geosynchronous communications satellite employs several graphite/epoxy parts including: 1. the launch adaptor, and 2. five different structural support strut configurations for primary and secondary applications. The use of graphite/epoxy parts reduced the satellite's weight by 25 lb. (Ref. 2)

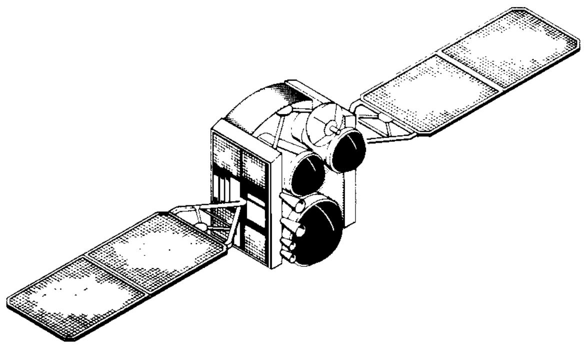

Figure 5. Defense Satellite Communications System III

There are many other examples from past, current, and future space projects which call for graphite/epoxy composite structures. Future planned composite use include:

1. the Space Telescope depicted in Fig. 6,
2. cryogenic tanks,
3. advanced antenna systems,
4. Space Tug,
5. Space Station, which is discussed in greater detail below, and
6. Small, lightweight satellite systems.

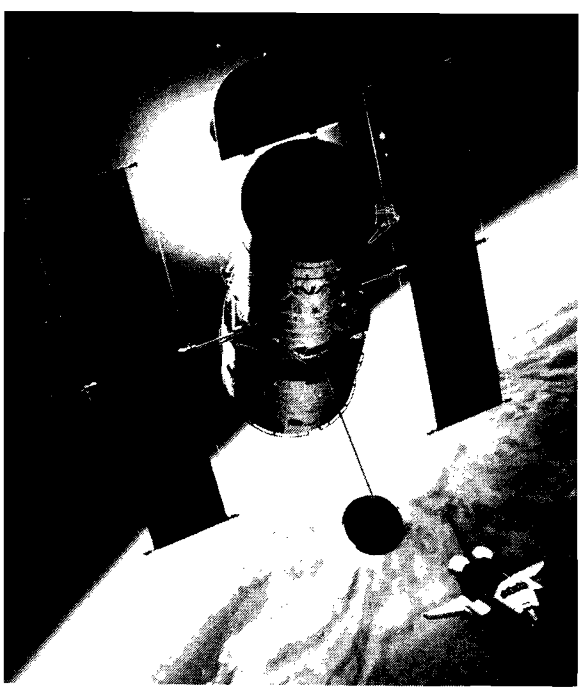

Figure 6. The Space Telescope (NASA photo)

THE SPACE ENVIRONMENT AND COMPOSITES

The space environment is not very conducive to unprotected graphite/epoxy composite systems or most other organic materials. Of particular interest is the environment surrounding low-earth orbit (LEO) which is where many orbital spacecrafts, including the Space Shuttle and Space Station, are designed to operate.

Specific environmental concerns include:

Radiation

Space radiation, comprised of electrons and protons in the earth's magnetic field, can alter the dimensional stability and thermomechanical properties of graphite/epoxy composites; in fact, any part with an organic constituent can be adversely affected by radiation if not properly protected. Radiation produces damaging effects in organic compounds, such as graphite/epoxy composites, through chain-scission and cross-linking at various radiation doses ranging from 10^5 to 10^9 rads. (Ref. 3) This causes a reduction of a composite's glass transition temperature (T_g).

Radiation damage effects include changes in structural

1. melting and softening points,
2. hardness,
3. electrical properties,
4. ultimate tensile strength,
5. elongation,
6. modulus of elasticity and
7. dimensional instability. (Ref. 3)

Since radiation effects are cumulative, structures planned for long service life need adequate protection from radiation exposure. The Space Station will see the equivalent of 15 years of radiation exposure during its planned life.

Thermal cycling

Most spacecraft missions involve orbits around the earth. During these orbits, a spacecraft passes in and out of the earth's shadow and experiences extreme minimum and maximum temperatures on a cyclical schedule. This cycling can induce microcracks in composite resins which reduce part stiffness and changes the overall coefficient of thermal expansion (CTE). (Ref. 4)

Thermal cycling effects can be prevented by using protective coatings over exposed composite parts. Typical protective coatings include aluminum foils. The purpose of these protective coatings is to distribute temperatures uniformly around and along the exposed structure.

As structures are scheduled for increased service life in space, thermal cycling will become more important. As an example of the magnitude of this cycling, the Space Station during its 30 year life will experience 175,000 cycles. (Ref. 5)

Atomic oxygen

Atomic oxygen is the major constituent in the LEO environment between 200 km and 500 km. It is also now considered a significant concern when spacecraft are designed for near earth applications. (Ref. 5)

The effects of atomic oxygen were observed on early Space Shuttle flights. Experiments on Space Shuttle (STS) flights 5, 8, and 41-G showed that non-metals, including graphite/epoxy composites, are very reactive to atomic oxygen while metals are nearly unaffected. Graphite/epoxy systems react with atomic oxygen to form volatile oxides which cause the material to dissolve. Given sufficient time, atomic oxygen could completely dissolve a composite part in LEO.

