

Ultralight Linerless Composite Tanks for In-Space Applications

Kaushik Mallick^{*}, John Cronin and Michael L. Tupper[†]
Composite Technology Development, Inc., Lafayette, Colorado, 80026

Lorie Grimes-Ledesma[‡] and Joseph C. Lewis[§]
*California Institute of Technology, Jet Propulsion Laboratory
4800 Oak Grove Drive, Pasadena CA 91109-8099*

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Chris Paul^{**} and Jeffrey S. Welsh^{††}
*Air Force Research Laboratory (AFRL/VSSV)
3550 Aberdeen Ave SE, Kirtland AFB, NM 87117-5776*

NASA missions are becoming increasingly more demanding of propulsion capability, driving the mass of propulsion systems higher, even as the science mass of electronics is reduced. Typically, the propulsion tank is the single largest highest dry mass item of an in-space propulsion system. Ultralight linerless composite tanks (ULLCTs) promise to achieve the efficiencies that will make future propulsion systems viable and minimize propulsion system mass growth. ULLCTS may offer up to a 25 percent weight reduction compared to conventional metal lined composite overwrapped tanks, allowing increased reactant storage and/or reduced launch mass. For successful design of such a tank, the composite shell itself is required to provide an integral impermeable barrier, in addition to carrying the pressure and environmental loads for in-space propulsion. Significant materials technologies are required to achieve the microcrack resistance of the composites in order to contain small molecule gases such as helium (He). The goal is to develop a material that can limit the leakage rate of gaseous He to 10^{-4} scc/sec at 1% biaxial strain level. The current paper details an integrated systematic approach to developing novel composite materials that can meet such performance requirements. It also explains how micromechanical models and material testing can be combined to define material performance indicators critical for designing an ULLCT, such as the material's resistance to microcracking and permeability.

^{*} Senior Project Manager, Kaushik@CTD-materials.com, email: kaushik@ctd-materials.com, AIAA member

[†] Vice President

[‡] Engineering Staff

[§] Principal Engineering Staff

^{**} Lt., Space Vehicles Directorate

^{††} Director, Space Vehicles Directorate

Nomenclature

p	= internal pressure
V	= volume of pressure vessel
w	= weight of pressure vessel
η	= pressure vessel efficiency
σ_{θ}	= hoop stress in a pressure vessel
σ_a	= axial stress in a pressure vessel
$\pm \theta$	= helical ply angle

I. Introduction

NASA solar system exploration missions are undergoing a transition from fly-by observers to missions that orbit, land on, and return samples from planetary bodies. These missions are more demanding of propulsion capability, driving the mass of propulsion systems ever higher, even as the mass of electronics is reduced. Significant materials technologies are required to achieve the efficiencies that will make future propulsion systems viable and minimize propulsion system mass growth. Although ultimately in-space propulsion systems will likely utilize non-chemical propulsion technologies like nuclear propulsion, near to mid-term explorations will likely continue to utilize advanced chemical propulsion systems.

Typically, the propulsion tank is the single highest dry mass item of an in-space chemical propulsion system. Monolithic titanium construction is the current state-of-the-art for chemical propellant tanks, while composite overwrapped pressure vessels (COPV's) with a metallic liner are the current state-of-the-art for solar electric propulsion (SEP) tanks. In both cases, the metallic liner is used to provide a permeation barrier, preventing gas leakage through the composite. By eliminating the liner, a major portion of the tank mass, cost and fabrication time be saved. However, fiber-reinforced composites using state-of-the-art matrix resins are too permeable when subjected to the high strains characteristic of highly efficient in-space tanks. However, fiber-reinforced composites using state-of-the-art matrix resins are too permeable when subjected to the high strains characteristic of highly efficient in-space tanks. A significant material development effort will be required to fabricate ultralight linerless composite tanks (ULLCT's) for enabling nuclear propulsion systems for in-space applications. With a switch to ULLCTs, significant mass, cost, and fabrication time savings can be realized. Table 1 compares state-of-the-art tank technology to ULLCTs.

Table 1: Comparison of state-of-the-art tank technology to ULLCTs.

Tank Application	Current State-of-the-Art	ULLCT	Mass Savings	Cost Savings	Schedule Savings
High pressure Gas Containment (electric propellant tanks (Xe, Ar, etc.), He storage for chemical propellant tank purge)	Metal-lined Composite Overwrapped Pressure Vessel: 0.030-inch thick aluminum liner, carbon fiber/ epoxy resin overwrap	Carbon fiber/ resin ULLCT	50%	80%	80%
Chemical Propellant Storage (contains liquid propellant and gas, typically helium)	Monolithic titanium construction	Carbon fiber/ resin ULLCT	60%	0%	25%

II. Motivation

Composite materials, using continuous graphite reinforcement and a polymeric resin matrix, allow for better optimization of material strength, and consequently lower mass tank designs, like the one used in NASA's Helios aircraft (Figure 0). The characteristics that make composite materials so effective in tank applications are their high strength and stiffness along the fiber direction, and their significantly lower density than metals.

