Dimensional Stability of CFRP Composites for Space Based Reflectors

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ABSTRACT

In the light of the recent successes in utilizing CFRP composites for fabrication of ultra-lightweight, micron-accuracy reflectors for space telescopes, this paper provides a recent assessment of the main factors influencing dimensional stability of composites. Two recent examples of all-composite reflector designs that demonstrate the validity of the composite choice for this type of space applications are presented.

Keywords: CFRP, dimensional stability, CTE, CME, moisture absorption, microcracking, cyanate ester.

1. INTRODUCTION

For the majority of spacecraft components, CFRP composites are widely accepted as the material choice for designers because they provide the highest tradeoff metrics based on weight, cost, and performance. Yet composites are not considered the obvious choice for high accuracy space components such as micron accuracy reflectors and telescope mirrors. The most commonly used materials for these applications are still metals (aluminum and beryllium) and glasses (ULE and Zerodur, and fused silica). Without a doubt, composites offer significant reduction in mass and cost over these materials. However, the limited understanding of their dimensional stability remains a serious deterrent against the selection of CFRP composites for this class of space structures.

For fabrication of ultra-stable space components, designers are primarily concerned about dimensional stability of CFRP composites because of their susceptibility to two main causes of instability: microcracking due to thermal cycling and expansion due to moisture absorption. Both phenomenons are directly related to the morphology, structure, and chemistry of the specific constituents (fiber/resin) of the composite used. For epoxy matrix composites, the effects of moisture absorption and microcracking are fairly well characterized for conventional spacecraft applications. In ultra-stable structures where micron level dimensional stability is required, there is an obvious need for quantitative assessment of the magnitude these effects contribute to distortions in shape and surface accuracy. Clearly, such assessment will ensure that the composite option is not systematically eliminated from the tradeoff space at the material selection phase, thus opening the door for enormous weight saving potential that could not be realized with any other material available.

With the growing demand for improved performance especially in the aerospace and the electronic packaging industries, new resin systems with enhanced thermo-mechanical properties were developed and commercialized in the last ten years. First a class of toughened epoxies offered an improved performance over standard epoxies in terms of microcracking resistance but they still suffered from unacceptable moisture absorption levels. In recent years, cyanate ester resins have emerged as a replacement for epoxies in CFRP composites. Cyanates offer an interesting set of hygrothermal characteristics that make them well suited for dimensionally stable structures. These properties include very low moisture absorption, superior microcrack resistance, and negligible cure shrinkage.

In this paper, a brief discussion of the material aspects with direct influence on dimensional stability of CFRP composites is presented. Two recent examples that demonstrate successful utilization of these composites in micron-accuracy reflectors are presented.

2. PRIMARY ASPECTS OF DIMENSIONAL STABILITY

2.1 Coefficient of Thermal Expansion

Coefficient of Thermal Expansion (CTE) is the material property of primary influence on dimensional stability as it represents materials response to changes in temperature. Consequently materials with low CTE are highly desirable for precision structures especially large optics where thermal gradients and temperature fluctuations at the operating environment could cause substantial change in dimensions leading to distortion in mirrors shape and figure accuracy. Furthermore, sufficiently low CTE materials would result in little change in dimensions (strain) as the precision component is taken from room temperature to its final operating temperature after deployment. An obvious advantage of CFRP composites in this regard is the inherent tailorability of their thermo-mechanical properties. With the appropriate choice of fiber type, resin chemistry, volume fractions, and lay-up orientation, CFRP laminates of near-zero CTE can be easily and affordably produced using standard fabrication methods.

A factor of prime importance when considering the CTE effect on dimensional stability is the change in CTE itself with temperature. Like other material thermal and mechanical properties, CTE varies significantly with temperature. In almost all materials, this change is nonlinear over the temperature range of interest for most optical structures. Therefore, it is important to take under consideration two important factors when selecting a low CTE material for a given application: the average CTE values at the operating temperatures, and the change in average CTE values between the operating temperature and the temperature at which the structure is fabricated. To demonstrate this point, consider selecting a material for a stable optical component operating at cryogenic temperatures lower than 100 K. Figure 1 shows reported CTE curves for a number of candidate materials commonly used or considered for stable structures. Considering the CTE values at cryogenic operating temperatures only, it is clear from Figure 1 that SiC and CFRP composite would be the best candidates as they possess the lowest CTE's at these temperatures. However, when the change in CTE from room temperature (fabrication temperature) to operating temperature is taken under consideration, CFRP would be the best selection. Typically SiC has a nominal CTE of about 2.2 ppm/C at room temperature and decreases gradually to approach near-zero values at temperatures lower than 100 K. Said otherwise, a SiC mirror fabricated at room temperature would experience a total strain of about 240 PPM upon cool-down to cryogenic temperatures. On the other hand, the same mirror fabricated from CFRP would exhibit strains of less than 10 ppm over the same cool-down range. This can be seen clearly when the thermal expansion behavior of both materials is presented in terms of strain (dL/L) instead of CTE as shown in Figure 2.