Atomic oxygen degradation is so severe that one paper noted:

> "For many years, the assumption was that the aspects most degrading to materials in the low earth orbital environment were ultraviolet radiation and thermal vacuum exposure. From the results of early experiments conducted on the Space Shuttle, it now appears that atomic oxygen effects will by far be more damaging." (Ref. 5)

To prevent damage to graphite/epoxy parts in space, LEO exposed composites need protective coatings which are non-reactive with atomic oxygen. The Space Station, for example, will require aluminum foil, probably 4 to 5 mils, over the graphite/epoxy struts used in the connecting truss. This concept is simple and economical; in addition, besides atomic oxygen, aluminum foil should provide long term protection for other environmental problems.

GRAPHITE/EPOXY STRUTS FOR SPACE STATION APPLICATIONS

Earlier Space Station requirements based on the proposed dual keel rectangular truss structure, shown in Fig. 7, called for nearly 23,000 ft of graphite/epoxy struts. Updated baseline concepts, such as the version shown in Fig. 8, will require fewer struts initially, but could still be easily expanded to the earlier proposed structure.

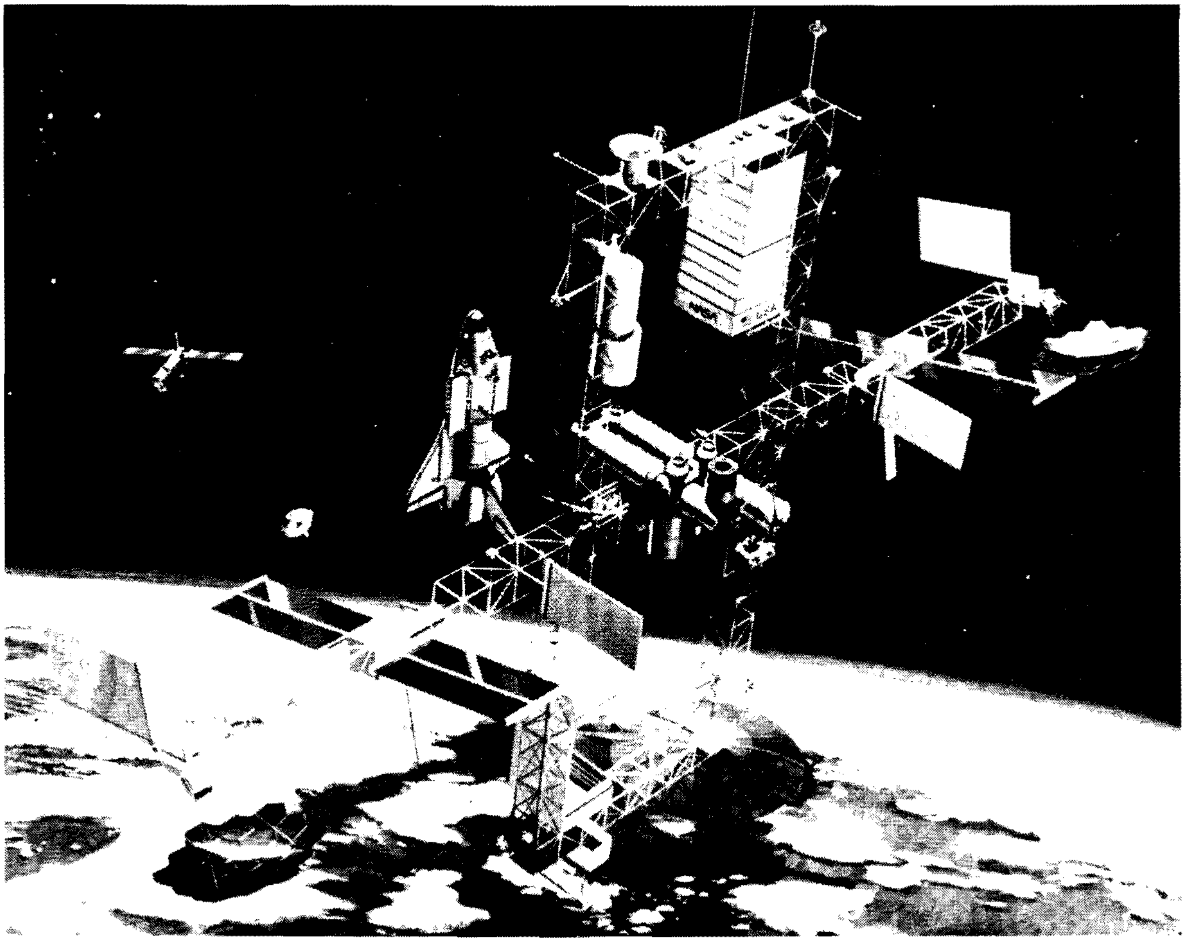

Figure 7. Space Station Dual Keel 5-meter Truss Configuration (NASA photo)