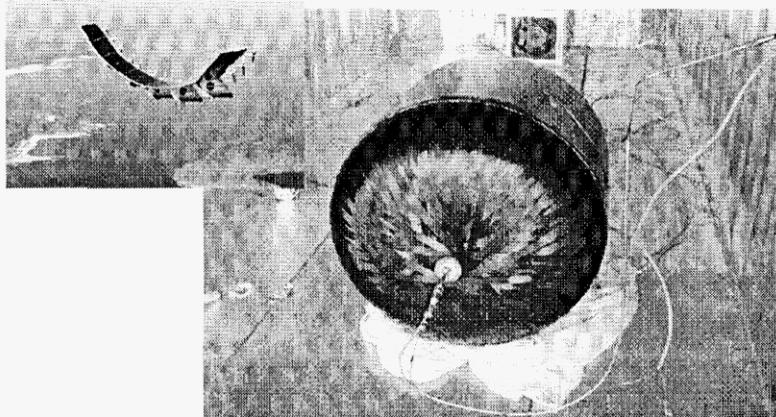


Figure 0: Lightweight Composite Pressure Vessel to be used in NASA's Helios Aircraft.

However, the adoption of composite materials in pressure vessels for space-critical applications has been slowed by concerns over long-term structural integrity, material compatibility and permeability. In an effort to address

these concerns, most current COPVs incorporate a thin metallic or polymeric inner liner, which serves as an inert permeation barrier. The liner prevents the contained gases from leaking through the composite laminate that tends to form microcracks and leak paths at high strain levels. Metal-lined COPVs have space flight heritage dating back to the Apollo program. Currently, COPVs used to store xenon gas for solar electric propulsion (SEP) spacecraft are typically constructed with thick metal (titanium, aluminum or stainless steel) liners overwrapped with a fiber-reinforced composite. The liner on these tanks is typically 0.030 and 0.100 inches thick, and the overwrap is 0.2 to 0.6 inch thick, depending on size and pressure. Fabrication of the liner requires many processing steps, including *complicated forming and detailed welding operations*, typically resulting in several months of work. Consequently, the metal liners are difficult to fabricate and can constitute up to 50 percent of the tank's total mass¹ and a significant percentage of the total cost and time to fabricate the tank.

Since the late 1980's, there has been substantial interest in developing and testing composite linerless tanks for *launch vehicle and spacecraft applications*. *Linerless composite tanks have been identified by both NASA and DoD as an enabling technology for future reusable launch vehicles (RLV's)*, where they may offer up to a 25 percent weight reduction compared to conventional tanks, allowing increased reactant storage and/or reduced launch mass. Similar, if not more convincing, justifications support their use in in-space propulsion systems, where reduction of overall system mass is of paramount importance. Structural weight reductions will translate directly to additional payload margins, and thus improved mission capabilities and reduced cost.

The potential advantages of a linerless composite pressure vessel are easily appreciated by comparing different classes of composite pressure vessels in terms of a common engineering yardstick. One such measure is pressure vessel efficiency, η , generally defined as²:

$$\eta = pV/W$$

where, p is the design burst pressure, V is the tank volume, and W is the tank mass. To improve efficiency, it is imperative that the composite structure be optimized to provide the highest possible burst strength, while reducing the tank weight and maximizing the storage volume. Figure 0 shows the efficiency advantage of linerless designs, compared to the types of composite pressure vessels most commonly used in the aerospace industry³. It illustrates how a linerless all-composite tank like an ULLCT can reduce total tank mass, and hence increases efficiency and therefore provides the most efficient storage vessels for in-space propulsion systems.

To achieve the engineering design goals of an ULLCT, concerns over long-term structural integrity, leakage due to microcracking, and contamination of composite materials need to be alleviated. Development of suitable materials, along with appropriate design and manufacturing methods, is required. The material needs and requirements can be considered as follows. Figure 0 illustrates the laminate architecture in a typical filament wound composite tank. The shell consists of several alternating layers of hoop and helical ($\pm\theta$) plies. We assume also that the composite laminate consists of polymeric matrix and a high performance graphite fiber (such as Toray T1000) since it provides the best consistency in static rupture, stress rupture and fatigue performance. According to published data from Toray, the maximum strain-to-failure of T1000 carbon fiber is 2.2 percent, measured by strand testing (tensile testing of the carbon fiber alone). However, the actual strain-to-failure of composite laminates using this fiber is lower, due to factors which include but are not limited to:

- Imperfect compatibility with the resin matrix.
- Imperfect interfacial strength.
- Inconsistencies in fiber volume fraction.
- Residual stresses from manufacturing.
- Manufacturing defects.
- Statistical variation of test results.

Previous experience in designing 5,000-psi and 10,000-psi composite pressure vessels suggests an A-basis strain-to-failure value of 1.5 percent for T1000 carbon fiber/epoxy matrix composites with a nominal fiber volume fraction of 60%. This means that there is a 95% statistical confidence that 99% of the T1000/epoxy composites will fail at a strain at or above 1.5 percent when strained along the direction of the fibers.

Linerless composite pressure vessels for in-space propulsion must be highly optimized structures. Based on a factor of safety of 1.5³ and an A-basis composite strain-to-failure of 1.5 percent, the principal strain in the composite shell (along the hoop direction in Figure 0) at the mean operating pressure (MEOP) is calculated to be 1 percent (Figure 0).^{**} A 1 percent strain level is not detrimental to the structural integrity of the tank laminate, but is likely to cause microcracking in the helical plies.

