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Development of zero coefficient of thermal expansion composite tubes for stable space structures

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ABSTRACT

Advanced composite materials are well suited for stable space structures due to their low Coefficient of Thermal Expansion (CTE), high stiffness and light weight. For a given design application, composite hardware can be tailored for strength, stiffness, CTE, and Coefficient of Moisture Expansion (CME). Computer modeling and laminate testing of high modulus graphite/epoxy tubes were evaluated for compressive strength, stiffness, CTE, CME and microcracking. Thermal cycling and microcracking effects on CTE were evaluated. Thin graphite/epoxy plies exhibited reduced microcracking. A zero CTE thin wall tube design resulted from the development program. Recent work on low moisture absorption resin systems is also discussed.

1. INTRODUCTION

The advantages of advanced composites in stable space structures are numerous. High specific strength and stiffness, low Coefficient of Thermal Expansion (CTE), thermal stability and tailorable nature make composites excel in space structure design and manufacture. The task involved was to develop a dimensionally stable thin wall tube with a high compressive modulus and low CTE for use in advanced space structure applications. The design team included members from design engineering, structures, materials engineering and manufacturing engineering. The product of our initial efforts was a list of design requirements which are as follows:

● Stiffness	E_c	20 msi
● Strength	F_{cu}	40,000 psi
● CTE	α_x	$0.0 \pm 0.1 \times 10^{-6}$ in/in/°F
● Moisture Expansion	β_x	$< 150 \times 10^{-6}$ in/in/%M
● Thickness	-	< 0.020 inches

The design requirements were well defined, therefore existing material properties were used to evaluate tube designs using computer modeling programs, such as SQ-5.[1] Fifteen candidate designs were fabricated into flat laminates and tested for physical and mechanical properties. From the initial results, five designs were used to fabricate one, two, and three inch diameter tubes which were tested for thermal and mechanical properties (See Table 1). The final design was tested to full qualification.

2. DESIGN

The SQ-5 computer modeling program was used to evaluate different fiber types and ply orientations in an attempt to develop a zero CTE and zero Coefficient of Moisture Expansion (CME) laminate.[2] Due to the large number of possibilities and time constraints, the zero CME requirement was redefined.

Another desirable ply orientation requirement was the use of a balanced/symmetrical ply orientation in order to reduce the effects of thermally induced twist on thin wall tubes.[3] The availability of thin ply prepreg, 0.002 to 0.003 inches, allowed the use of adjacent plies at equal and opposite angles to the axis instead of off axis 0.005 inch ply previously used in thin wall tubes. The use of thin graphite/epoxy plies to reduce microcracking caused by thermal cycling has been documented.[4] Since microcracking generally increased the negative CTE of composites, thin ply laminates should produce a more dimensionally stable structure. Five of the design concepts are shown in Table 1. The design evolution revolved around GY-70 in the center-line ply for stiffness and T-50 for the angle plies for CTE control and stability.

DESIGN CONCEPT	PLY ORIENTATION	MATERIALS (Fiber/Resin)
DC-2	$0_{(1)},\pm70_{(1)},0_{(2)},\mp70_{(1)},0_{(1)}$	[1] 0.0034" T-50/934 [2] 0.005" GY-70SE/934*
DC-6	$0_{(1)},\pm70_{(1)},0_{(2)},\mp70_{(1)},0_{(1)}$	[1] 0.0034" T-50/934 [2] 0.0035" GY-70/934**
DC-11	$0_{(1)},\pm70_{(1)},0_{(2)},\mp70_{(1)},0_{(1)}$	[1] 0.002" T-50/934 [2] 0.0035" GY-70/934**
DC-15	$0_{(1)},\pm70_{(1)},0_{(2)},\mp70_{(1)},0_{(1)}$	[1] 0.002" T-50/934 [2] 0.005" GY-70SE/934*
DC-16	$0_{(1)},+70_{(1)},0_{(2)},-70_{(1)},0_{(2)},-70_{(1)},0_{(2)},+70_{(1)},0_{(1)}$	[1] 0.002" T-50/934 [2] 0.002" P-75/934