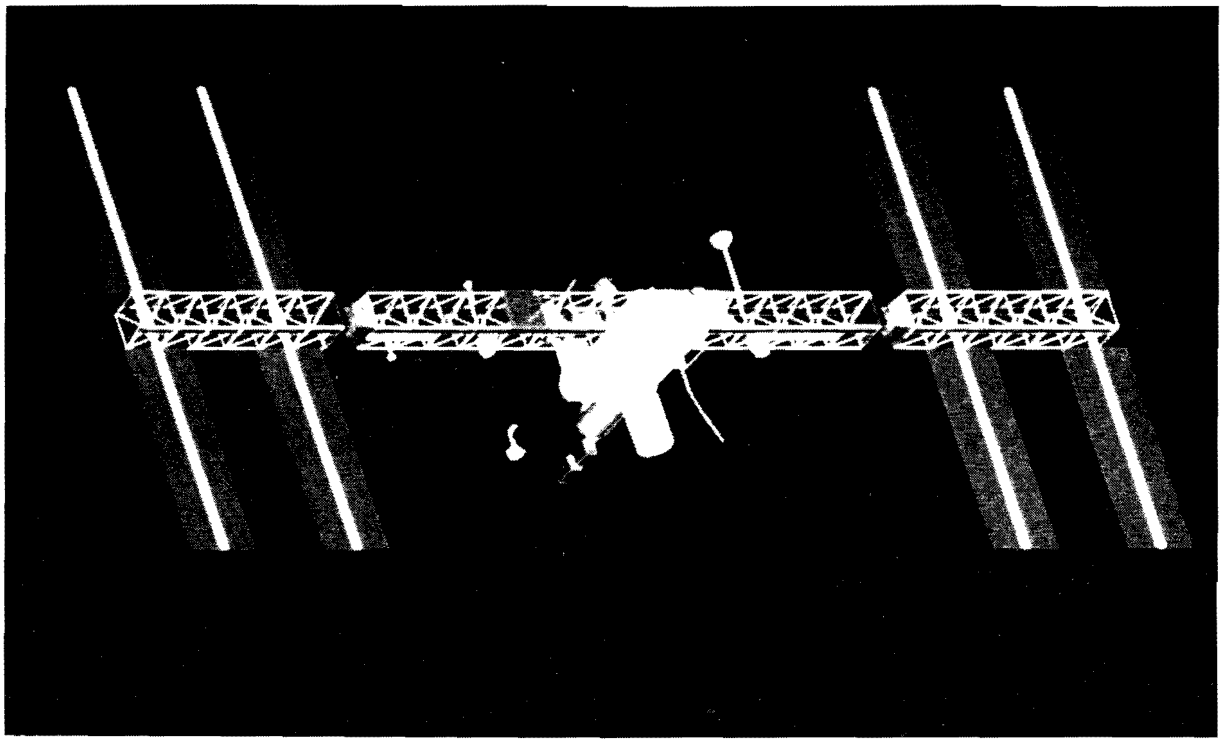

Figure 8. Current Space Station Phase I Baseline Design. The Horizontal Truss Will Be Made From Graphite/Epoxy Struts to Which Laboratory and Habitation Modules and Solar Panels are Attached (NASA photo)

Selected for high stiffness, minimum thermal distortion and low weight characteristics, graphite/epoxy components will be required to survive 30 years in low earth orbit, 250 nautical miles above the earth's surface. Construction of the Space Station is scheduled for the early to mid 1990s, 500 years after Christopher Columbus sailed to the New World.

To meet the requirements for the Space Station truss structure, a program to design, fabricate and test graphite/epoxy composite struts was implemented. Components of this program are explained below.

Requirements

Major Space Station design requirements set forth in early 1985 were: (Ref. 6)

- Dimensional stability: Dimensional stability is one of two key design drivers that dictate the use of low coefficient of thermal expansion (CTE) materials for the struts. Because of their low weight, graphite/epoxy composites are favored over metals for the truss struts. Satisfying the dimensional stability requirement ensures trouble-free assembly of the truss and maintains pointing and tracking accuracy of the on-board experiments and power generation equipment during thermal exposure.
- Axial stiffness: Axial stiffness is the other key design driver affecting the selection of materials for the Space Station truss structure. An analysis of the overall structure's flexural (EI) and torsional (GJ) stiffness requirements leads to a design governed by longitudinal modulus (E_1) of the struts.
- Strength: Strength is not a major design factor for the Space Station struts due to the expected low operational loads. The area of most interest is the transition region between the composite strut and end fittings where the highest loads are anticipated.
- Column stability: Column stability also is a concern because of the effect end fittings have on end fixity rather than the magnitude of the loads involved.
- Age life: Age life in space is a major materials selection factor and creates concerns with the use of composites because of atomic oxygen and thermal cycling.
- Atomic oxygen: Since atomic oxygen particles degrade the epoxy in a graphite/epoxy system and thermal cycling causes microcracks to form in the epoxy due to CTE mismatch between the graphite fiber and epoxy resin, protective metallic coatings and "toughened" resins are necessary.
- Damage resistance and repair: Damage resistance and repair are practical requirements necessary for the low cost implementation of composites to the Space Station. Damage resistance is a function of material selection, fiber orientation and external protection.