^{**} This does not include any effect of temperature, and the allowable strain value will be lower if the tank is to be operated in the cryogenic conditions of deep space.

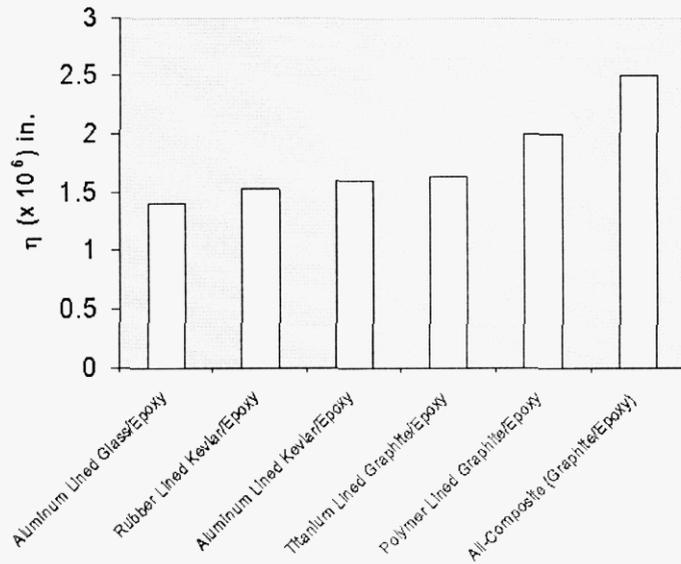


Figure 0: A comparison of composite pressure vessel efficiencies.

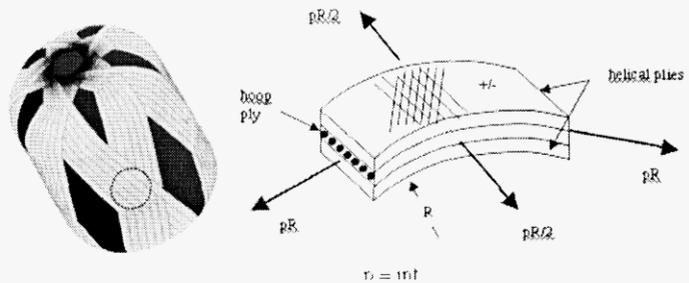


Figure 0: Stress resultants in a filament wound composite tank shell.

The authors at the Jet Propulsion Laboratory (JPL) have performed internal research to determine if common, commercially available resin systems could be used to create linerless tanks. Four resins were evaluated: a standard COPV epoxy system, a cyanate ester, and two different toughened epoxy resins commonly used for resin transfer molding. Test tanks designed to operate at 5,000 psi were fabricated and tested for short-term permeability. Of the 15 tanks tested, one tank made from the toughened epoxy resins met permeability requirements (1×10^{-4} scc/sec) at 2,300 psi. None of the tanks met permeability requirements at 5,000 psi. These results showed that commercially available resin systems may be adequate in the short term and at lower composite strains, but not at the high strains required for ULLCTs. A significant material development effort will be required to fabricate ULLCTs for enabling nuclear propulsion systems for in-space applications. The following sections outline the ongoing material development effort at CTD as part of a Phase II SBIR program for linerless composite tanks being developed for DoD/MDA's space program. Although this program aims at developing materials that provide structural integrity and adequate microcrack resistance against harsh chemicals, the philosophy of the material development effort applies also for ULLCT's for in-space propulsion needs.

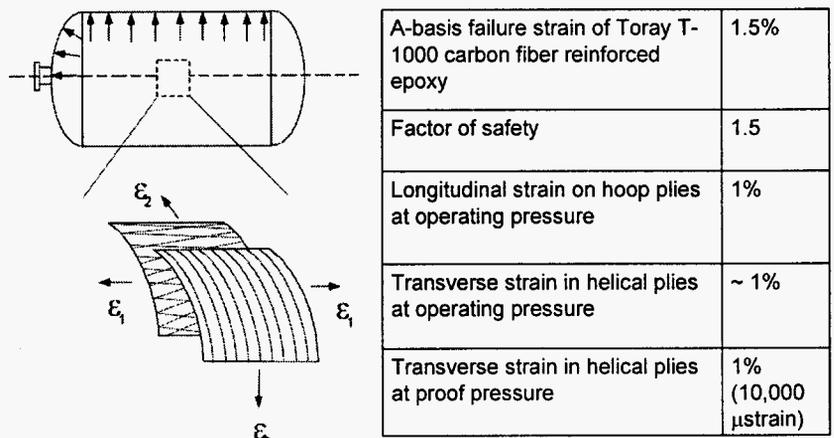


Figure 0: Allowable strain level in composite plies for ULLCTs

These results showed that commercially available resin systems may be adequate in the short term and at lower composite strains, but not at the high strains required for ULLCTs. A significant material development effort will be required to fabricate ULLCTs for enabling nuclear propulsion systems for in-space applications. The following sections outline the ongoing material development effort at CTD as part of a Phase II SBIR program for linerless composite tanks being developed for DoD/MDA's space program. Although this program aims at developing materials that provide structural integrity and adequate microcrack resistance against harsh chemicals, the philosophy of the material development effort applies also for ULLCT's for in-space propulsion needs.