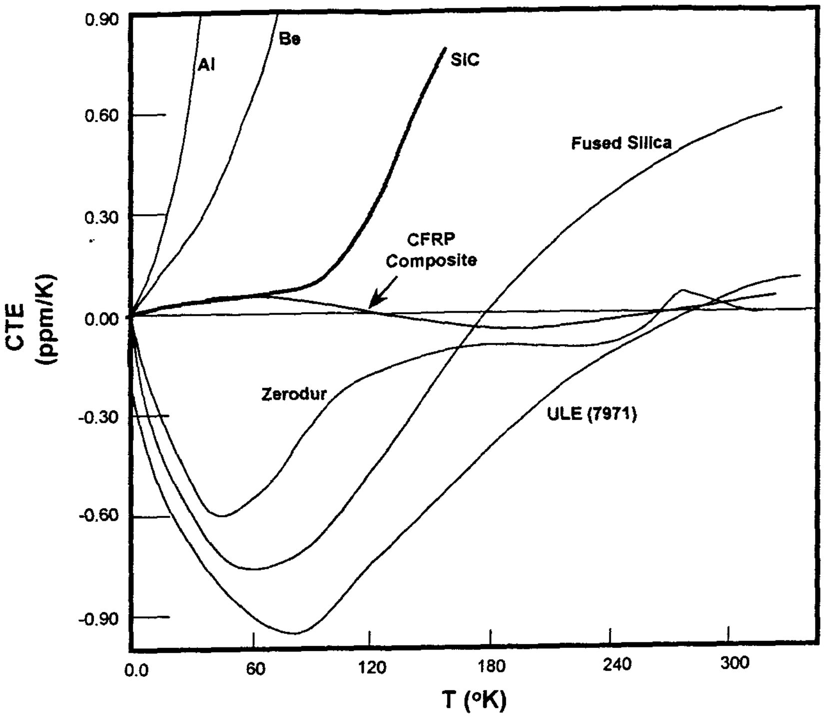

Figure 1. CTE vs. temperature curves for materials commonly used for stable structures. (All CTE curves except for CFRP composite were obtained from reference 4. The CTE curve for the CFRP composite was measured at COI.)

