AFRL-ML-WP-TP-2006-435

PREDICTION OF PRESSURE CYCLE INDUCED MICROCRACK DAMAGE IN LINERLESS COMPOSITE TANKS

Kevin Ryan, John Cronin, Steven Arzberger, Kaushik Mallick, Naseem Munshi, Frank Yazdani, Alan Kallmeyer, Brandon Arritt, and Jeffry S. Welsh

MARCH 2006

Approved for public release; distribution is unlimited.

STINFO COPY

This work was funded in whole or in part by Department of the Air Force contract F29601-03-M-0302. The U.S. Government has for itself and others acting on its behalf an unlimited, paid-up, nonexclusive, irrevocable worldwide license to use, modify, reproduce, release, perform, display, or disclose the work by or on behalf of the Government. All other rights are reserved by the copyright owner.

MATERIALS AND MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
March 2006	Conference Paper Postprint	

4. TITLE AND SUBTITLE
PREDICTION OF PRESSURE CYCLE INDUCED MICROCRACK DAMAGE IN LINERLESS COMPOSITE TANKS

5a. CONTRACT NUMBER
F29601-03-M-0302

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
N/A

6. AUTHOR(S)
Kevin Ryan, John Cronin, Steven Arzberger, Kaushik Mallick, and Naseem Munshi (Composite Technology Development, Inc.)
Frank Yazdani and Alan Kallmeyer (North Dakota State University)
Brandon Arritt and Jeffry S. Welsh (AFRL/VSSV)

5d. PROJECT NUMBER
N/A

5e. TASK NUMBER
N/A

5f. WORK UNIT NUMBER
N/A

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Composite Technology Development, Inc.
Lafayette, CO 80026

North Dakota State University
Depts. of Civil and Mechanical Engineering
Fargo, ND 58105

Air Force Research Laboratory (AFRL/VSSV)
Kirtland AFB, NM 87117-5776

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Materials and Manufacturing Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7750

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL-ML-WP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-ML-WP-TP-2006-435

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Conference paper postprint from the AIAA Structures, Structural Dynamics and Materials Conference, published by the American Institute of Aeronautics and Astronautics, Inc.

 This paper contains color. PAO Case Number: AFRL/WS 06-1065, 24 Apr 2006.

14. ABSTRACT
Linerless composite tanks made from continuous carbon fiber reinforced polymers will enable significant mass and cost savings over lined, composite overwrapped tanks. The key technical challenge in developing these linerless tanks will be to choose and/or design the material to resist microcracks that may lead to leakage. Microcracks are known to form in the matrix of a composite due to mechanical stresses transverse to the reinforcing fiber direction. This paper presents an approach for characterizing the accumulation of microcracks in linerless composite tank materials under cyclic mechanical loading associated with multiple fill-and-drain pressure cycles. The model assumes that the rate of microcrack-damage accumulation is related to the microcracking fracture toughness of the material through a modified Paris-law formulation. A key artifact of this model is that microcrack-damage accumulation under cyclic load can be predicted from only two material constants. This damage accumulation model is validated through a series of coupon tests, and an illustrative example is presented to demonstrate how the model can be used to predict the microcracking performance of a linerless composite tank subjected to fatigue cycles.

15. SUBJECT TERMS Linerless, microcracks, fracture, carbon fiber

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			Vernon Bechel
Unclassified	Unclassified	Unclassified	SAR	18	19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Confere
1 - 4 May 2006, Newport, Rhode Island

AIAA 2006-2201

POSTPRINT

Prediction of Pressure Cycle Induced Microcrack Damage in Linerless Composite Tanks

Kevin Ryan[*], John Cronin[*], Steven Arzberger[†], Kaushik Mallick[‡] and Naseem Munshi[§]
Composite Technology Development, Inc., Lafayette, Colorado, 80026

Frank Yazdani[**] and Alan Kallmeyer[††]
Depts. of Civil and Mechanical Engineering, North Dakota State University
Fargo, ND 58105

and

Brandon Arritt[‡‡] and Jeffry S. Welsh[§§]
Air Force Research Laboratory (AFRL/VSSV), Kirtland AFB, NM 87117-5776

Linerless composite tanks made from continuous carbon fiber reinforced polymers will enable significant mass and cost savings over lined, composite overwrapped tanks. The key technical challenge in developing these linerless tanks will be to choose and/or design the material to resist microcracks that may lead to leakage. Microcracks are known to form in the matrix of a composite due to mechanical stresses transverse to the reinforcing fiber direction. This paper presents an approach for characterizing the accumulation of microcracks in linerless composite tank materials under cyclic mechanical loading associated with multiple fill-and-drain pressure cycles. The model assumes that the rate of microcrack-damage accumulation is related to the microcracking fracture toughness of the material through a modified Paris-law formulation. A key artifact of this model is that microcrack-damage accumulation under cyclic load can be predicted from only two material constants. This damage accumulation model is validated through a series of coupon tests, and an illustrative example is presented to demonstrate how the model can be used to predict the microcracking performance of a linerless composite tank subjected to fatigue cycles.