III. Evaluation of Microcrack Resistant Composites

Composite Technology Development, Inc. (CTD) has developed and implemented an Integrated Systematic Approach (ISA) for developing novel microcrack resistant materials to meet the performance targets of linerless composite tanks like an ULLCT. Utilization of an ISA requires the concurrent development of tank specifications, engineering and micromechanics models, novel resins and purpose-designed composite materials and innovative processing techniques. ISA is implemented by testing and characterizing the materials in the laboratory, with the help of mechanics-based analytical tools, and incorporating the same tools in describing the material's behavior in the design, analysis and optimization of the pressure vessels. The effort

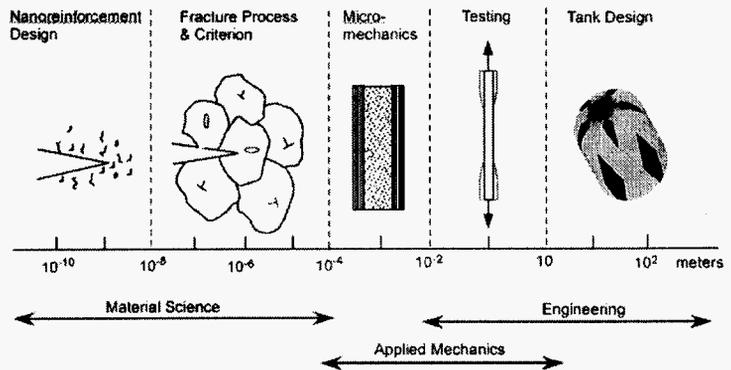


Figure 0: Breadth of expertise required for developing linerless composite tanks.

The effort spans the range from nano-scale material science efforts to macro-scale tank design activities, as shown in Figure 0. It essentially relies on an iterative effort to improve both material properties and structural design, with micromechanics bridging the information gap between material science and structural design. This is inherently superior to conventional design efforts, which use off-the-shelf materials, or unfocused material development efforts that do not consider the end-use application. Understanding of the material behavior on the micro-scale helps to identify the material characteristics crucial for the ULLCT performance as detailed below.

A. Transverse Tensile Strength

For successful design of an ULLCT, the composite shell itself is required to provide an integral impermeable barrier, in addition to carrying the pressure and environmental loads. The permeability of the composite shell depends on the degree of microcracking in the composite laminate and the opening of the microcracks under load. Matrix microcracking is usually the first mode of failure in composite

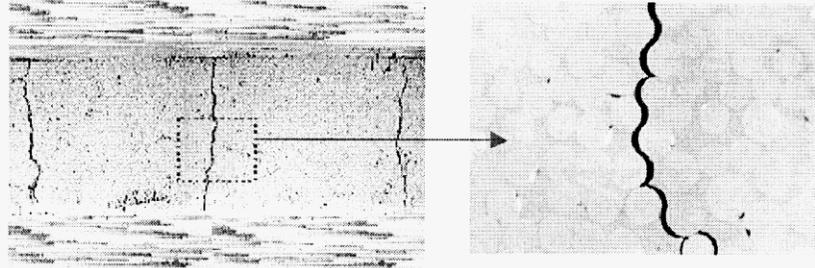
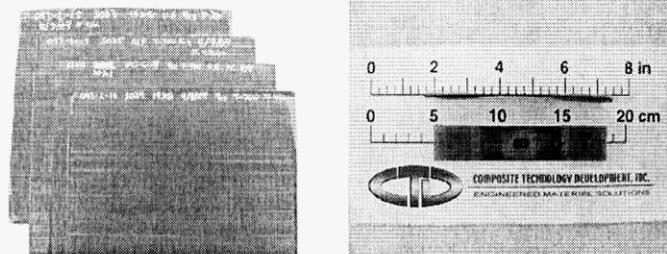


Figure 0: Microcracking in composites due to transverse stress

tanks and appears as cracks perpendicular to the fiber direction (Figure 0). The microcracks generally penetrate through the thickness of individual lamina and parallel to the direction of the fibers.⁴ Since matrix microcracking is primarily caused by tensile stress perpendicular to the fiber directions, the transverse tensile strength of a unidirectional composite can provide a good indicator of the material's resistance to microcracking. The microcracks may not precipitate catastrophic failure of the pressure vessel, but can cause leakage of the contained gaseous fluids by viscous flow. Microcrack damage in a lamina also leads to a decrease in the elastic stiffness of the lamina, redistribution of load among adjacent laminae, as well as reduction in stiffness of the whole laminate⁶⁻⁸.

Transverse tensile strength test is the first step in screening the microcrack resistant matrix materials at CTD. Such tests have been used to compare several toughened epoxy resins being developed as part of an ongoing SBIR Phase II program funded by MDA. The new matrix materials are used to fabricate composite laminates using a wet lay-up procedure using a high temperature hydraulic press for compaction and cure of the laminate. All laminates used the same type of carbon fiber, Toray T-700S and the same volume fraction of fiber ($v_f=60\%$), but with different resin systems. Specimens were machined from the composite laminates, tabbed and strain gauged and then subjected to transverse tensile tests according to ASTM D3039. A



(a)

(b)

Figure 0: a) Typical cured laminates after cure. b) Transverse tensile test specimen - machined, tabbed, strain gauged and ready to be tested.