* SINGLE END TAPE
** UNI-DIRECTIONAL CLOTH

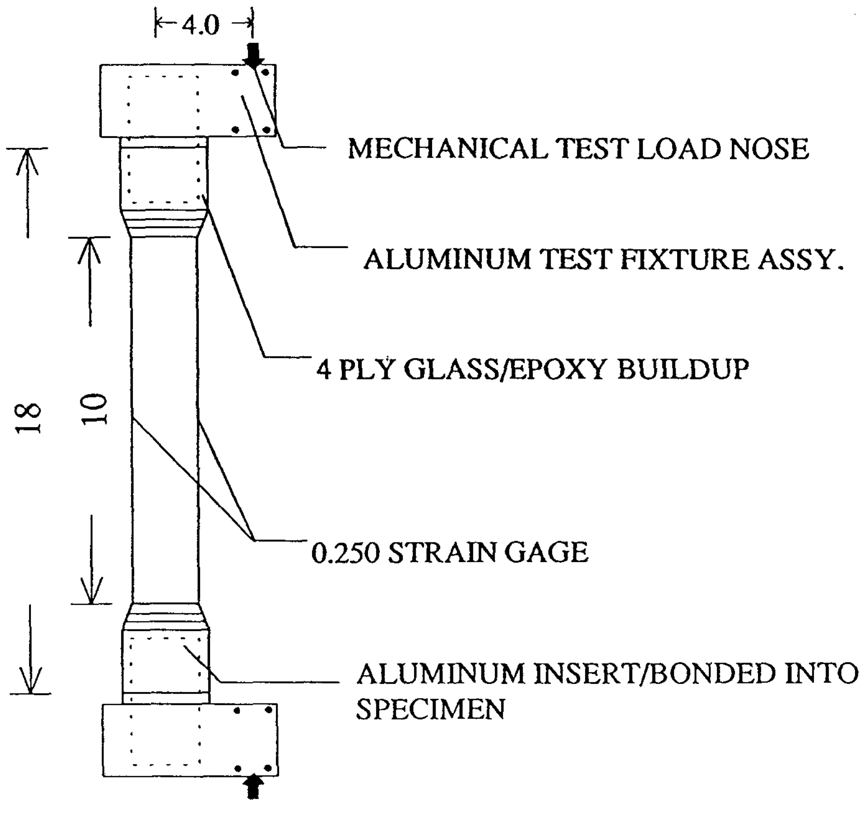
TABLE 1. DESIGN CONCEPT CANDIDATES

3. EXPERIMENTATION

To evaluate designs and correlate the modeling data, flat laminates were fabricated and tested for tensile strength, modulus, and CTE. A total of fifteen design concepts were initially evaluated.

Five design concepts were chosen as possibilities for meeting the requirements and used to fabricate one, two and three inch diameter tubes for physical and mechanical testing. The one inch diameter tubes were cut into five inch long specimens and built-up with glass cloth on both ends, bonded to aluminum plugs, and tested in torsion on a universal mechanical tester. The two and three inch diameter tubes were cut into 18 inch long coupons, bonded to aluminum plugs on both ends and built up with fiberglass cloth. The tubes were tested off-axis (four inch moment) in bending/compression also on a universal mechanical tester (See Figure 1). From the bending/compression test, tensile modulus, compression strength and modulus of the tubes were measured. Note that tensile failure does not occur during this test because the tensile strength of the laminate is higher than the compression strength and the tensile stress in the specimen is less than the compressive stress due to the test geometry. Several two inch diameter tubes were also sent to Composite Optics, Inc for CTE testing before and after thermal cycling 200 times to ± 280 °F. CTE was measured using a laser interferometer over a temperature range of -300 °F to +200 °F.[5]

After test data evaluation, the DC-15 configuration was selected for CME testing. Two tubes, two inches in diameter and six feet long, fabricated from the DC-15 layup, were CME tested at Composite



CALCULATIONS
THE BENDING / COMPRESSION ULTIMATE STRENGTH WAS CALCULATED USING THE FOLLOWING FORMULA

$$Fc = \frac{P}{\pi \times D \times t}\left[\frac{16}{D} + 1\right]$$

t = Tube wall thickness
P = Ultimate load
Fc = Compressive stress
D = Diameter

FIGURE 1. BENDING / COMPRESSION TEST ARTICLE

Optics, Inc.[6] A chamber was built to measure tube moisture desorption axial length changes as well as twist and bending. The first tube was conditioned at 70 % RH and at room temperature until equilibrium. After a weight gain measurement the tube was placed in the chamber, and evacuated to 10^{-3} torr. The tube desorption changes were monitored for 50 days, 20 days @ room temperature, 10 days @ 150 ^{o}F, and 20 days @ 100^{o}F. The tube was also thermal cycled to measure CTE, ten times to -200^{o}F and +100^{o}F. Thermal expansion measurements were made at 50 ^{o}F intervals. The second tube was conditioned at 50 % RH and at room temperature until equilibrium and the CME test was repeated.