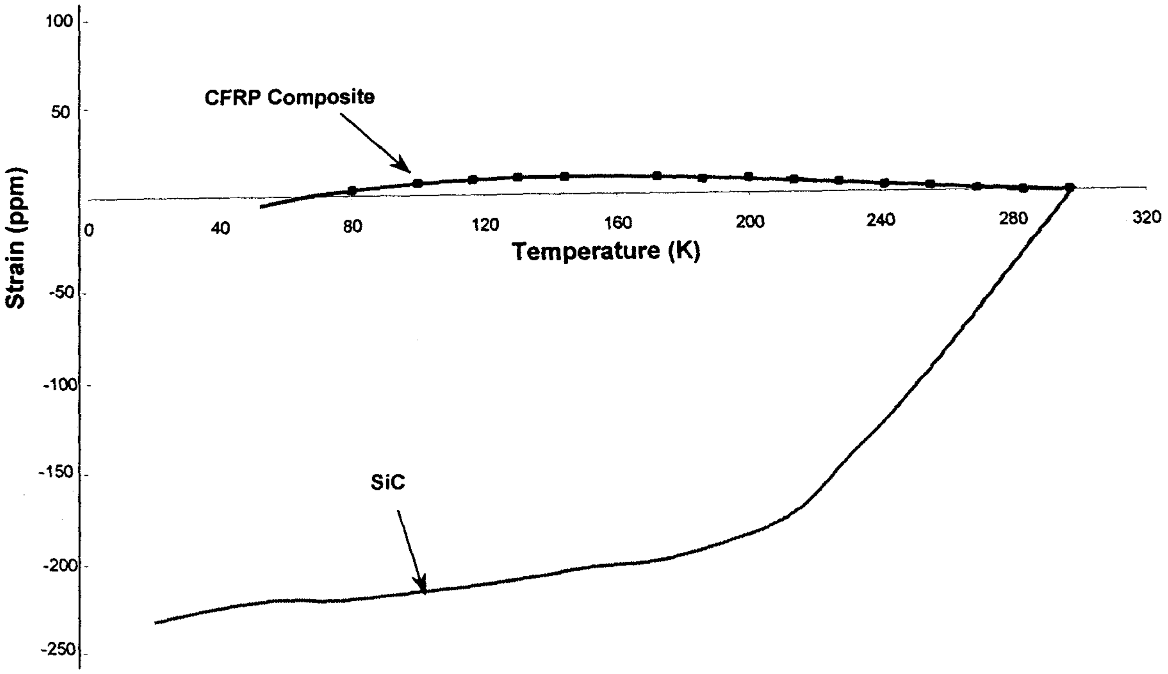

Figure 2. Strain vs. temperature curves for M55J/954-3 composite (measured at COI) and SiC (reference 4).

2.2 Moisture Expansion

Coefficient of Moisture Expansion (CME) and the maximum moisture content are the two parameters commonly used to characterize moisture expansion in composites. Analogous to the relationship between CTE and the change in temperature, CME represents the potential for material's change in dimensions (strain) as a result of moisture pickup. Provided most epoxies and cyanates used in space have comparable CME values, it is the maximum moisture uptake that really controls the amount of hygroelastic strain (moisture-induced strains) in a given composite material.

There is no doubt that the introduction of cyanate esters as a replacement for epoxies in space applications has substantially reduced the magnitude of the moisture problem in composites to levels that allow for successful fabrication of micron accuracy components. Typical moisture saturation levels (by weight) in cyanates are 60% to 80% lower than epoxies (see Figure 3). To quantify the magnitude of this effect in terms of change in dimensions, typical hygroelastic strains in cyanate composites are 10 to 20 PPM (microstrains) at saturation under normal temperature and humidity conditions. With reasonable control of the humidity levels during storage and assembly, these strains can be easily reduced to sub-PPM levels.

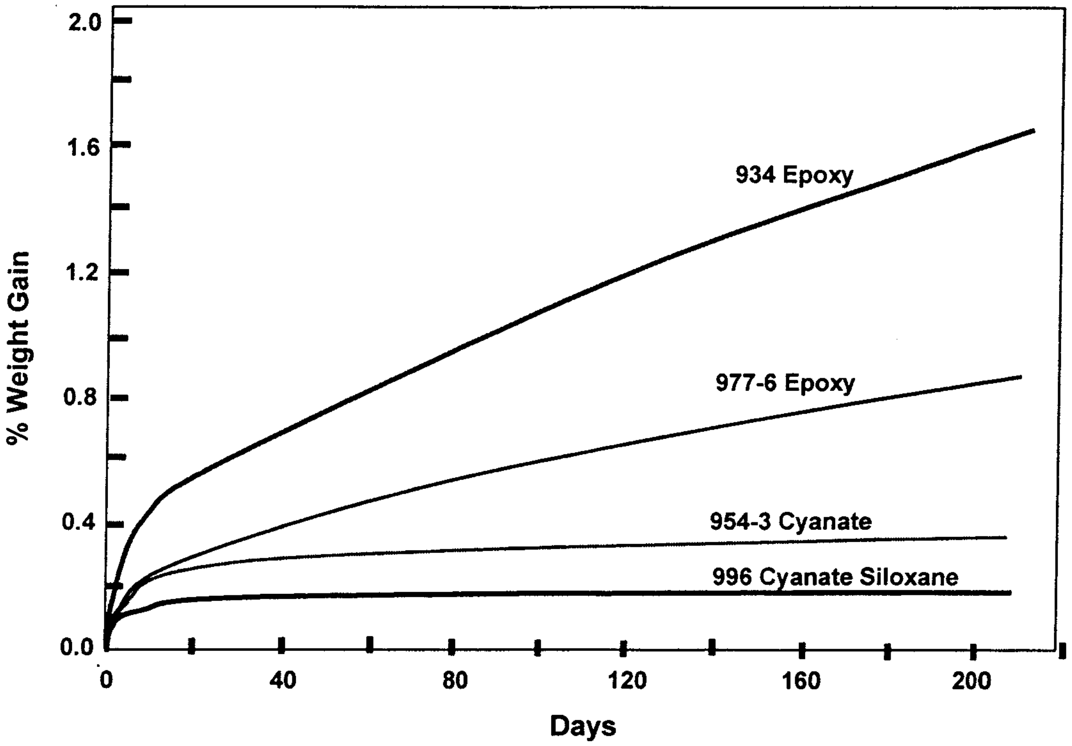

Figure 3. Moisture absorption curves for selected cyanates and epoxies at room temperature and 50% relative humidity (data obtained from Hexcel Space Products).