A family of typical cured laminates and a typical test specimen are shown in Figure 0 below. Tests were performed on a MTS Systems Servo-Hydraulic test machine using a ± 20 kip load cell with a ± 1 kip load range card. All specimens were loaded at a constant rate while load, displacement, and strain data were taken. Specimens were loaded until failure occurred. A total of 31 different formulations have been tested to date. Two of those, were Cytec's 977-2 and 977-3 toughened epoxy resin used as control materials or baseline materials. The remaining 15 systems were developed at CTD. Each system was tested using a total of at least 7 specimens. The highest and the lowest data points of each test set were discarded and the remaining 5 tests were used for averaging the test results. A summary of the test results can be found in Figure 0 below. The target for the screening test was to select matrix materials with the best value of transverse strain to failure, preferably in excess of 1.0% and those that can match the elastic modulus of the Cytec's 977-2 and 977-3 systems.

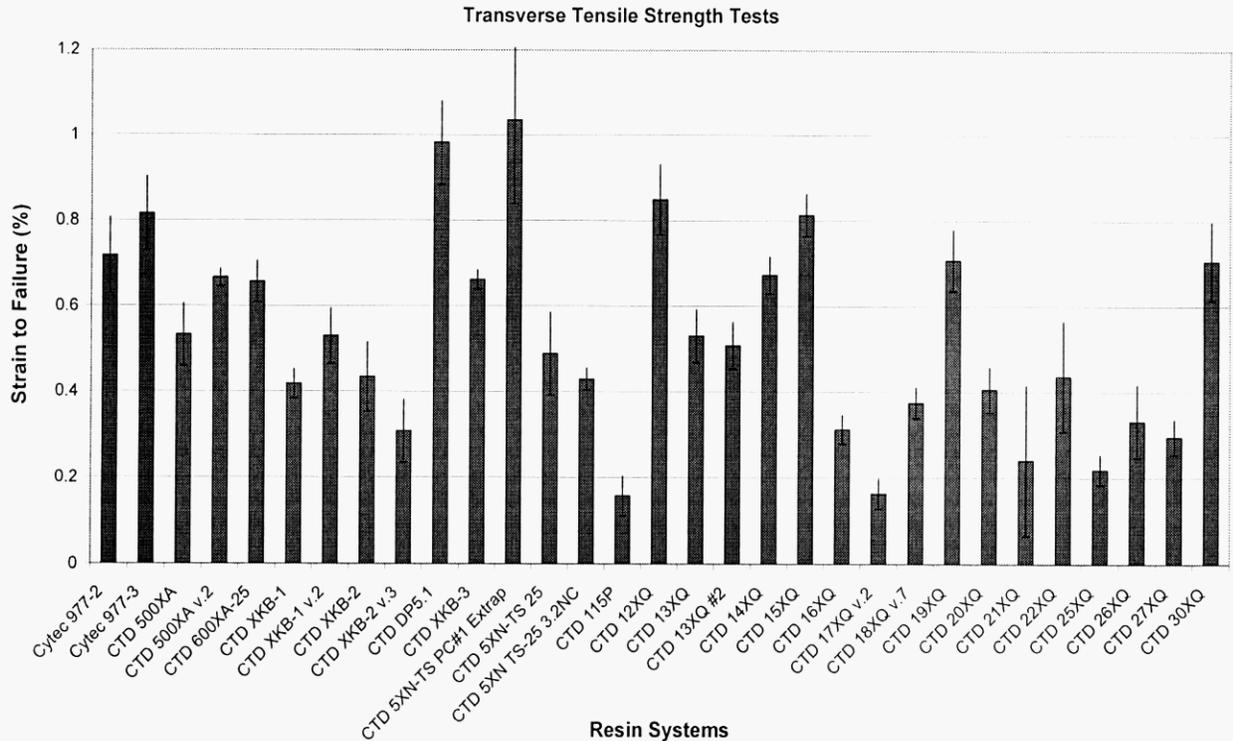


Figure 0: The percent strain to failure of transverse tensile tests. The error bar indicates the standard deviation of each test set.

B. Microcrack Fracture Toughness

Classical Laminate Theory (CLT) is the most common tool for designers for predicting the onset of microcracks^{9,10}. Such an analysis tool needs transverse tensile strength as an input parameter. However, the transverse tensile strength is not an invariant property of the material, but rather it depends on the laminate architecture and lamina thickness, a dependency which is not predicted by traditional strength criteria applied to stress predictions from Classical Laminate Theory (CLT)¹¹. The concept of ‘microcracking fracture toughness’ (MFT) has been shown to be an effective failure criterion to assess damage accumulation in composite laminates.^{12,13} The basic assumption of the microcracking fracture toughness theory is that microcracking damage occurs by fracture events in which full microcracks, spanning the ply thickness, appear instantaneously. The instant of formation of the microcrack is predicted when the total energy released by the formation of that microcrack reaches the critical energy release rate for microcracking, G_{mc} , or the microcracking fracture toughness. With proper use of this model of microcracking, one can predict results for a wide variety of laminates from a single value of G_{mc} . More importantly, the measurement of G_{mc} for composite materials provides a sound micromechanics-based index for polymer chemists to develop resins more resistant to microcrack formation as well as a database for composite tank designers. In addition to providing a quantitative comparison of the materials’ resistance to microcracking, the MFT test, as described below, sheds light on the threshold strain that initiates microcracking in the material.

