Proc. of SPIE Vol. 1303, Advances in Optical Structure Systems, ed. J Breakwell, V L Genberg, G C Krumweide (Oct 1990) Copyright SPIE

Composite structures for a large optical test bed

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ABSTRACT

A T50/ERL1962 graphite epoxy laminate was selected as the primary structural material for an optical test bed manufactured by Composite Optics, Incorporated (COI) for use by Eastman Kodak's Federal Systems Division to develop the design of lightweight optical systems with dynamic damping and active control of multi-segment primary mirrors.

The composite structures for this project consist of a 100 inch diameter 12 inch deep Aft Structure Assembly and six 190 inch long round tubes double tapered from a 3.65 inch midspan I.D. to a 0.90 inch I.D. at the ends.

A pseudoisotropic .09 inch thick layup was used for the aft structure to provide a low coefficient of thermal expansion and to meet requirements for stiffness and weight. The tubes were made with a ,06 inch thick $(0_2°/\pm 60°)_S$ layup for low longitudinal coefficient of thermal expansion (CTE) and high axial stiffness.

The aft structure will support a primary mirror consisting of a center segment and six outboard petal segments. The six composite tubes which attach to actuators at the outboard ends of the aft structure will support the secondary mirror for the Ritchey Chretien optical system.

INTRODUCTION

The objective of this development program is to evaluate certain theoretical approaches to the control of a multi-mirror optical imaging system. Testing will be done to develop methods to control aberrations and to align segments of the primary mirror and to demonstrate the potential of a system for active structural damping.

Lightweight composite structures were specified for this system to complement the lightweight frit bonded optics and provide the desired thermal and dynamic characteristics. The expected hygroscopic effects of these structures will be compensated for by use of the control systems.

A schematic of the optical test configuration is shown in Figure 1. The design includes a 102 inch diameter multi-segment primary and 15 inch diameter secondary mirror. The Figure 2 photograph shows the graphite epoxy structural components, an aft structure assembly and six double tapered 190 inch long tubes, assembled for dynamic testing with primary mirror mass simulators.

For optical testing the composite structures shown will be reassembled with a center segment primary mirror and one or more off axis petal mirrors. Each petal mirror will be supported by a control structure with an array of actuators for position and shape control. The petal control structure is also a graphite epoxy design currently being fabricated by COI. The following sections of this paper will describe only the requirements and design of the composite structures.