Nomenclature

A	=	experimentally determined material constant
a	=	distance between microcracks
α	=	coefficient of thermal expansion
β	=	functions of the elastic properties of the material
C_3	=	constant based on properties of the material
$\chi(\rho)$	=	excess strain energy in a 'unit cell' of damage caused by microcracks

[*] Engineer, 2600 Campus Drive, Suite D, AIAA member.
[†] Senior Chemist, 2600 Campus Drive, Suite D.
[‡] Senior Project Manager, , 2600 Campus Drive, Suite D, phone: 303-664-0394, x114, email: kaushik@ctd-materials.com, AIAA member.
[§] President, 2600 Campus Drive, Suite D.
[**] Chief Engineer.
[††] Professor.
[‡‡] Senior Deputy PM, Integrated Structural Systems, 3550 Aberdeen Ave SE.
[§§] Manager, Integrated Structural Systems, 3550 Aberdeen Ave SE.

D = microcrack density
dA = change in total crack area
dD = change in microcrack density
dN = change in number of applied cycles
$\Delta\alpha$ = difference in fiber and transverse composite coefficient of thermal expansions
ΔG_m = microcracking energy release rate
$\Delta\sigma$ = uniaxial cyclic load reversal
ΔT = change from stress-free temperature to test temperature
E_o = effective modulus of the cross-ply laminate
E_T = transverse-ply modulus
E_1 = longitudinal composite modulus
E_2 = transverse composite modulus
G_m = microcracking energy release rate
G_{mc} = critical engery release rate for microcracking
G_{12} = composite shear modulus
N = number of applied cycles
n = experimentally determined material constant
ν_{12} = Poisson's ratio
ρ = normalized microcrack spacing
σ_{max} = maximum stress level
σ_{min} = minimum stress level
t_1 = thickness of the 90° unidirectional plies in a cross-ply laminate
t_2 = thickness of the 0° unidirectional plies in a cross-ply laminate

I. Introduction

Composite tanks and pressure vessels that are widely used in commercial and aerospace applications typically incorporate a metallic liner. The design of metal-lined, composite-over-wrapped pressure vessels (COPVs) is well understood and standardized.[1] These structures have demonstrated significant weight savings over the lightest available monolithic metallic designs, and have spaceflight heritage dating back to the Apollo program. However, the mismatch in the thermal expansion characteristics between the metallic liner and composite shell of a cryogenic COPV tank poses serious challenges. In addition, the metal liners are difficult to fabricate, can constitute up to half of the tank's total weight, and require a significant percentage of the tank fabrication time and cost. Consequently, the next significant advancement in the evolution of composite tanks will come through elimination of the liner, resulting in a less expensive, lighter-weight, linerless composite tank.

A. Potential Impact of Linerless Composite Tank Technology

Linerless composite tanks are being considered by the Department of Defense for applications that can benefit from the weight, cost, and schedule advantages that these structures offer. Because of their lower launch mass, fewer part count, and quick manufacturing turn-around time, reusable linerless composite tanks will be enabling for launch vehicles, especially in their upper stages, for the 'Operationally Responsive Space Launch Initiative' (Figure 1). Ultra-lightweight linerless composite tanks will also be essential for Unmanned Air Vehicles and High Altitude Airships where the tanks must survive multiple fill and drain cycles to complete their missions.

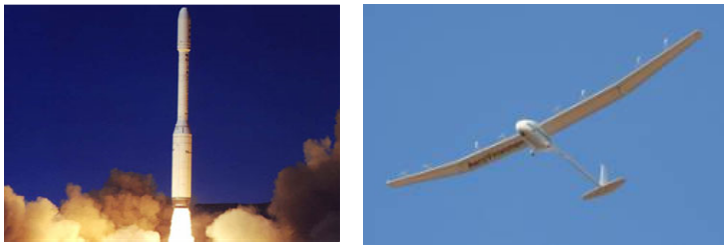

Figure 1. Linerless composite tanks will enable several future missions such as launch vehicles for Responsive Space (left) and Unmanned Air Vehicles (right).

Composite Technology Development (CTD) has developed Kiboko™ lightweight composite tanks, which due to the lack of a liner, provides for the lightest possible weight pressure vessels for a given set of requirements.[2] Designs have shown an approximately 50% weight savings over metal tanks and approximately a 15% weight savings over metal lined, composite overwrapped tanks, allowing increased fuel storage volume and/or reduced total system mass and volume. If properly designed, Kiboko pressure vessels can also reduce the

operational risks and maintenance costs over their lifetime due to their inherently simple construction. Kiboko tanks, which do not utilize a polymer or metallic liner, require the composite shell to serve both as a permeation barrier as well as the structure necessary to carry all pressure and environmental loads. Previous attempts at linerless composite tanks, by others, showed that these tanks prematurely leaked and structurally degraded. CTD has overcome these inadequacies by developing engineering methods that define specific material performance requirements to prevent this premature leakage and structural failure. Furthermore, CTD has developed and demonstrated materials that provide the performance dictated by these engineering models.[3]

B. Designing Linerless Composite Tanks to Minimize Permeation

Realizing practical linerless composite tanks involves numerous technical challenges. For these tank structures to be reusable over several fill-pressure-drain cycles, the composite materials must exhibit long-term structural integrity and minimal leakage due to accumulation of damage under mechanical fatigue load. Furthermore, unlike traditional lined tanks, linerless composite tanks depend on the composite shell to serve as a permeation barrier in addition to carrying all pressure and environmental loads. Therefore, understanding the microcracking damage propagation and the resulting permeation of fluids under the tank's operating conditions is a primary concern for optimizing the design of these tank structures. Success in developing these new tanks will hinge on success in developing new, toughened resin materials that are specially tailored for the applications, and new analysis tools and test protocols that can verify the new materials meet both the macro-scale and the micro-scale requirements.[3]