Evaluating a material’s MFT involves tensile tests of cross-ply laminates $[0/90_n]_s$ construction where n is the number of plies in the 90° plies sandwiched between the 0° plies (see Figure 0). Laminates for MFT tests were manufactured by CTD using a wet lay-up procedure using a high temperature hydraulic press for compaction and cure with a fiber volume fraction of 0.6. The dimensions of the test samples are 0.5 inches wide by 8 inches long with a nominal thickness of 0.066 inches. Each edge of the specimen was sanded and polished by 3 microns diamond slurry.

During the MFT test, the specimen is subjected to tensile strain in increments. The edge of the specimen is inspected with the help of a 10x hand-held digital microscope connected to a personal computer at each strain increment. The number of microcracks in the central ply is counted on the computer monitor while the microscope traverses the length of the specimen edge. The microcrack count is performed for each edge of the specimen and the average microcrack density (number of microcracks divided by the specimen edge length) is reported for each strain level. The procedure is repeated until the tensile failure of the specimen is complete. Determining the microcrack density in the specimens in situ the test frame avoids dismantling the specimens from the testing machine and remounting them under an optical microscope for counting of microcracks. More importantly, microcracks are easily identified and more accurately counted when the specimen is strained, since previous researchers have reported closure of microcracks in the absence of load.

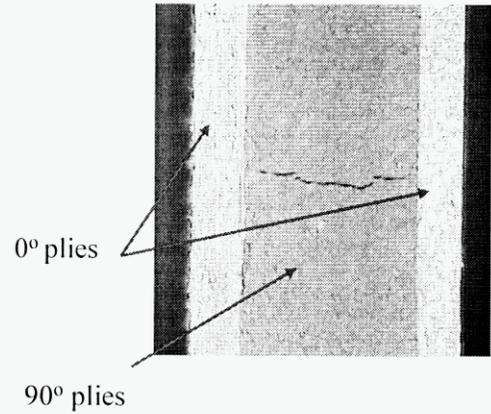


Figure 0: The polished edge of a MFT test specimen of $[0/90]_s$ layup.

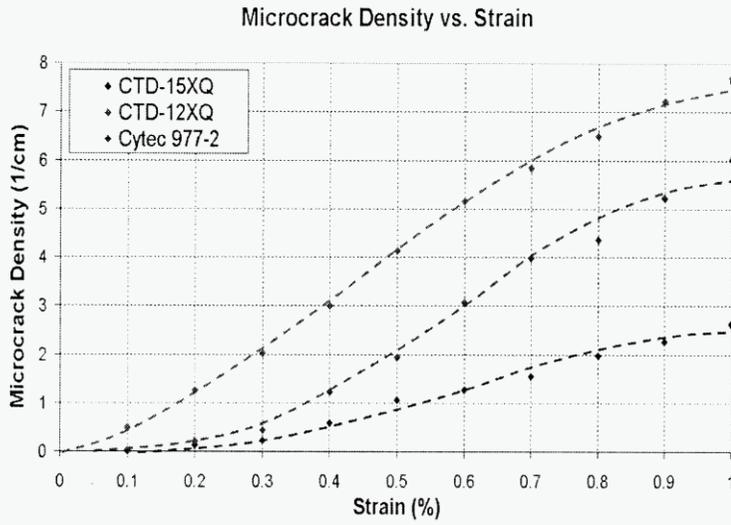


Figure 0: Growth of microcracks vs. strain in a cross-ply laminate

Figure 0 shows the microcrack density as a function of the applied strain for three different composite materials. The plot illustrates the fact that the composite materials fabricated with three different matrix materials (977-2, CTD-12XQ and CTD-15XQ) have different propensity to microcrack despite the fact that all three had similar strain to failure, 0.72%, 0.85% and 0.81% respectively, in the transverse tensile strength tests. The higher the microcrack fracture toughness of a material, the lower the microcrack density at a given strain level, which in turn will allow less permeation of gases contained in the ULLCT. Therefore, the experimental determination of the microcracking fracture toughness parameter (G_{mc}) is the most effective methodology to rank the materials for ULLCT application. It can be determined from the plot of microcrack density vs. applied stress (or strain) in conjunction with analytical

derivations based on micromechanics as explained in the Appendix.

IV. Microcracking and Permeation

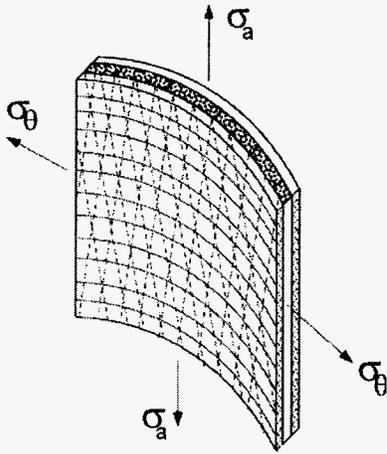
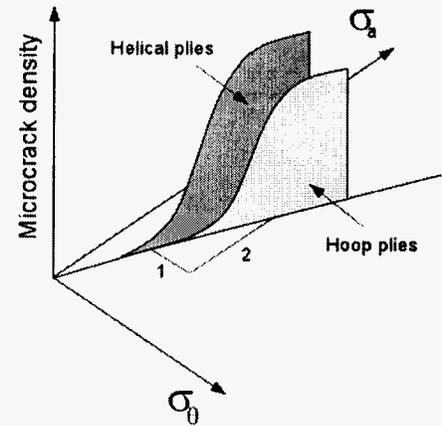