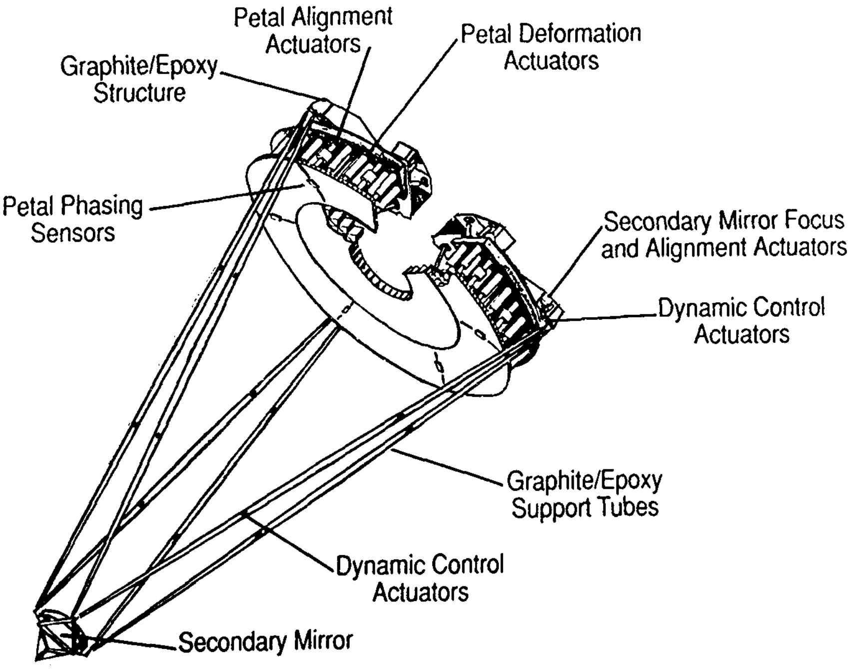

Figure 1. Optical test configuration

REQUIREMENTS

System level considerations

An optical system baseline minimum resonant frequency of 20 Hz was established to provide adequate stiffness consistent with what can be expected for the size of the optical system, in consideration of the use of lightweight graphite epoxy structures. Basic dimensions and material properties for the Aft Structure Assembly and Secondary Mirror Support Tubes were determined by MSC/NASTRAN finite element model (FEM) analyses of concept designs considering the interface requirements for mirror, actuators, and main mount attachment points.

Aft Structure Assembly (ASA)

The ASA was configured as shown in figure 3 and fabricated out of .090 inch thick 12.0 msi modulus pseudoisotropic panels as required to meet system level stiffness requirements. Minimum local fitting stiffness requirements were determined (using FEM analysis) by varying local stiffnesses until the image motion from base excitations was optimized for the test environment.

ASA thermal stability is controlled by the use of psuedoisotropic graphite epoxy with an in-plane CTE requirement of $0.0\pm0.4\times10^{-6}$in/in/°F. Front to back warping of the structure is minimized by the requirement that the average CTE difference between top and bottom skins be limited to 0.050×10^{-6}in/in/°F. Interface fittings in the optical support path have local thermal stability requirements which range from 2.0×10^{-6}in/°F to 5.0×10^{-6}in/°F within a 3 inch radius of the interface point. All interface fittings are fabricated from Invar to meet the stability requirements and to provide a metal interface.

Variations in hygroscopic properties were minimized by utilizing the same material lot and process controls for all laminate fabrication.