Design and analysis

Using laminated plate theory (LPT), numerous fiber orientations and material systems were evaluated; there are a number of materials and fiber orientations which satisfy the proposed requirement with weight and cost the obvious trade-off. Sample designs are listed in Table 1.

Since mechanical requirements for Space Station struts are rather straight forward, elementary hand calculations and LPT evaluations provided sufficient design and analysis information.

As composite studies continued, the issue of potential thermal cycling induced matrix microcracking required a design change. Resin microcracking occurs readily in composites with high angle cross-ply lay-ups, such as a $[\pm 75°_m / \pm 15°_{Pn}]_S$ combination, when exposed to the temperature extremes typical of low earth orbit. Composites with lower angle cross-ply lay-ups are less susceptible to microcracking due to lower interlaminar thermal stresses. So, $[\pm 45°/0°_4]_2$ and $[\pm 45°/\pm 15°/0°_2]_S$ lay-ups using .005 in. thick plies were selected for further studies

Table 1

SAMPLE LONGITUDINAL CTE AND MODULUS VALUES FOR P75/934 GRAPHITE/EPOXY TUBE DESIGNS

Layup	Ply Count	Ply Thickness (in.)	CTE x 10^{-6} (in./in. °F)	Modulus (msi)
$[\pm 75/\pm 15_5]_S$	24	0.0025	-0.53	28.4
$[\pm 75/\pm 15_2]_S$	12	0.005	-0.37	23.2
$[\pm 10/\pm 30_5]_S$	24	0.0025	-1.22	26.6
$[\pm 10/\pm 30_2]_S$	12	0.005	-1.22	26.6
$[\pm 75/\pm 45_2]_S$	24	0.0025	-0.51	25.4
$[\pm 45/\pm 15_5]_S$	24	0.0025	-0.99	23.7
$[\pm 45/\pm 15_2]_S$	12	0.005	-0.88	25.8
$[\pm 45/0_4]_S$	12	0.005	-0.72	27.6
$[\pm 45/\pm 15/0_2]_S$	12	0.005	-0.96	24.6

88253-1C

Strut fabrication studies

A variety of fabrication methods were studied during the initial development effort. A matrix comparing the advantages and disadvantages of several fabrication methods is shown in Table 2.

- Transverse tape rolling: The selected process was transverse tape rolling because of its layup versatility, low void content and, if automated, very low cost. Ply orientations from 0° to 90° in numerous combinations and consistent void contents below .5 percent have been demonstrated using this process. This process, shown in Fig. 9, was chosen because of its outside dimensional control capability, ease of use and high quality surface finish. The machine used in this process is pictured in Fig. 10.

- Filament winding: Filament winding was not selected because it is not well suited for long struts with small diameters. Morton Thiokol studies show it is inefficient to filament wind parts with a length/diameter ratio greater than 10 when low angle orientations (less than ±30°) are used due to equipment constraints. The low wind angles would be required to meet minimum CTE requirements for the struts.

- Braiding: Because of numerous fiber crossovers and the program's low void content requirements, braiding was not selected. Typically, braided parts have higher void contents and lower fiber volumes than unidirectional tape. Braided parts can range from 0 to 8 percent voids while unidirectional tape parts vary from 0 to 2 percent voids. Also, when the original fabrication trade studies were completed, high modulus fibers (above 40 msi) could not be braided without considerable damage.

- Pultrusion: Pultrusion processing could net high production rates at 5 to 15 ft per minute but was not selected because of high equipment costs, problems with using epoxy resins and lack of ply angle versatility.

- Convolute strut winding: As with pultrusion methods, convolute strut winding could reach high production rates but was not selected

Table 2

COMPARISON OF SPACE STATION STRUT FABRICATION METHODS

	Versatile Layup (0-90 deg)	Versatile Materials 1	Low Production Cost	L/D Ratio	Multiple Diameters	Multiple Lengths	Straight Fibers	Low Void Content	Easy Overwrap 2	High Strength Part	High Production Rate	In-House Tooling
Tape Rolling	•	•	•	•	•	•	•	•	•	•	•	•
Filament Winding		•	•		•	•	•	•		•		•
Pultrusion				•		•	•	•		•	•	
Convolute Winding		•	•	•	•	•	•	•	•	•	•	
Braiding			•	•	•	•				•		•