4. TEST RESULTS

A summary of the five design concepts physical and mechanical properties are shown in Table 2. All data in Table 2 is as fabricated; test specimens fiber volume ranged from 58 to 62 %. The bending/compression test results show about a 5% higher modulus in tension than in compression. As stated in the testing section, all tubes failed in compression; the tensile strength of the tubes is therefore not reported in the table. Design concept fifteen (DC-15) had the highest compression strength and modulus, 49,000 psi and 21.2 msi for the two inch diameter and 43,500 psi and 21.5 msi for the three inch diameter tubes. The one inch diameter torsion tubes test results also were the highest for the DC-15 design, 29,770 psi and 2.41 msi for torsional strength and shear modulus, respectively.

The CTE testing was performed at Composite Optics, Inc. The results after thermal cycling are shown for selected design concepts also in Table 2. The CTE of DC-15 as shown in Table 3, ranges from +0.00 in/in/^{o}F to -0.10 in/in/^{o}F over a temperature range of -300 ^{o}F to +200 ^{o}F. Thermal cycling had no significant effect on CTE of DC-15 due to the use of 0.002 inch thin ply T-50 prepreg. A thermal cycled DC-15 tube was sectioned and is shown in Figure 2. Microcracks were measured at < 5 cracks per inch throughout the tube.

The results of the two tubes tested at Composite Optics for CME are shown on Figure 3. The equilibrium moisture content (M_e) of each tube was 0.84 % and 0.54 % at 70 % and 50 % RH respectively. The desorption strain was -0.95×10^{-6} in/in from 70 % RH for tube number one and -85×10^{-6} in/in from 50 % RH for tube number two. The calculated CME values are therefore 113 in/in/M% and 157 in/in/M% respectively. The slight difference in CME is probably due to resin content differences, less than 100 % moisture equilibrium, and measurement errors. The tubes were thermal cycled after the dry out and the CTE's were measured at -0.10×10^{-6} in/in/^{o}F. Note that this is consistent with previous CTE test results.

5. CONCLUSIONS

It has been demonstrated that through the use of modeling, combined with verification testing, advanced composites due to their unique properties can be tailored to meet the increasingly stringent requirements of dimensionally stable spacecraft designs.

Computer modeling allowed us to design a layup that would meet all of our objectives. A goal of developing a zero CTE and zero CME laminate was not possible due to material, time and cost limitations. Zero CTE and zero CME laminates were designed but they failed to meet our high stiffness requirements. The DC-15 layup was chosen for our application for its excellent mechanical properties. CME results were higher than expected at 50 % RH (157 PPM/%M), but the strain (-85 PPM) was well within our budget.

Design validation testing was used to evaluate designs and tailor changes in materials and ply orientation to allow us to meet our goal of developing a near zero CTE composite tube. All the design requirements of low thermal expansion, high strength, stiffness and definable CME were met.