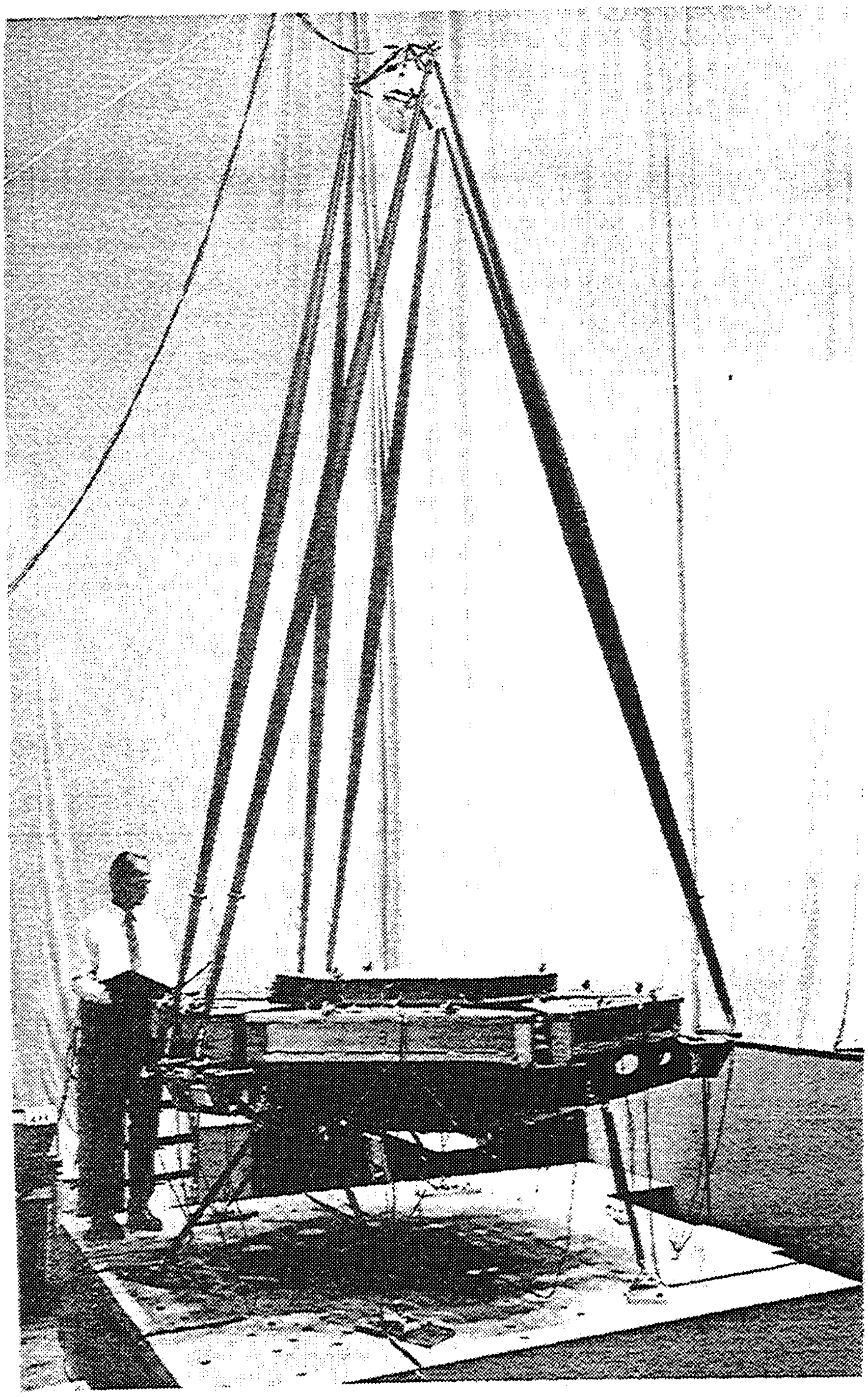

Figure 2. Dynamic test assembly

Strength requirements are modest since the greatest loading is the result of shipping/handling operations. These operations require that the structure be capable of withstanding a 3.0g static loading in any direction without permanent deformation or damage. Interface fitting loads were determined by math model analysis to be in a range from 60 pounds to 2400 pounds.

Secondary Mirror (SM) Support Tubes

For the SM support tubes the elastic modulus and geometry were specified to achieve a 10 Hz lateral frequency and buckling critical of 300 lbs. A double tapered tube geometry was specified to meet the requirements with a minimum optical obstruction. In consideration of COI's recommendation to use a T50/ERL1962 prepreg (with a low CTE layup), the minimum elastic modulus was specified at 16.0 msi. The SM support tubes are shown in figure 2.

An axial CTE requirement of $0.0 \pm 0.1 \times 10^{-6}$in/in/°F was specified to assure minimal tube to tube CTE variability and provide the desired alignment stability. The CTE requirement is specified over any 6.00 inch length of the tube. Invar fittings were specified to provide low CTE attachment points at the tube ends.

Variations in hygroscopic properties were minimized by utilizing the same material lot and process controls for all laminate fabrication.

Each tube is required to support an axial load of ±300 pounds and a lateral load of 15 pounds, applied at the tube center, without permanant deformation or damage. Load requirements are from a 3.0g static load factor associated with the environmental conditions for shipping and handling operations.