Numerous research efforts in the past have focused on models to predict the fatigue life of composite materials based on the failure stress vs. cycles (S-N) curves of the material.[4-8] Several studies have also focused on phenomenological models, based on continuum damage mechanics, to predict residual stiffness/strength of composites subjected to cyclic load.[9-12] Unfortunately, these models fail to take into account the matrix-dominated damage modes like microcracking or delamination. Progressive-damage models, which are based on a physically sound modeling of underlying damage mechanisms, have been proposed recently to address matrix cracks and delamination.[12,13] A vast body of research has also focused on characterizing composites to prove their feasibility in propellant tanks for reusable launch vehicles with thermal cycle profiles that include cryogenic temperatures. [13-17]

The progressive damage mechanics model that shows the most promise for predicting microcrack damage (and subsequent permeation), is based on the concept of microcracking fracture toughness originally proposed by Nairn. [18-22] 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 (i.e., there are no partial microcracks). The instant of formation of the microcrack is predicted when the total energy released by the formation of that microcrack, G_m 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}. CTD has already adopted this modeling technique to screen and rank composite materials suitable for fabricating linerless composite tanks according to their G_{mc}. Extension of this concept to cyclic thermo-mechanical loading supplements the material characterization done to date in CTD and provides a robust methodology for optimizing the tank performance against pressure cycles.

The goal of the current paper is two-fold: 1) explain, through analytical models, the mechanism of damage initiation and growth in a linerless composite a tank material subjected to cyclic mechanical loading; and 2) characterize, through experiments, the damage-resistant performance of a new, toughened resin material being developed by CTD for these applications.

II. Analytical Modeling

The analytical model used in this paper for describing microcrack evolution in composite laminates was originally proposed by Nairn et al,[4-8] and uses an empirical parameter called the microcracking fracture toughness to predict the growth of microcrack density in a cross-ply, composite laminate subjected to mechanical loads (see Figure 2). Since a cross-ply laminate is the building lock of essentially all laminate architectures for linerless composite tanks,[3] tank designers can use this analytical model to optimize the tank design to maximize the amount of cycles before microcracking and leakage occurs. The model predicts how microcracks in the transverse (i.e., 90º) ply of the unit cell evolve as a function of cyclic loads. Specifically, this model relates microcrack density to the global constitutive response (e.g., elastic modulus) and the material microcrack fracture toughness.

As derived by Nairn, the microcracking energy release rate, ΔG_m, due to the formation of new microcracks under a uniaxial cyclic load of $\Delta\sigma$ in a cross-ply laminate is: [3,19]

$$\Delta G_m = \left(\Delta\sigma^2 \frac{E_T^2}{E_O^2}\right) t_1 C_3 \left[2\chi\left(\frac{\rho}{2}\right) - \chi(\rho)\right] \tag{1}$$

where, C_3 is a function of the transverse-ply modulus E_T and the thicknesses of the unidirectional plies of the cross-ply laminate t_1 and t_2 shown in Figure 2. E_o is the effective modulus of the cross-ply laminate, ρ is the normalized crack spacing ($\rho = a/t_1$ as related in Figure 2), and $\chi(\rho)$ is the excess strain energy per unit cell caused by microcracks and is given by:

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

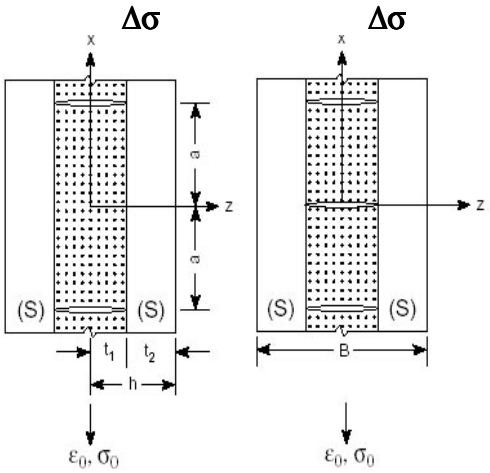

Figure 2. A unit cell of damage for microcracking in $[0/90]_s$ laminates.

where, α and β are functions of the elastic properties of the material. The microcrack density, D, is the number of cracks over a set length. This relation can be seen in Figure 2 as:

$$D = \frac{1}{2\alpha} = \frac{1}{2\rho t_1} \tag{3}$$

The microcrack energy release rate, ΔG_m, as derived from Eq. (1) through Eq. (3), is plotted as a function of the microcrack density, D, in Figure 3.

The increase in microcrack density per cycle, dD/dN, is determined from experiments, where D is the measure of damage variable or crack density and N is the number of cycles. The change in microcracking energy release rate, ΔG_m, during the mechanical cyclic load is computed from analytical models.[18] Combining these effects, a modified Paris law of the form[18,19]

$$\frac{dD}{dN} = A(\Delta G_m)^n \tag{4}$$

is hypothesized for the composite materials, and is to be verified from material testing.