88218-1G

• Favorable Capability

Notes: 1. Ability to use different material systems
2. Ability to easily apply protective overwrap materials as aluminum foil

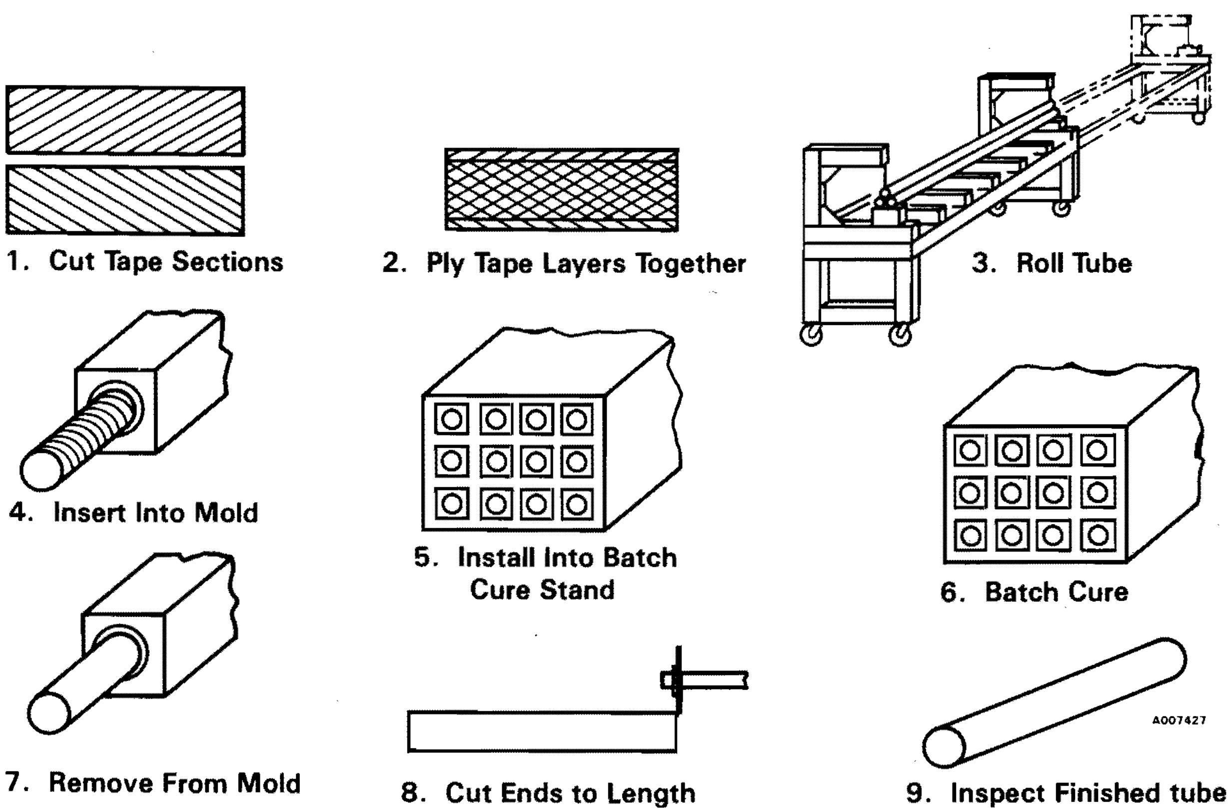

Figure 9. Space Station Strut Fabrication Process

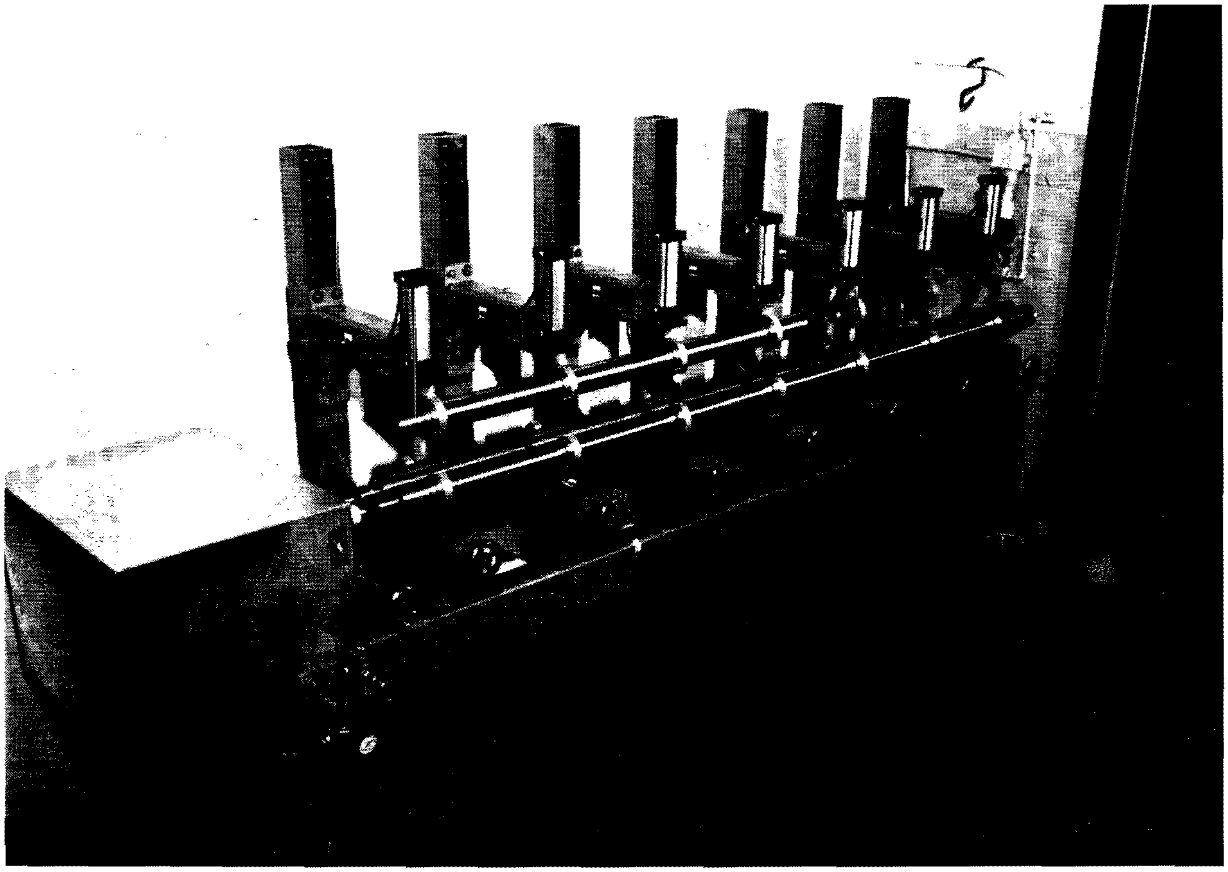

Figure 10. Strut Rolling Machine Designed and Built By Morton Thiokol, Inc.

because of expensive equipment requirements. In addition, the process is not well suited for flexible fiber orientation and layup variations which is important to develop the optimum strut layup.

Strut fabrication process

To fabricate a Space Station, strut sheets of preimpregnated tape were cut and laid to a specific orientation as determined by the design; a sample layup is shown in Fig. 11. The layup was then placed on the feed table of the strut rolling machine and fed into the machine to be rolled up on the mandrel. The tape was then automatically pulled into the machine and rolled under controlled compaction. This process was very quick and required only a few mandrel revolutions to roll the strut.

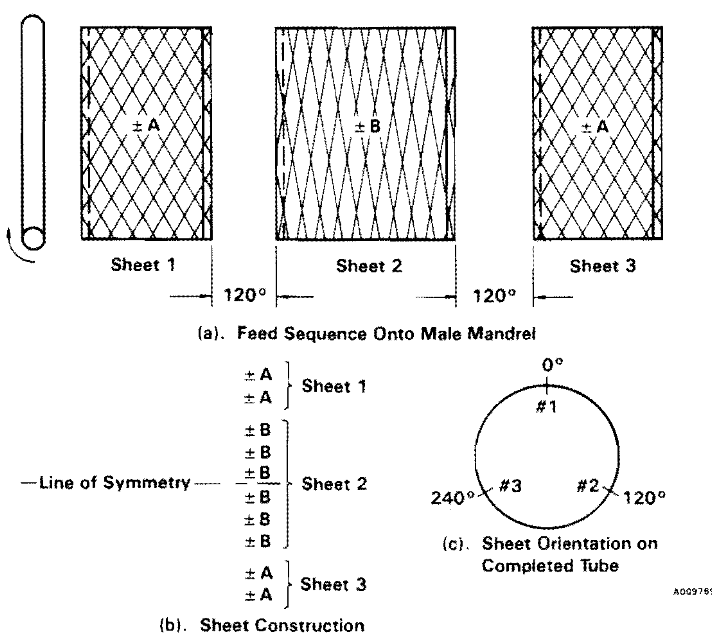

Figure 11. Sample Graphite/Epoxy Tape Layup for Space Station Struts

The rolled strut was then placed in a female mold, stacked in a rack, and placed in an oven for curing. After cure and cool down, the strut was pulled from the mold. This was easily done by hand since the CTE difference between the mold and strut allowed for sufficient clearance.

Once the strut was removed, the ends were parted to length. Tests showed that void content was less than .5 percent with a finished straightness (per ANSI Y14.5) of less than .03 percent per 10 ft length. Additional tests measured fiber volumes of 60 percent, surface finishes of 8 rms, and outside diameter tolerance of ± .001 in.

With co-cured protective coatings, it was possible to apply various foils to the inside and outside of a strut without additional processing. To apply an aluminum foil coating to the outside, an aluminum sheet was rolled up with the strut as the last wrap during the rolling process. It was then placed in the mold and cured. The mandrel during cure forms the foil and strut tightly together to produce a voidless bond.