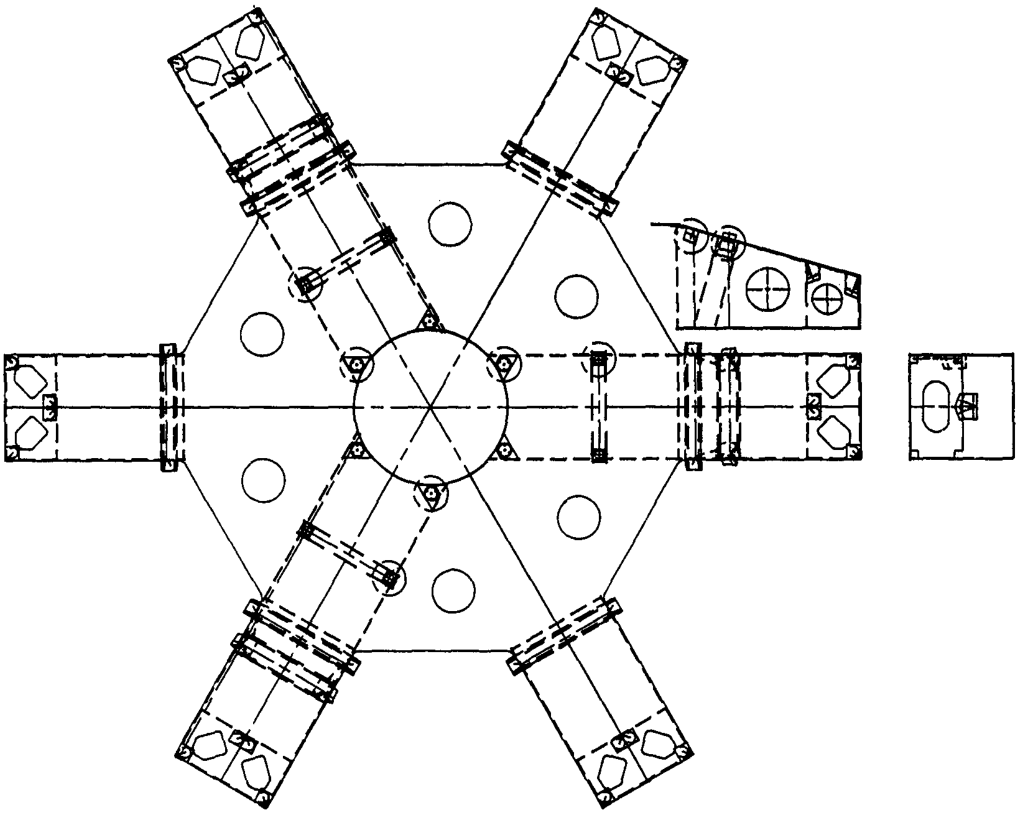

Figure 3. Aft Structure Assembly configuration

DESIGN AND ANALYSIS

From the established design requirements the detail design and analysis of the composite structures was undertaken by Composite Optics, Incorporated. During this detail design phase, consideration was given to materials selection, local joint configuration, interface fitting configuration, analysis techniques, and tooling and fabrication methods.

After investigating several graphite epoxy material systems, T50/ERL1962 (manufactured by Amoco Performance Products, Inc., Barkhamsted, Conn.) unidirectional tape prepreg was chosen as the baseline material for both the ASA and SM Support Tubes. The ASA CTE, stiffness, and strength requirements were met using a pseudoisotropic layup. Table 1 gives a summary of tested pseudoisotropic laminate properties.

Table 1.

T50/ERL1962
PSEUDOISOTROPIC TEST $(0,\pm60)_{NS}$ SUMMARY

TEST DESCRIPTION	TEMPERATURE	NO. OF SPECIMENS	MEAN	"B" ALLOWABLE	"A" ALLOWABLE
TENSILE STRENGTH (0° DIR)	RT	26	62.94 KSI	49.09 KSI	39.14 KSI
TENSILE MODULUS (0° DIR)	RT	5	12.57 MSI	----	----
TENSILE POISSON'S RATIO (0° DIR)	RT	5	.297	----	----
TENSILE (90° DIR)	RT	17	50.24 KSI	43.55 KSI	38.84 KSI
TENSILE MODULUS (90° DIR)	RT	5	13.58 MSI	----	----
TENSILE POISSON'S RATIO (90° DIR)	RT	5	.335	----	----
COMPRESSION STRENGTH (0° DIR)	RT	38	47.72 KSI	39.9 KSI	34.18 KSI
COMPRESSION MODULUS (0° DIR)	RT	10	11.68 MSI	----	----
COMPRESSION POISSON'S RATIO (0° DIR)	RT	10	.318	----	----
FLATWISE TENSILE	RT	14	1752 PSI	----	----
CTE (0°)	-4°F to +120°F	2	$.46 \times 10^{-6}$ IN/IN/°F	----	----
CTE (90°)	-4°F to +120°F	2	$.31 \times 10^{-6}$ IN/IN/°F	----	----
COMPRESSION STRENGTH (90° DIR)	RT	36	48.49 KSI	41.81 KSI	36.94 KSI
COMPRESSION MODULUS (90° DIR)	RT	5	12.76 MSI	----	----
COMPRESSION POISSON'S RATIO (90° DIR)	RT	5	.334	----	----
2-RAIL SHEAR STRENGTH	RT	12	32.63 KSI	28.52 KSI	25.66 KSI
SBS	RT	11	10.64 KSI	9.07 KSI	7.98 KSI

A $(0_2°/\pm60°)_S$ laminate orientation was selected for the 190 inch long, double tapered tubes. This orientation with T50/ERL1962 material combine to yield a near 0.0 CTE and high stiffness in the axial direction. Table 2 summarizes different ply orientations and the predicted laminate properties.