The material constants A and n in Eq. (1) can be determined using the following experimental procedure. First, the microcrack density of the specimen, D, is determined at several applied-load cycles, N. Theses results are then plotted as shown in Figure 4, and the slope in linear region of the plot, which is dD/dN, is identified. Finally, results

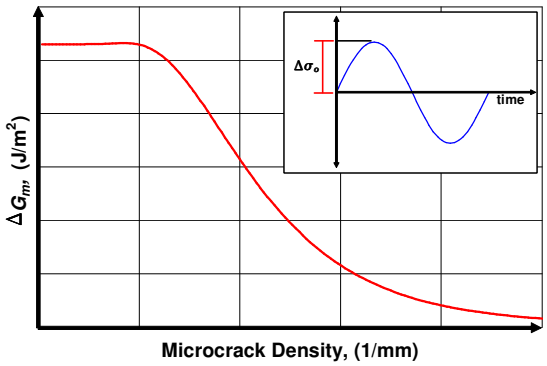

Figure 3. Energy release rate versus microcrack density due to cyclic loading.

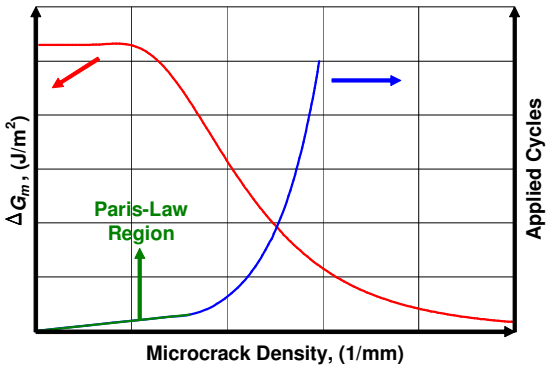

Figure 4. Paris-Law region for experimental fatigue data for a cross-ply $[0_x,90_y]_s$ laminate.

for dD/dN can be plotted versus ΔG_m (as determined using Eq. (1)) on a log-log plot, and the constant A (from Eq. (4)) can be calculated from the intercept, and n can be calculated from the slope of the log-log plot. The constant A describes a threshold value for microcrack initiation during cyclic loading and n represents the rate of growth of microcrack density. A lower value of A indicates a greater resistance to microcrack initiation. A lower value of n indicates a lower rate of microcrack nucleation and multiplication during fatigue cycling.

The elegance of this progressive-damage-accumulation model lies in the fact that it only requires experimental determination of two material-dependent parameters, A and n. These two experimentally determined parameters are unique to the material, and once determined, can be used for a variety of laminate geometries and architectures. This eliminates the need for repeated fatigue testing of different laminate architectures.

III. Materials and Experimental Procedures

A. Selection of Material System

The material system selected for testing was Toray T700S carbon fiber impregnated with CTD-7.1 resin system. CTD-7.1 is a highly toughened matrix system developed by CTD that has shown significant resistance to microcrack formation under static mechanical load.[3] In addition it has a low viscosity and long working time suitable for wet filament winding of linerless composite tanks. The goal of the current work is to investigate how this composite material system performs under cyclic mechanical loading.

B. Laminate Fabrication and Test Sample Preparation

Test specimens were cut from laminates that were fabricated from Toray T700S carbon fiber tow and CTD-7.1 resin using a wet-filament-winding process on a flat paddle (Figure 5). The flat paddle mandrel was designed to be rotated 90 degrees in between plies, thereby allowing a $[0,90_2]$ cross-ply laminate architecture to be fabricated. The cross-ply orientation was selected to simulate the laminate construction of a filament-wound composite tank which typically comprises interspersed hoop and low-angle-helical plies. The laminates were cured under consolidation pressure provided by a heated laminate press to achieve a nominal cured thickness of 1.55 mm and a fiber volume fraction of 60 percent.

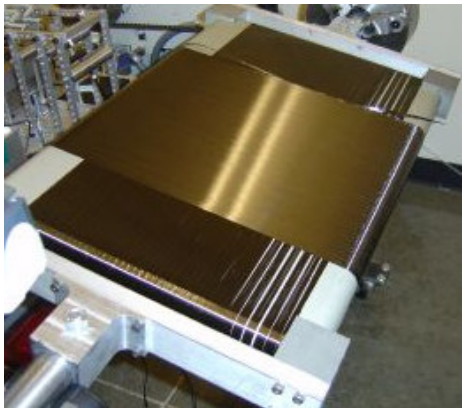

Figure 5. Laminate for making test specimens being filament-wound on a flat paddle.

Test specimens of $[0,90_2]_s$ configuration were then cut from these laminates with the 0^o plies on the outside being orientated in the loading direction and the inner 90^o plies oriented transverse to the loading direction. The test specimens were machined to a nominal length of 200 mm and width of 12.7 mm. Fiberglass tabs were bonded to the specimen to facilitate gripping the specimen while lessening grip affects. Both edges of each specimen were polished up to a 3 micron Al_2O_3 slurry to ensure visibility of the microcracks in the 90^o plies of the test coupons. A single strain gage oriented in the 0^o direction was affixed to the center of the specimen. The specimen was gripped using a set of serrated compression grips that were tightened directly onto the specimen using a series of bolts. Prior to testing, the polished edges of the samples were inspected to insure that the specimen was not damaged during preparation.