Strut testing

Several different test programs have either been completed or are in progress to verify the ability of graphite/epoxy struts to meet Space Station requirements. The programs are:

- Mechanical testing: Room temperature tension and compression tests were completed on 26 specimens. The maximum load used was approximately 2,500 lb, which is typical of operational loads in an orbiting space structure and well below the strength capability of the struts. LPT design analyses determined the theoretical modulus of elasticity for each lay-up tested.
- Table 3 shows results obtained from ten $[\pm 45°/0°_4]_S$ and $[\pm 45°/\pm 15°/0°_2]_S$ lay-ups. The data, obtained from specimens made from one lot of material, slightly exceeded theoretical predictions.
- Short-term thermal cycling: In 1988, tension, compression and CTE tests are planned for short-term thermal cycled specimens. The thermal proposed tests will simulate the LEO environment 1,000 times.
- Long-term thermal cycling: Long-term thermal cycling tests will begin soon at the Center

Table 3

COMPARISON OF TWO GRAPHITE/EPOXY STRUT DESIGN MECHANICAL TESTS

	Test Number	Tension Modulus (msi)	Compression Modulus (msi)	Predicted Modulus (msi)
P75S/934 $[\pm 45°/\pm 15°/0°_2]_S$	1	24.7	23.8	
	2	25.5	24.6	
	3	26.0	25.1	
	4	25.2	24.2	
	5	27.7	26.7	24.6
	6	26.6	25.6	
	7	26.0	25.1	
	8	24.7	23.9	
	9	26.6	25.6	
	10	26.9	25.7	
	Average	26.0	25.0	
P75S/934 $[\pm 45°/0°_4]_S$	1	31.8	30.7	
	2	29.9	28.9	
	3	25.9	25.0	
	4	28.1	27.1	
	5	28.0	27.0	27.6
	6	28.8	27.9	
	7	30.1	29.1	
	8	30.6	29.6	
	9	33.0	31.7	
	10	29.8	29.2	
	Average	29.6	28.6	

88253-1D

for Space Engineering. Utah State University, Logan, Utah under a joint program with Morton Thiokol, Inc. The test will subject strut samples to a -150°/210°F environment 10,000 times using the fixture shown in Fig. 12.

- End fittings: Different concepts for integrating end fittings with struts during fabrication are being designed, fabricated and tested. Integrated end fittings would offer reduced fabrication cost and increased joint reliability.

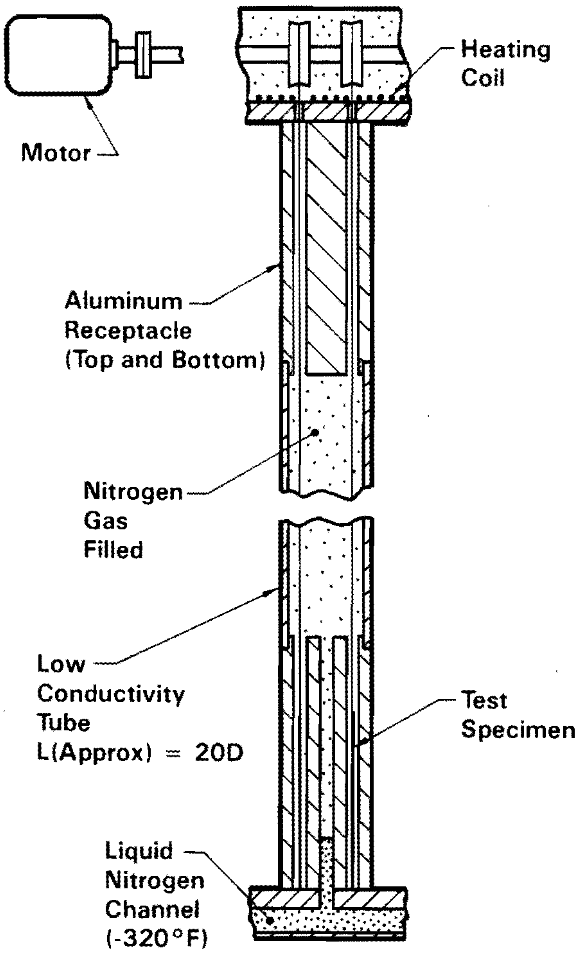

Figure 12. Long Term Thermal Cycling Test Fixture Designed and Built at Utah State University

Other Strut Uses

The strut process developed for Space Station applications readily lends itself to other projects. Diameters, lengths, and layups can easily be varied depending on the design.

For example, the design, fabrication, and test experience described above has been used in developing preliminary concepts for the Deployable Mast Subsystem (DMS). The DMS, shown in Fig. 13 and designed by Astro Aerospace Corporation and Harris Corporation, uses small diameter (.5, .75, and 1.0 in.) graphite/epoxy struts of different lengths to build a 180 ft long tower for large space structure simulations. This deployable tower will be transported to and from orbit via the Space Shuttle.