An effective and affordable practice of alleviating moisture effects is to keep parts under positive flow of N2 when they are not being assembled or tested. Alternatively, periodic dry-out cycles would be sufficient to achieve the same goal if continuous N2 purge becomes prohibitive. This is facilitated by the fact that moisture absorption and desorption rates in cyanates are the same. Furthermore, the mechanism of moisture absorption in cyanates is Fickian in nature and the diffusion rates are an order of magnitude faster than epoxies. Although higher diffusion rates result in faster moisture pick-up leading to shorter saturation times, they are advantageous from dry-out standpoint. Obviously, the previous statement is true only if the moisture absorption/desorption process is totally reversible within the life cycle of the structure. Our experience with cyanate-composites show that this is the case provided that the dry out is performed at temperatures higher than 60°C. At lower temperatures, dry-out requires longer times and may result in incomplete moisture desorption due to a small portion of bound water molecules that require higher temperature to be driven out of the molecular structure of the resin.

2.3 Thermal Cycling

Microcracking due to thermal cycling has been the subject of numerous studies ever since CFRP composites were first used for space applications. Over the years, however, spacecraft designs have successfully managed to design around microcracking in conventional space components that do not require stringent dimensional stability. In these applications, the microcracking effect on performance is exemplified by reduction in primary mechanical properties such as strength and stiffness. Once the magnitude of this effect is quantified, it is commonly accounted for by applying appropriate knockdown factors to the respective properties in the design phase.

Thermal microcracking of CFRP composites usually occurs after cool-down from the curing temperature and /or due to thermal cycling of the composite structure under simulated or operational conditions. In epoxy composites, it is observed that the density of microcrack formation with thermal cycling decreases asymptotically until it reaches saturation limit after a certain number of cycles. Therefore, it has become an accepted practice for some spacecraft manufacturers to subject the composite structures to repetitive thermal cycling on the ground until complete microcracking has occurred before launch. Although this might seem deleterious, this approach would nonetheless eliminate potential for in-orbit dimensional changes due to thermal cycling.

Unfortunately, the above methodologies of designing around the microcracking phenomenon are not adequate for high accuracy precision structures because the variability in magnitude and spatial distribution of microcrack formation usually overshadow the level of accuracy required in these components. For example, different locations of a reflector mirror or a metering structure might expand or contract non-uniformly with microcracking leading to unpredictable and unacceptable levels of distortion. Consequently, the microcracking effect had to be eliminated from the composite behavior to allow successful fabrication of micron-accuracy composite parts. This became possible with toughened epoxies in recent years and was finally achieved with the introduction of cyanate esters. With the right selection of fiber/resin combination, it is now easy to fabricate CFRP laminates that can survive a wide range of thermal cycling without microcracking.

3. TECHNOLOGY DEMONSTRATION

To demonstrate the validity of the composite choice for micron-level accuracy structures, we briefly present two examples of all-composite reflector designs fabricated by COI in the last few years.

3.2 MLS Primary Reflector

The Microwave Limb Sounder (MLS) is a limb-sounding radiometer sensing emissions in the millimeter and sub-millimeter range. MLS will contribute to an understanding of atmospheric chemistry by assessing stratospheric and tropospheric ozone depletion, climate forcings and volcanic effects. The heart of the antenna is the primary reflector, constructed from graphite/cyanate composites in a facesheet/core construction. The reflector has an aperture of one square meter, a mass of 8.7 kg and final figure accuracy of 4.37 microns rms. A comparison between the requirements and the actual (measured) measurements on the flight hardware mirror are shown in Table 1. Figure 4 shows a photograph of the MLS primary reflector.