C. Experimental Procedure

The goal of the experiments was to determine a plot of microcrack density versus applied fatigue cycle for three different loading conditions. All tests were performed on a servo-hydraulic test machine at room temperature (25^o C). Specimens were fatigued to a maximum of 50,000 cycles under load-control conditions. The loading conditions were chosen to represent the pressure cycles of a composite tank in use. The three loading conditions, based on laminate strains of 0.5%, 0.67%, and 0.75%, were applied. All of these loading conditions resulted in a measurable number of microcracks within the maximum tested cycles.

Each specimen was loaded in tension using displacement control initially to determine the load corresponding to the desired strain level. Once this maximum load, and corresponding maximum stress, σ_{max}, was determined, the test machine was programmed to operate under load control and the sample was fatigued between the minimum, σ_{min}, and the maximum, σ_{max}, stress levels. The tests were conducted at 1 Hz using a ratio of minimum-to-maximum stress of $\sigma_{min}/\sigma_{max}$=0.1. The test was stopped at specified intervals to count the microcracks along the specimen's polished edges using a handheld digital microscope (Figure 6). The microcrack density was obtained by averaging the microcrack count from both sides divided by the specimen gage length. A plot of applied cycles versus microcrack density was obtained for each specimen by repeating this procedure at increasing numbers of completed cycles and by averaging the results of multiple specimens for each loading condition.

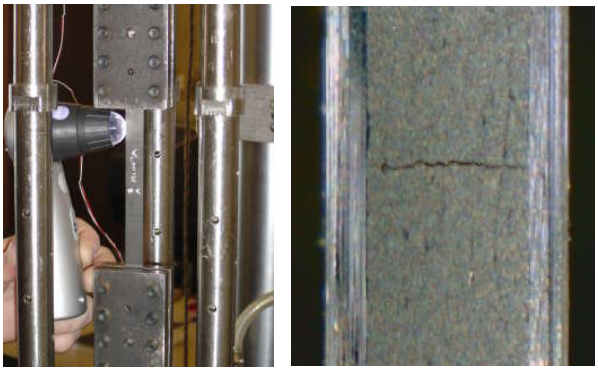

Figure 6. Microcrack as detected with the digital microscope.

IV. Experimental Results

The test results of microcrack density versus applied cycles for the CTD-7.1 material are shown in blue in Figure 7 through Figure 9. These three plots show how microcracks form under fatigue loading at the three loading conditions. In these plots, the microcrack density, D, is plotted along the abscissa and the number of fatigue cycles, N, is plotted on the right-hand ordinate. For microcrack densities up to D = 0.2-0.3, the D vs. N data are well represented by a linear fit, indicating a constant rate of microcrack growth, dD/dN (green lines in Figure 7 through Figure 9). This confirms the validity of Eq. (1) within this region.

The microcrack energy release rate, $\Delta G_{m,}$, can be calculated using Eqs. (1) through (4) and the material properties and specimen dimensions shown in Table 1. The ply thicknesses are defined by t_1 and t_2 as shown in Figure 2. The loading stress corresponding to the various strains of 0.5%, 0.67% and 0.75% were used in Eqs. (2) and (4) to attain microcrack energy release rate for each case. These results are also plotted in Figure 7 through Figure 9 (see red curves) and referenced to the left-hand ordinate in these plots.

Table 1. Material properties of T700/CTD-7.1 composite and specimen geometry used to calculate the microcrack energy release rate.

E_1	ν_{12}	E_2	G_{12}	$\Delta\alpha$	ΔT	t_1	t_2
(Pa)		**(Pa)**	**(Pa)**	**(1/K)**	**(K)**	**(mm)**	**(mm)**
1.27E+11	0.28	8.91E+9	3.45E+9	1.45E-5	-58	0.52	0.26

In order to determine the two material-dependent parameters, A and n, a log-log plot was made of microcrack energy release rate, ΔG_m, versus the crack growth rate, dD/dN, within the linear region of response. A power curve was fit to this data in Figure 10, and the best-fit values for the material constants A and n were found to be 1.18E-14 and 3.76, respectively. It is easy to see by the linear fit of the data on the log-log plot in Figure 10 that the power-law relationship matches well with the experimental data. This good-quality data fit validates that the analysis method described above accurately captures the microcracking response under cyclic loading. The key result of this analysis-test correlation is that the resistance of materials to microcrack formation can be compared by comparing just two material constants, A and n. A lower value of A indicates greater microcrack resistance, whereas a lower value of n indicates a lower rate of microcrack nucleation and multiplication during fatigue cycling. These parameters provide an easy basis for comparison of materials, and allows for new materials that will function better in tank applications to be more easily developed.