In addition to mechanical property considerations, economy and confidence in laminate properties were also a factor in choosing T50/ERL1962. While this material is not inexpensive, it is an economical choice when compared with some ultra-high-modulus fiber systems. COI also had a large data base of T50/ERL1962 mechanical properties from previous work and was confident that the proposed laminates would meet the design requirements with minimal risk.

Table 2.

PREDICTED LAMINATE ELASTIC CONSTANTS

T50/ERL1962

LAMINATE CONFIGURATION	E_X (MSI)	E_Y (MSI)	ν_{XY}	G_{XY} (MSI)	α_X (PPM/F)	α_Y (PPM/F)
0	33.2	1.08	.26	.68	-.419	17.7
$(0,90)_S$	17.17	17.17	.016	.68	.288	.288
$(\pm10)_S$	30.15	1.09	1.04	1.58	-.896	16.83
$(\pm20)_S$	18.85	1.17	2.13	3.88	-2.08	14.06
$(\pm30)_S$	8.10	1.38	1.84	6.50	-2.98	9.16
$(\pm40)_S$	3.52	1.94	1.14	8.21	-1.68	3.0
$(\pm45)_S$	2.52	2.52	.855	8.45	.288	.288
$(0,\pm60)_S$	11.98	11.98	.313	4.56	.288	.288
$(0,\pm60,\bar{0})_S$	15.02	1.07	.313	4.00	.056	.59
$(0_2,\pm60)_S$	17.29	9.68	.312	3.60	-.065	.854
$(0,\pm45,90)_S$	11.98	11.98	.313	4.56	.288	.288
$(0,\pm45,90,\bar{0})_S$	14.3	11.04	.313	4.13	.099	.521
$(0_2,\pm45,90)_S$	16.2	10.18	.312	3.78	-.128	.726

Primary considerations in adhesive selection for instrument structures are strength and resistance to long term creep deformation. Hysol's EA9394 adhesive was selected for the ASA and SM support tube all-bonded constructions. This adhesive is a good compromise in that, after cure, it is relatively hard but retains good peel and shear strength. While more ductile adhesives may provide better peel and shear strength, they can allow bond line creep, especially when used in ground based instrument structures subject to continuous 1g loading. This bond line creep may lead to long term optical instability problems in passive systems.

Figure 3 shows the overall configuration of the ASA. The six arms are equally spaced at 60° and form a 100 inch diameter envelope. The center section of the structure is 12.50 inches deep with each arm tapering to approximately 6.00 inches deep at the ends. The top and bottom skins are made from three pieces joined by one inch wide splice strips. These splices also increase the frequency of skin panel vibration modes. A cylinder, 18.00 inches in diameter, is bonded to both the top and bottom skins and forms a closure for the 18.00 inch center hole of the aft structure. Internal structure consists mainly of six continuous ribs which run from the center cylinder to the ends of three alternate arms. These long ribs also serve as side plates for the three alternate arms. Several holes have been provided to allow access for actuator installation and structure venting.

Invar 36 with a CTE of $+0.8\times10^{-6}$in/in/°F was chosen for the machined interface fittings. Structural details were developed to provide for the attachment of fittings so that through-the-thickness CTE effects of the laminate and adhesive were minimized. For CTE critical interfaces the fittings were bonded directly to internal ribs to eliminate through-the-thickness CTE effects. Figure 4 shows several examples of configurations which accomplish this design goal.

Stiffness and strength requirements for the ASA were met by providing ribs at or adjacent to highly loaded interfaces. This configuration provides a stiff load path and adequate fitting to graphite epoxy bond area. Table 3 shows design requirements and analytical predictions for local interface stiffnesses.