Table 1. MLS Composite Primary Reflector Performance

Parameter	Requirement	Actual
Dimensions	1.6 x 0.8 meter ellipse	Same
Mass	10 kg (22.05 lb)	8.6 kg (19.1 lb)
Areal Density	7.8 kg/m^2	6.7 kg/m^2
Stiffness	80 Hz	228 Hz (kinematic, calculated)
Surface Accuracy (as-fabricated)	8.5 microns rms	4.37 microns rms (measured)
Surface Stability (on-orbit environment)	18 microns rms	6.1 microns rms (calculated-no correction)
Absorptance	0.40	0.43
Absorptance/emittance	$1 < \alpha/\varepsilon < 2$	1.3

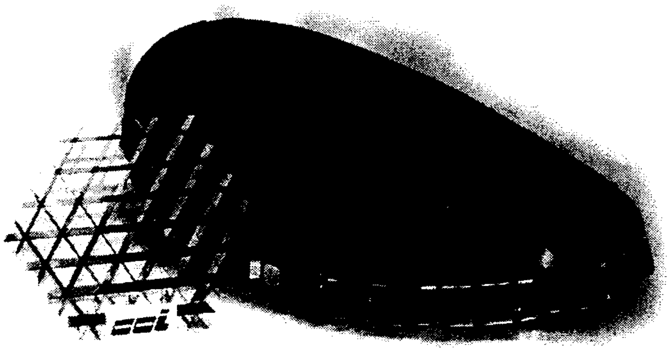

Figure 4. MLS Primary Reflector

3.2 FIRST Primary Reflector

The Far Infrared and Submillimeter Telescope (FIRST), is an ESA cornerstone mission for spectroscopy in the 80 to 670 μm range. The telescope requirements (shown in Table 1) are driven by the need to be diffraction limited at 80 μm. Considering the mass breakdown of the telescope components, the primary mirror engrossed the bulk of the telescope's mass. As a result, a low-mass, low-CTE, COI-design using carbon fiber reinforced polymer (CFRP) composite was selected for the primary reflector.

Table 2. Key Telescope Requirements

Bandwidth	80 - 670 μm
Telescope wavefront error (WFE)	≤ 10 μm rms., ≤ 6 μm rms. goal
Diameter	3.5 m
Focal Length of primary	1.75 m
System focal length	28.50 m
System f number	8.68
Field of view	± 0.25°
Surface roughness	≤ 0.6 μm rms.
Operating temperature	70 to 90 K
Relative spectral transmission	≥ 97% at delivery of telescope
Mass	260 kg

Under contract from JPL, COI designed and fabricated a 2-m in diameter, all-composite, demonstration mirror shown in Figure 5. After fabrication and testing, the actual areal weight of the mirror was 10 Kg/m^2, and the figure accuracy was 2.3 microns RMS at room temperature. Based on these results, it was clear that meeting the requirements for the full size mirror (3.5 meter in diameter) are within reach.

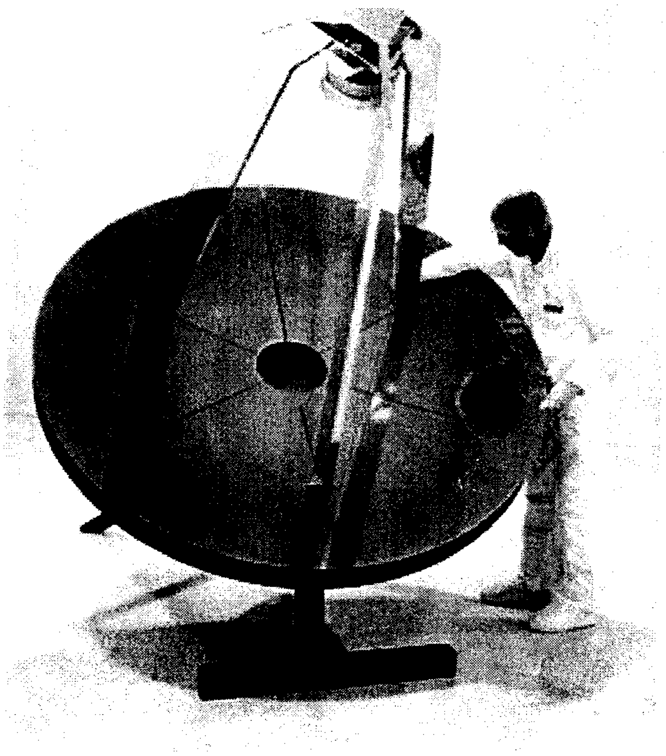

Figure 5. FIRST 2-Meter Primary Reflector

4. CONCLUSIONS

State of the art CFRP composites can be successfully used for fabrication of precision structures that require micron levels of dimensional stability. This success is attributed in the major part to the utilization of cyanate esters instead of epoxies in recent years resulting in total elimination of the microcracking phenomenon and substantial reduction in the moisture effect. The impressive combination of less than 10 kg/m^2 areal weight and less than 10 micron rms surface accuracy of the two mirror examples provided in this paper demonstrate the legitimacy of the composite approach.

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