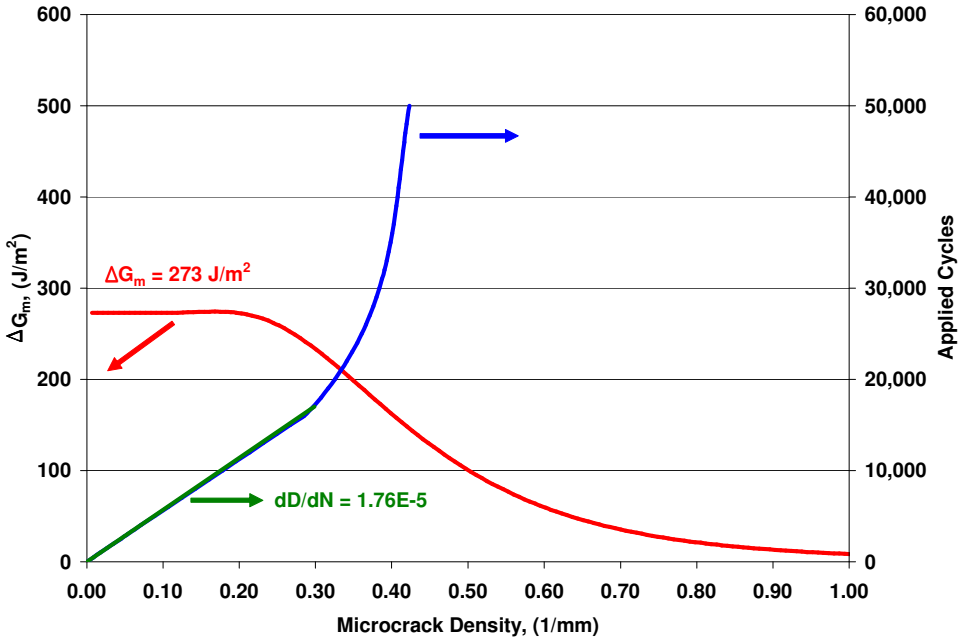

Figure 7. Microcrack energy release rate and applied cycles versus microcrack density for an applied stress corresponding to an initial strain of 0.50%.

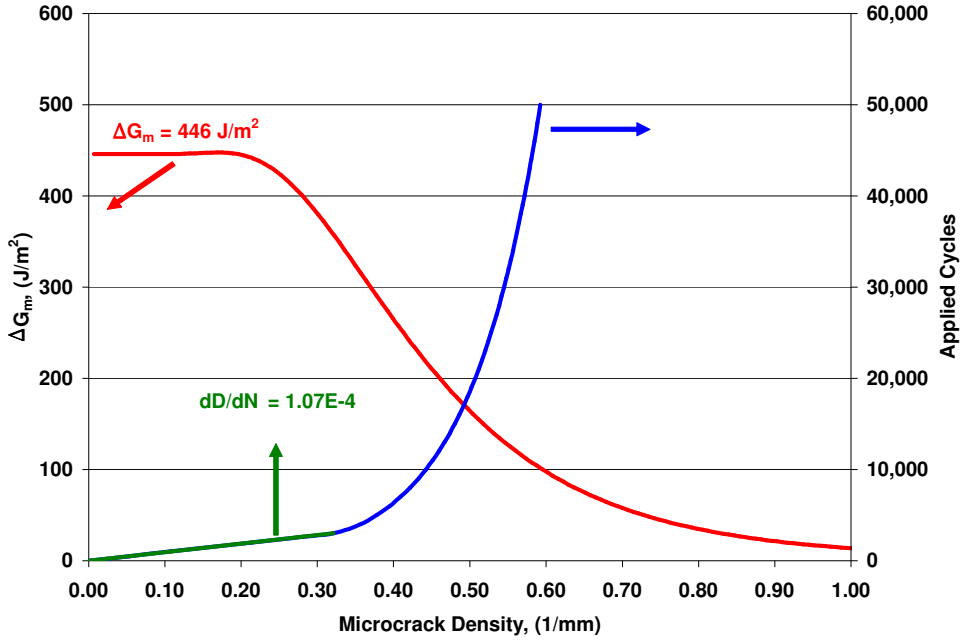

Figure 8. Microcrack energy release rate and applied cycles versus microcrack density for an applied stress corresponding to an initial strain of 0.67% .

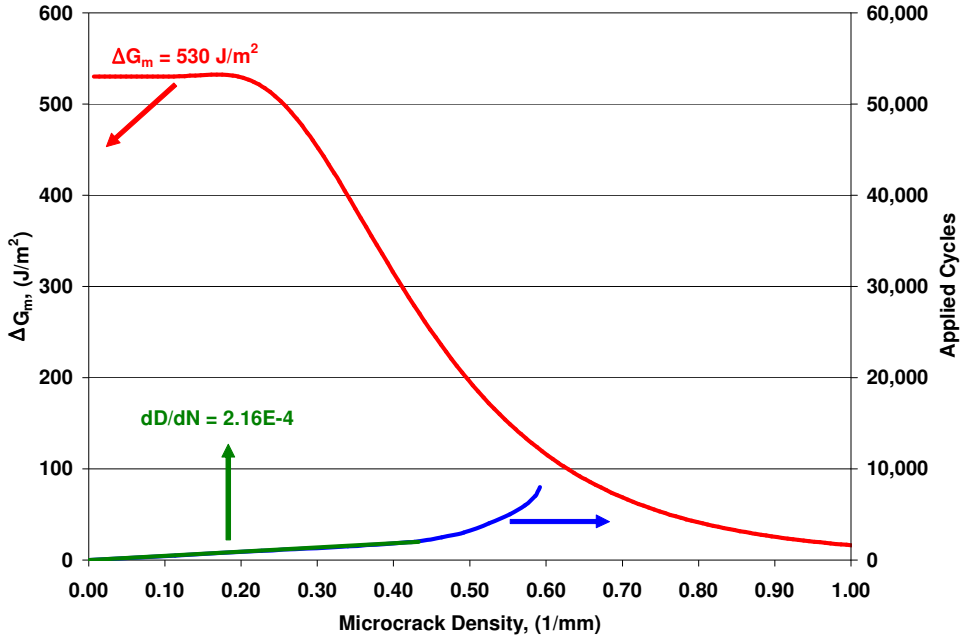

Figure 9. Microcrack energy release rate and applied cycles versus microcrack density for an applied stress corresponding to an initial strain of 0.75%.