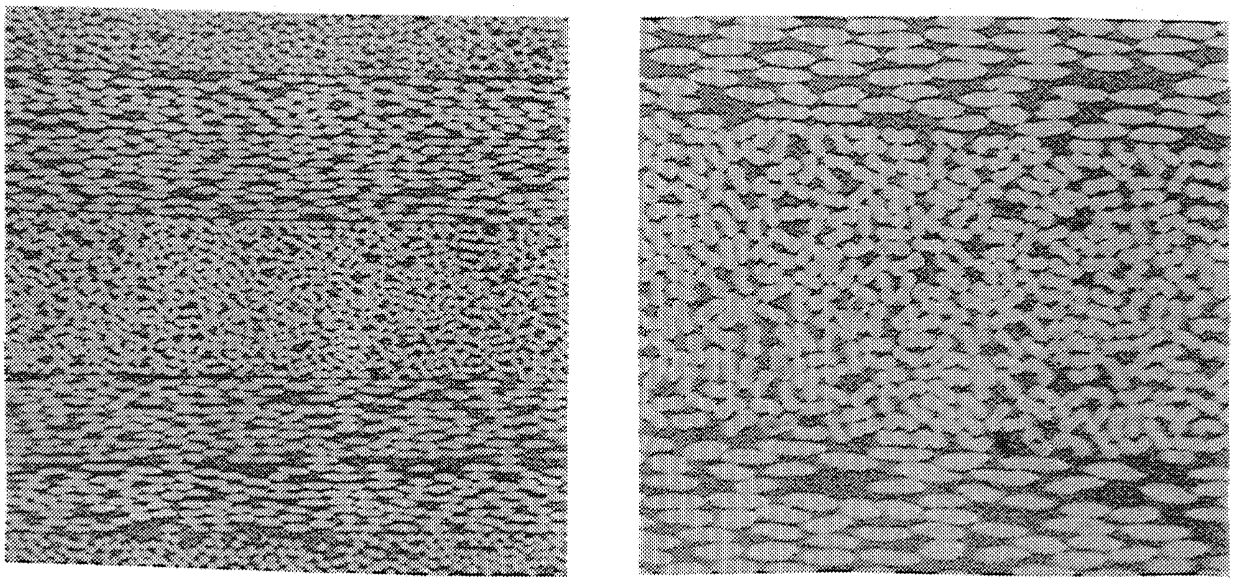
Design Concept	Tube Diameter (inches)	Compressive Strength (psi)	Compressive Modulus (msi)	Tensile Modulus (msi)	Torsional Strength (psi)	Shear Modulus (msi)	CTE Average (in/in/^{0}F)
DC-2	1	-	-	-	24,200	2.67	+0.10
	2	45,100	17.4	18.5	-	-	-
	3	47,700	17.4	17.8	-	-	-
DC-6	1	-	-	-	16,800	2.88	+0.16
	2	37,600	15.6	16.1	-	-	-
DC-11	1	-	-	-	23,425	2.34	-0.20
	2	36,800	16.1	16.8	-	-	-
DC-15	1	-	-	-	29,770	2.41	-0.08
	2	49,000	21.2	22.0	-	-	-
	3	43,500	21.5	22.0	-	-	-
DC-16	1	-	-	-	22,250	2.03	-0.12
	2	40,700	23.0	22.0	-	-	-
	3	43,000	22.8	22.0	-	-	-

TABLE 2. MECHANICAL PROPERTIES

COUPON NUMBER	CTE* (As Fabricated) ($x10^{-6}$ in/in/^{o}F)	COUPON NUMBER	CTE* (Thermal Cycled)** ($x10^{-6}$ in/in/^{o}F)
1A	-0.06	1C	-0.07
1B	-0.01	1D	-0.05
2A	-0.02	2C	+0.01
2B	-0.02	2D	-0.07