Figure 0: Cylindrical section of a filament wound pressure vessel subjected to a biaxial load

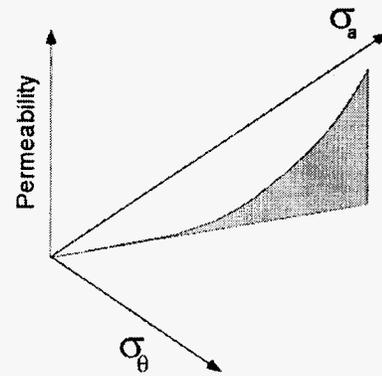
The above section has identified the material performance indicator against microcracking under uniaxial load. However, in a composite pressure vessel, the composite shell is subjected to a biaxial load. The successful design optimization of an ULLCT will require an understanding of the degree of microcracking in the individual plies and how that affects the permeation or flow of gaseous fluid through the laminate¹⁴. A typical filament wound tank shell consists of several layers of mixed ply laminates $[90/(\pm\theta)]_s$ in series, where the angle θ is determined by the polar opening of the tank and the relative thickness of the hoop (90°) plies; all angles being measured with respect to the cylinder axis. The thickness of the helical ($\pm\theta$) plies are determined by optimization of the tank shell for a given design pressure. For simplicity one can assume that the building block of the cylindrical shell consists of a hoop (90°), a helical ($\pm\theta$) and a hoop (90°) ply as schematically shown in Figure 0. Such a building block can be repeated to meet the design strength and pressure carrying

capability of the cylinder section of the tank shell.

As the tank is pressurized, equilibrium dictates that the ratio $\psi = \sigma_\theta / \sigma_a = 2$ remains constant in the cylinder section, where σ_θ is the hoop stress and σ_a is the axial stress. Since the helical plies are subjected to a higher transverse stress magnitude of $\sigma_\theta = 2\sigma_a$, they will experience microcracking before the hoop plies. The expected evolution of microcrack density in the composite laminate is illustrated schematically in Figure 0(a). Because of the biaxial stress state, analytical estimation of the growth of microcracks needs to be performed on the stress space of $\sigma_\theta - \sigma_a$. As long as the hoop plies maintain their integrity, they can prevent the viscous flow of the gaseous fluids through the laminate, thereby keeping the permeability of the laminate negligible in this regime. However, as the pressure is further increased, a critical value of axial stress, σ_a is reached that causes microcracking in the hoop plies as well, thereby providing an interconnected pathway for the gas to permeate through the entire laminate. The permeability of the laminate is directly related to the microcrack density and the microcrack opening displacement. Consequently, it increases nonlinearly as a function of the applied stress¹⁵ as shown in Figure 0(b). Engineering design of an ULLCT necessitates this fundamental understanding of the interdependence between the pressure, the degree of microcracking and the permeability of an ULLCT. Future effort at CTD will focus on developing an analytical correlation between the microcrack growth and permeability measured experimentally from composite laminates subjected to biaxial load.



(a)



(b)

Figure 0: Growth of microcracks and permeability in a composite laminate under biaxial load

V. Summary

Designing an ultra lightweight linerless composite tank for in-space applications demands a synergistic effort between material development, composite laminate design, and material failure analysis. Selection of a suitable microcrack-resistant matrix for such a tank can be a daunting task. The current paper provides some material performance targets to meet the design requirements of such tanks and explains the work in progress towards material development and selection. Transverse tensile strength provides the first level of information of material performance against microcrack resistance. Due to its simplicity, transverse tensile strength test is suitable for screening the candidate materials based on laminates fabricated identically with laminate characteristics typical of a filament wound tank construction. The paper presents the results of transverse tensile strength of several toughened epoxy materials developed at CTD and compares them to baseline materials typically used in the aerospace industry.

A more rigorous approach to the material selection process is the use of microcracking fracture toughness tests that provide information on microcrack accumulation under tensile load. The paper details the microcracking fracture toughness test procedure that has been developed at CTD and how these tests are being used to characterize the toughened matrix materials for their application in linerless composite tanks. Preliminary results have found that the rate of growth of microcracks in a cross-ply laminate subjected to a tensile load can be different for matrix systems even if they have similar transverse tensile strength. The experimentally determined microcracking fracture toughness is an intrinsic material parameter and can predict microcrack accumulation under a variety of loading conditions and laminate configuration without the need for repeating the experiments for different cases. This provides a significant advantage over transverse tensile strength that is dependent on laminate thickness and architecture and hence necessitates repeated material tests for different laminate configuration.

Most traditional composite overwrapped pressure vessels with metallic or polymeric liners are designed to safeguard against structural failure by rupture, since the liner is trusted to take care of the containment of the fluids. In essence the structural design of the tank is decoupled from the fluid containment requirement of the design. In contrast, the linerless composite tanks depend on the composite shell itself to serve as a permeation barrier in addition to carrying all pressure and environmental loads. Understanding the microcracking, damage propagation and the resulting permeation of fluids at the tank's operating conditions should therefore be a primary criterion for the design optimization for these tank structures. The paper provides a roadmap for such an understanding toward successful design of a linerless composite tank with the help of mechanical models and material testing.