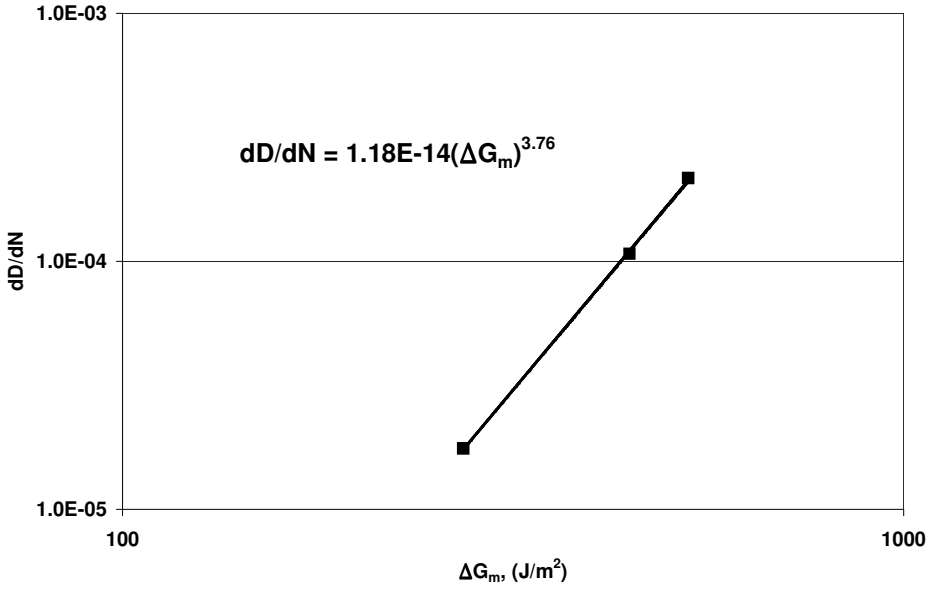

Figure 10. Log plot of microcrack energy release rate versus dD/dN.

V. Illustrative Example

An illustrative example is used to demonstrate how the analytical model proposed here can be used to predict the degree of microcracking in a composite tank subjected to cyclic pressure loads due to fill and drain. Since the cylindrical section of a filament-wound composite tank consists of interspersed layers of hoop and helical plies subjected to a biaxial stress state, a cross-ply laminate of $[0/90]_s$ construction can be considered to be a building block for damage (microcrack) analysis of the tank.[3] The constants, A and n, of the analytical model of damage growth are material constants and can now be used to predict the damage growth in a cross-ply laminate with ply thickness representing the tank wall.

The illustrative example chosen here uses ply thickness (see Figure 2) of $t_1 = t_2 = 0.15$mm which are typical of filament wound linerless composite tanks fabricated by CTD. These ply thicknesses are much smaller than those in the specimens used in the experiments. The material properties used in the computation for the illustrative example are the same as listed in Table 2. The loading conditions were once again selected based on laminate strains of 0.50%, 0.67% and 0.75% in the undamaged laminate. The microcrack energy release rates as well as the corresponding microcrack growth rate for each strain level are presented in Table 2. Figure 11 plots the applied cycles versus microcrack density for the theoretical tank laminate. These plots can be used to predict the number of pressure cycles that a linerless composite tank can be subjected to before a critical threshold of microcrack density is reached for a given operating strain that results in leakage.

Table 2. Microcrack energy release rates and corresponding microcrack growth rate for each strain level.

Strain (Cyclic) (%)	ΔG_m (J/m^2)	A	n	dD/dN (1/mm/cycle)
0.50	80	1.18E-14	3.76	8.05E-09
0.67	133	1.18E-14	3.76	1.93E-07
0.75	163	1.18E-14	3.76	6.80E-07