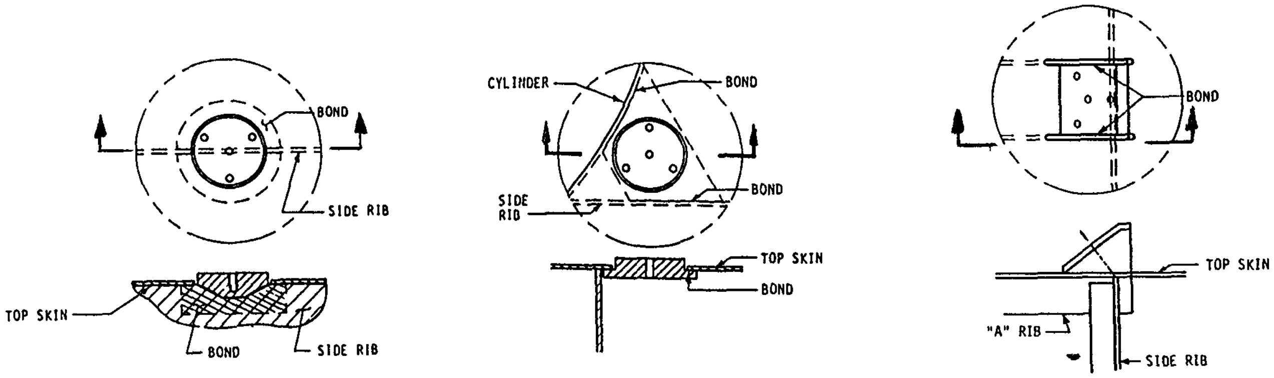

Figure 4. Interface fitting attachment details

Table 3. Interface stiffness (lbs/in)

Interface points	Minimum stiffness requirement Normal (axial) direction	Analysis results
A1-A6	1,000,000	1,000,000
B1-B12	600,000	1,050,000
C1-C6	600,000	907,000
D1-D6	600,000	1,867,000
E1-E12	600,000	1,450,000
F1-F12	50,000	145,000
G1-G24	250,000	905,000
H1-H6	200,000	1,000,000

Detailed structural analysis of the ASA was performed using MSC/NASTRAN finite element code. The overall FEM (shown in figure 5) contains all internal ribs and stiffeners, accounts for major access holes, and includes all fitting masses.

FEM modal analysis of the ASA showed a minimum natural frequency of 121 Hz. Static loads analysis of the structure was also performed to check material and bond line stresses.

Several finite element models of local areas around and including interface fittings were also developed to check local interface stiffnesses, CTE, and bond line loads. Figure 6 shows a typical local area FEM.