Appendix

The microcracking energy release rate, G_m , in a composite material due to nucleation of a microcrack (Figure 0) can be derived as follows:

$$G_m = \left(\sigma_0 \frac{E_T}{E_0} - \frac{\Delta\alpha\Delta T}{C_1} \right)^2 t_1 C_3 Y(D) \quad (1)$$

where,

σ_0 is the magnitude of the static load applied during test, E_L , E_T are the longitudinal and transverse modulus of the unidirectional plies and E_0 is the effective modulus of the effective cross-ply laminate, given by

$$E_0 = \frac{t_1 E_T + t_2 E_L}{t_1 + t_2}$$

$\Delta\alpha = \alpha_T - \alpha_L$, is the difference in the coefficient of thermal expansion in the transverse and the longitudinal direction of the unidirectional lamina,

$$\Delta T = T_s - T_0$$

is the difference between the test temperature, T_s and the stress-free temperature, T_0 of the lamina

$$D = \frac{1}{2\rho t_1}$$

is the crack density

$\rho = a/t_1$ is the normalized crack spacing

$Y(D)$ is a function that depends on crack density D given by:

$$Y(D) = 2\chi(\rho/2) - \chi(\rho) = 2\chi\left(\frac{1}{4t_1 D}\right) - \chi\left(\frac{1}{2t_1 D}\right) \quad (2)$$

The parameters χ and C_3 in Eqn. (1) are derived from material parameters as given below:

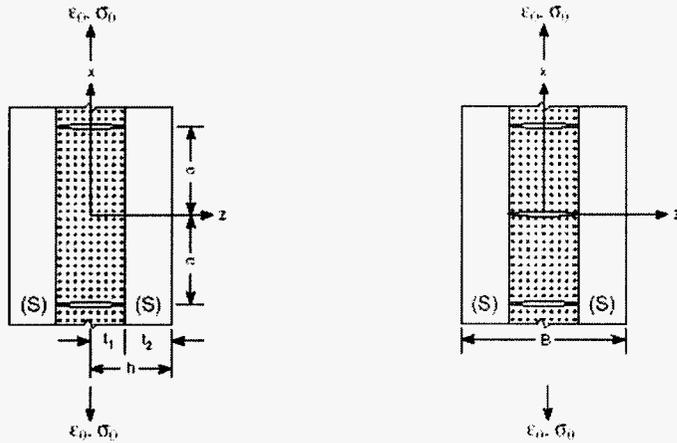


Figure 0: A unit cell of damage for microcracking in $[0/90^\circ n]_s$ laminates. (a) Two existing microcracks spaced by a distance $2a$. (b) The same laminate after formation of a new microcrack midway between the existing

$$\chi(\rho) = 2\alpha\beta(\alpha^2 + \beta^2) \frac{\cosh 2\alpha\rho - \cos 2\beta\rho}{\beta \sinh 2\alpha\rho + \alpha \sin 2\beta\rho}$$

$$C_3 = \frac{\lambda + 1}{60E_T} (3\lambda^2 + 12\lambda + 8)$$

$$C_1 = \frac{hE_o}{t_2 E_L E_T}$$

$$C_2 = \frac{\nu_T}{E_T} \left(\lambda + \frac{2}{3} \right) - \frac{\nu_L}{E_L} \frac{\lambda}{3}$$

$$C_4 = \frac{1}{3} \left(\frac{1}{G_T} + \frac{\lambda}{G_L} \right)$$

$$\theta = \tan^{-1} \sqrt{\frac{4q}{p^2} - 1}$$

$$p = \frac{C_2 - C_4}{C_3}, q = \frac{C_1}{C_3}$$

$$\alpha = q^{1/4} \cos \frac{\theta}{2}, \beta = q^{1/4} \sin \frac{\theta}{2}$$

$$\lambda = \frac{t_2}{t_1} \text{ is the ratio of the ply thicknesses}$$

Microcracks are formed when the energy release rate G_m given by eqn. (1) exceeds the critical microcracking energy release rate G_{mc} . Eqn. (1) can be reduced to:

$$\frac{E_T}{E_o} \frac{C_1}{\Delta\alpha} \sigma_0 = \frac{C_1}{\Delta\alpha} \frac{1}{\sqrt{C_3 t_1 Y(D)}} \sqrt{G_{mc}} + \Delta T \quad (3)$$

Defining,

$$\sigma_R = \frac{E_T}{E_o} \frac{C_1}{\Delta\alpha} \sigma_0 \quad (5)$$

$$D_R = \frac{C_1}{\Delta\alpha} \frac{1}{\sqrt{C_3 t_1 Y(D)}}$$

as the reduced stress variable and the reduced microcrack density variable, eqn. (3) can be re-written as:

$$\sigma_R = D_R \sqrt{G_{mc}} + \Delta T \quad (4)$$

Since G_{mc} is a material constant and the microcrack nucleation is described by eqn. (1), a plot of σ_R (unit of °C) vs. D_R (unit of °C m/J^{1/2}) should be linear per eqn. (4). The slope of the plot will provide the square root of the microcracking fracture toughness, G_{mc} (unit of J/m²) while the intercept will give the temperature differential, ΔT (unit of °C) causing the residual thermal stresses in the laminate.

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