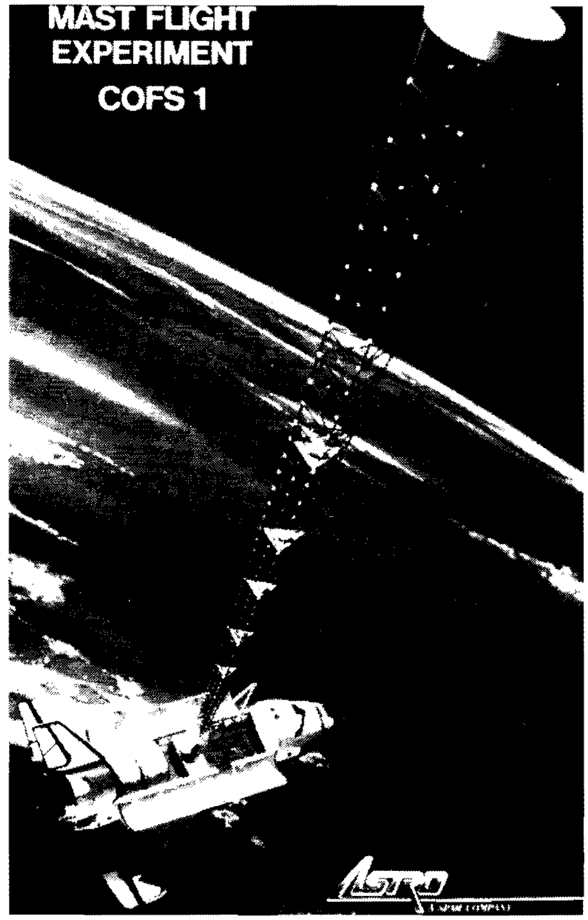

Figure 13. Deployable Mast Subsystem (Photo Astro Aerospace Corporation)

SUMMARY

The use of graphite/epoxy composite parts for space applications is already well established. Using graphite/epoxy parts for space vehicles and structures has many advantages including:

1. critical weight savings,
2. improved control of thermal distortions,
3. increased structural stiffness.

Spacecraft designers also must consider the severe space environment when specifying graphite/epoxy materials for their vehicles and structures. Radiation, atomic oxygen, and thermal cycling effects must be considered. Fabrication techniques do exist, however, which can easily protect graphite/epoxy material systems in the space environment.

Rolled composite struts designed for the proposed Space Station demonstrate that graphite/epoxy material systems readily can be used to meet the program's various mechanical and environmental requirements. At the same time, the Space Station struts and the associated fabrication process could be used for other spacecraft applications.

ACKNOWLEDGEMENTS

The author thanks Volker Teller, Ed Mason, Pete Evanoff and David R. Nelson of Morton Thiokol, Inc., and Harley J. Rockoff of Rockwell International's Space Station Systems Division for their assistance in preparing this paper.

ABBREVIATIONS

CTE .... Coefficient of thermal expansion
DMS............ Deployable mast subsystem
LEO .... Low earth orbit
LPT .... Laminated plate theory

REFERENCES

1. Mayer, N.J., Carbon Composites in Space Vehicle Structures, International Conference on Carbon Fibers, Paper No. 39, London, 1974.

2. Mazzio, V. F. and C. H. Bixler, Optimized Design and Fabrication Process for Advanced Composite Spacecraft Structures, American Institute of Aeronautics and Astronautics, Paper No. A79-19616, New York, 1979.

3. Mauri, R. E. and Crossman, F. W., Space Radiation Effects on Structural Composites, American Institute of Aeronautics and Astronautics, Paper No. A83-16808, New York, 1983.

4. Tompkins, Stephen S., Sykes, George F., and Bowles, David E., The Thermal and Mechanical Stability of Composite Materials for Space Structures, IEEE/ASM/ASME/SME Space Technical Conference, Anaheim, California, 1985.

5. Leger, L., Visentine, J., Santos-Mason, B., Selected Materials Issues Associated With Space Station, SAMPE Quarterly, Vol. 18, No. 2, January 1987, pp 48-54.

6. Lukez, R., Nelson, D., Teller, V., and Rockoff, H., Design, Fabrication, and Testing of Rolled Carbon/Epoxy Struts for Space Station Applications, 19th International SAMPE Technical Conference, Washington, D.C., 1987

BIOGRAPHY

Rudy Lukez is a design engineer in Morton Thiokol's Advanced Composite Structures Section. He is providing technical direction for a variety of composite strut development programs currently being pursued at Morton Thiokol's Aerospace Group. Mr. Lukez earned his B.S. in Mechanical Engineering at Cleveland State University, Cleveland, Ohio, in 1983 and has worked for Morton Thiokol since 1984. Prior to his employment at Morton Thiokol, Mr. Lukez worked for Hughes Aircraft Company's Radar Systems Group in El Segundo, California.