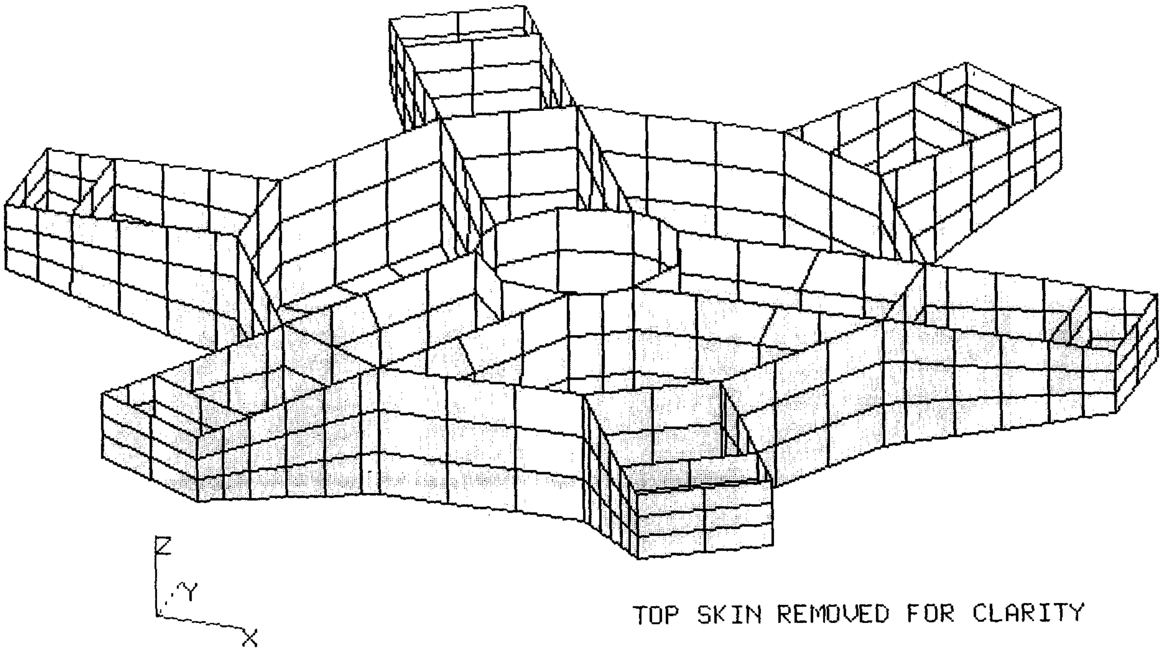

Figure 5. Aft Structure Assembly finite element model

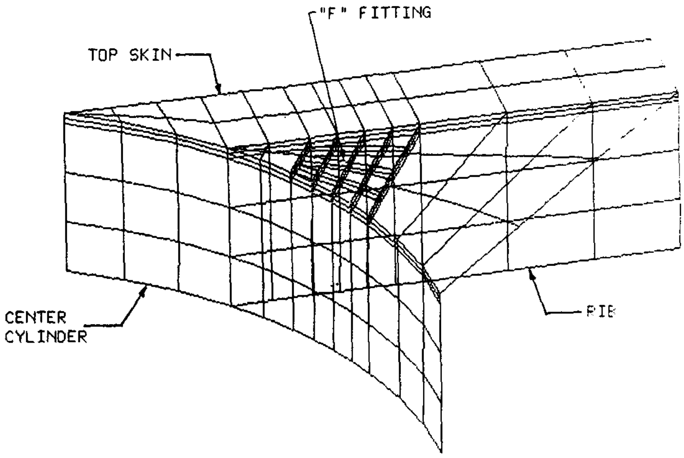

Figure 6. Local fitting area finite element model

FABRICATION

Fabrication of the ASA began with layup of flat graphite epoxy laminates. These 12 ply .090 inch thick laminates were laid up on flat aluminum caul plates and autoclave cured per the appropriate temperature and pressure profiles. For the tapered tubes the prepreg was cut into gore sections and laid up on tapered aluminum mandrels. The mandrel was sized to account for expansion during the elevated temperature cure.

After laminates were cured, work-in-process tests were performed to assure that the cured graphite epoxy parts met stiffness, strength, and CTE requirements. At this point, flat detail parts were cut from the laminates using the CNC router. The close accuracy of this computer controlled machine allows flat details to be cut to net size. This eliminates the need for trim templates and hand rework, reducing fabrication time and costs.

Assembly of the ASA was accomplished using aluminum assembly tooling which located one arm and associated fittings with respect to the center of the structure. This tool was inspected using a coordinate measuring machine in order to verify the accuracy prior to fabrication of the end item.

The assembly technique was to position the machined fittings using the assembly tool, then build the graphite structure around the individual fittings. The first assembly step was to place the upper skin on the assembly tool. The ribs were located using the interface fittings (held by the assembly tooling), dry fit checked, and then bonded. After ribs were assembled and bonded to the first arm, the partial assembly was rotated 60°, appropriate fittings positioned on the assembly tool, and the next set of ribs were assembled and bonded. This process was repeated until all ribs and fittings were assembled into the structure. At this point, the lower skin and arm end plates were bonded to the rib edges to complete the structure. Figures 7, 8, and 9 show several steps during the assembly sequence.