* CTE range -300 ^{o}F to +200 ^{o}F
** Thermal cycled 200 times $\pm$ 280 ^{o}F

TABLE 3. CTE TEST RESULTS, 2-INCH DIAMETER DC-15

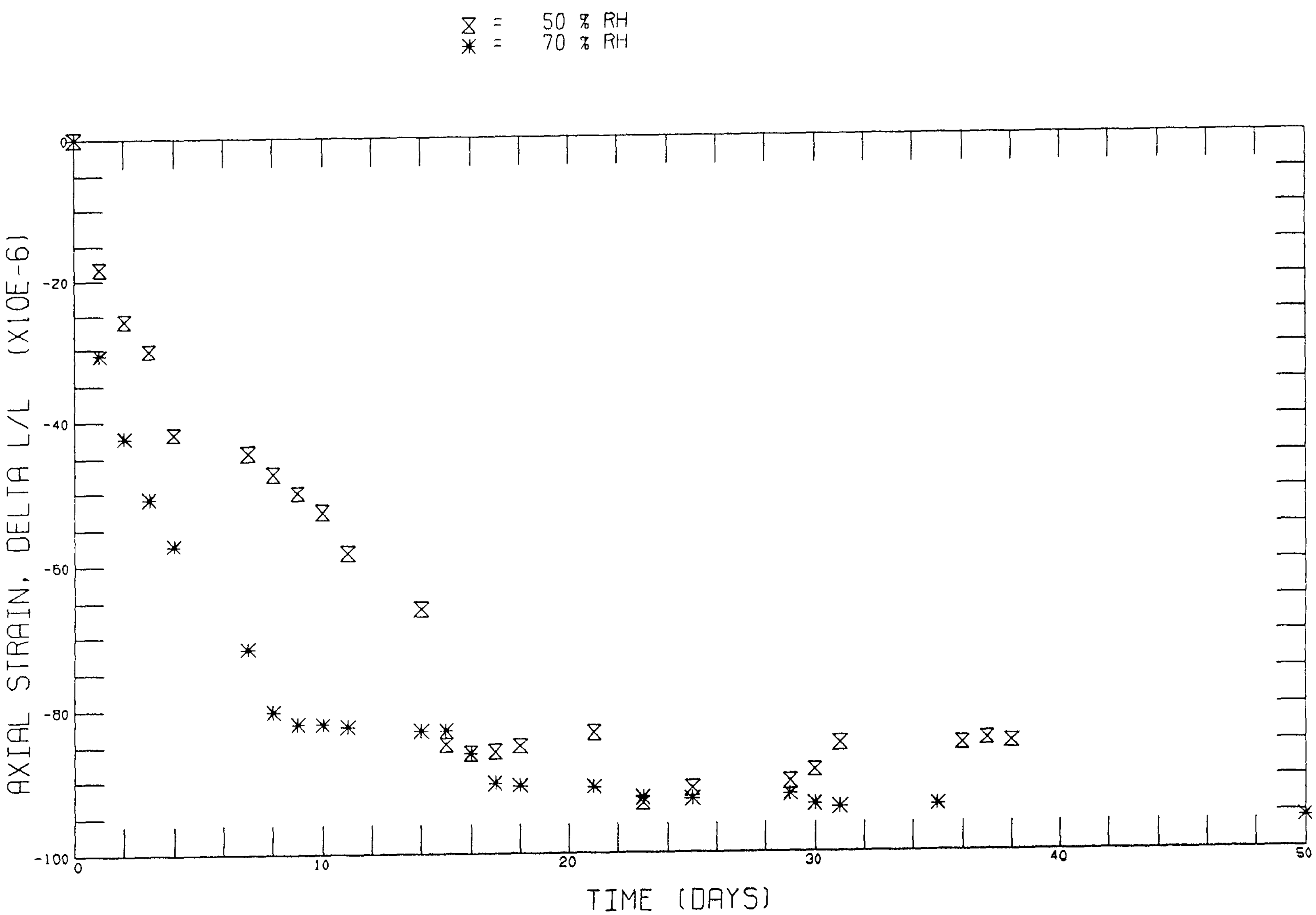


(200X) (400X)

FIGURE 2. MICROSECTION OF DC-15 AFTER THERMAL CYCLING

Note Microcracking Only Observed in Center: 0.005 inch GY-70 Ply

FIGURE 3. AXIAL DESORPTION CURVE



6. FURTHER WORK

The requirements for dimensionally stable structures are continually increasing. Yesterday's goal was low CTE but today's goal is low CTE and low CME. The development of low moisture absorption resins is the focus of our current development program. Matrix resins made from polycyanates are being evaluated to replace current epoxy systems. Recent testing shows the neat resin moisture (Mm) uptake of cyanates to be about 1 % versus 4 % for typical epoxy resins. Apparently the laminate strain due to moisture absorption can be reduced by a factor of four. We are currently evaluating the properties of polycyanate resin systems and their effect on mechanical properties, CTE and CME of graphite laminates.

7. ACKNOWLEDGEMENTS

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8. BIOGRAPHY

John D. Strock is a Project Materials Engineer in the Materials Engineering Department of TRW, Space and Defence Sector, Redondo Beach, California. He is responsible for managing materials development, testing and fabrication of Advanced Composite Hardware for space structures. Mr. Strock has been at TRW for 10 years and has received a Bachelor of Science, Manufacturing Engineering from California State University, Long Beach.

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