SUMMARY

Lightweight composite structures fabricated out of T50/ERL1962 graphite epoxy provide the desired thermal and dynamic characteristics for a large optical test bed which will be used to develop methods for active control of multi-segment primary mirrors and dynamic damping. Structure requirements were established by Eastman Kodak and used by COI to design, analyze, and fabricate the Aft Structure Assembly and Secondary Mirror Support Tubes. Stability concerns led to the selection of a good creep resistant structural adhesive and development of fitting attachment designs which minimize through-the-thickness CTE effects. FEM analysis was used to determine Aft Structure Assembly frequency response and to check material and bond line stresses, local interface stiffnesses, and CTE. Fabrication techniques minimized tooling, assembly fixturing and labor while meeting dimensional and structural requirements.

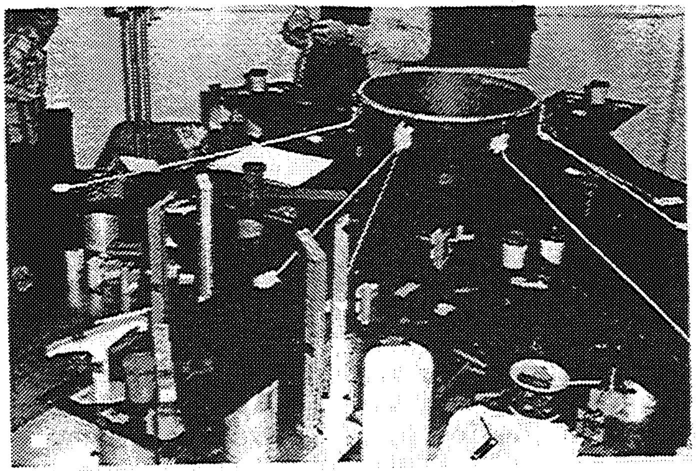

Figure 7. ASA assembly showing upper skin and aluminum fixturing

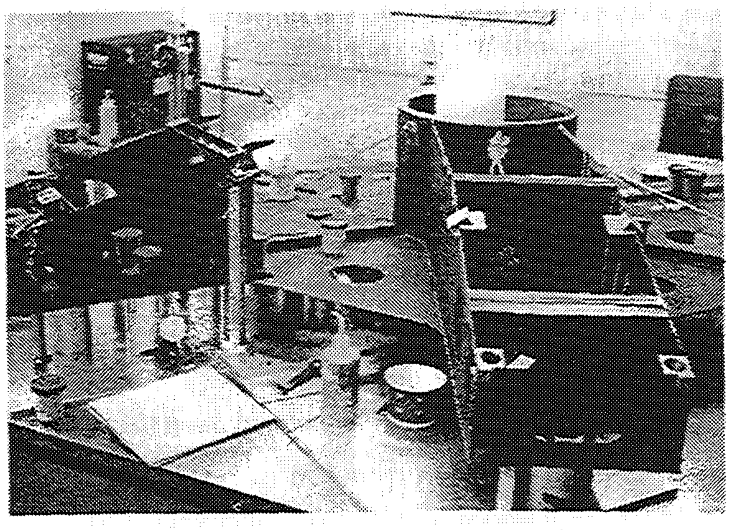

Figure 8. ASA fitting and rib assembly

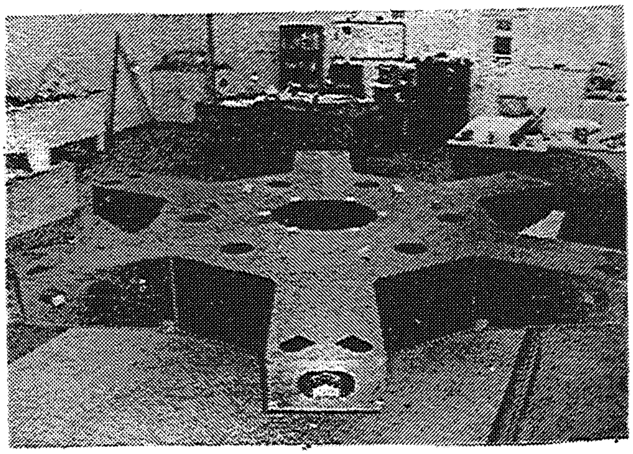

Figure 9. Completed ASA