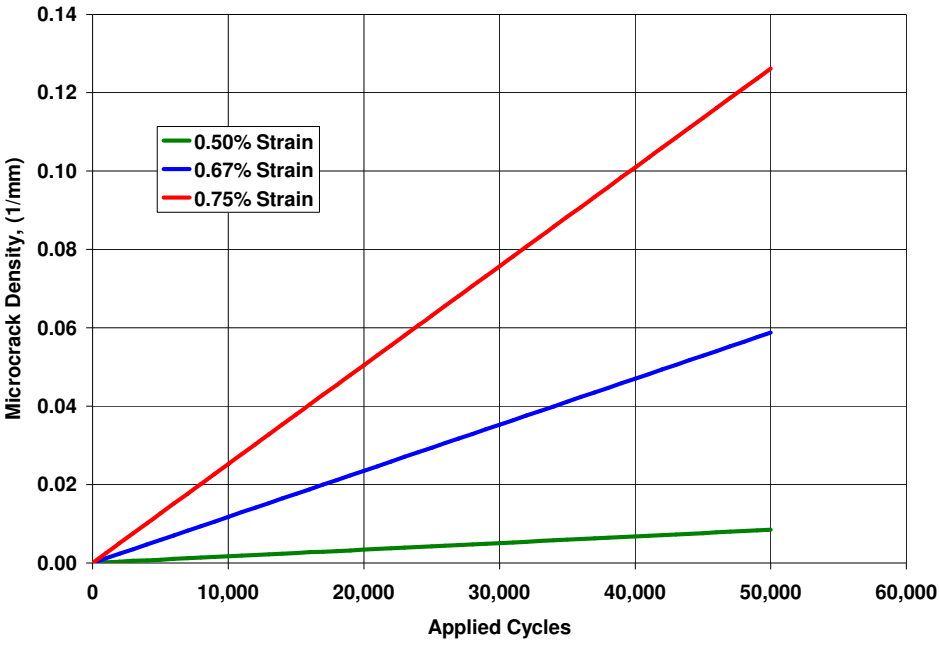

Figure 11. Applied cycles versus microcrack density for a representative tank laminate.

It can be seen from Figure 11, that the microcrack densities are extremely low, an order of magnitude less than the same reported in the experiments, even at the 0.67% strain level after 50,000 cycles. This is attributed to the fact that the resistance to microcrack formation in a composite ply is significantly better when the ply thickness is smaller.

VI. Summary

Microcracking in composite laminates subjected to cyclic mechanical loads is an obstacle to the development of linerless composite tanks. This damage can affect not only the structural integrity of the tank, but may lead to leakage of fluid through the tank walls. In this study, the evolution of damage in the form of microcracks in transverse plies of a cross-ply laminate subjected to uniaxial cyclic loading was investigated. First, an analytical model for damage accumulation under fatigue loading that is based on the concept of microcracking fracture toughness is discussed. The model assumes that the rate of damage growth in the material under uniaxial cyclic loading can be related to the microcracking energy release rate of the material through a modified Paris-law formulation. A key artifact of this model is that damage growth in composite materials can be predicted from only two intrinsic material constants: the microcracking fracture toughness and two Paris-law parameters.

To validate this damage-accumulation model, a series of tests were performed on cross-ply laminates of $[0/90]_s$ construction, which represent a typical "building block" for filament-wound composite pressure vessels. The material tested was a carbon-fiber composite laminate fabricated with one of CTD's novel, toughened matrices. Experimental results of microcracking as a function of cyclic load were analyzed and found to compare well with the trends assumed in the analytical model. An illustrative example was presented to demonstrate how the analytical model, along with the three empirically derived material parameters, can be used to predict the microcracking performance of composite laminates in a linerless composite tank under mechanical fatigue cycles.

Acknowledgments

This material is based upon work supported by the United States Air Force under Contract No. F29601-03-M-0302 and HQ0006-04-C-7088. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the United States Air Force.

References

1. Space Systems – Composite Overwrapped Pressure Vessels (COPVs), ANSI/AIAA, S-081A, 2004.
2. Mallick, K. et al., "Ultralight Linerless Composite Tanks for In-Space Applications," presented at the AIAA Space 2004 Conference, San Diego, Sept. 27-30, 2004.
3. Mallick, K. et al., "An Integrated Systematic Approach to Linerless Composite Tank Development," AIAA paper 2005-2089, 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Austin, Texas, 18 - 21 April 2005.
4. Hashin, Z. and Rotem, A., "A fatigue criterion for fiber reinforced composite materials," *Journal of Composite Materials*, No 7, 1973, pp. 448-464.
5. Ellyin, F. and El-Kadi, H., "A fatigue failure criterion for fiber reinforced composite laminae." *Composite Structures*, No 15, 1990, pp. 61-74.
6. Reifsnider, K. L. and Gao, Z., "A micromechanics model for composites under fatigue loading," *International Journal of Fatigue*, Vol. 13, No. 2, 1991, pp. 149-156.
7. Philippidis, T. P. and Vassilopoulos, A. P., "Fatigue strength prediction under multiaxial stress," *Journal of Composite Materials*, Vol. 33, No. 17, 1999, pp. 1578-1599.
8. Hwang, W. and Han, K. S., "Fatigue of composites- fatigue modulus concept and life prediction." *Journal of Composite Materials* No. 20, 1986, pp. 154-165.
9. Sidoroff, F. and Subagio, B., "Fatigue damage modeling of composite materials from bending test," *Sixth International. Conference of Composite Materials*, Volume 4, 20-24 July, London, UK, 1987, pp. 4.32-4.39.
10. Wand, V. P. and Degrieck, J., "Experimental setup for and numerical modeling of bending fatigue experiments on plain woven glass/epoxy composites," Composite structures, Vol. 51, No. 1, 2001, pp. 1-8.
11. Feng, X., Gilchrist, M. D., Linlich, A. J., and Mathews, F. L., "Development of a method for predicting the fatigue life of CFRP Components," *Proc. Int. Conference on fatigue of composites*, 3-5 June, Paris, France. 1997, pp. 407-414.
12. Henaff-Gardin, C., Lafarie-Frenot, M. C., and Goupillad, I., "The use of a characteristic damage variable in the study of transverse cracking development under fatigue loading in cross-ply laminates," *Fatigue of Composites*, 7.4-7.5, 2000.
13. Bechel. V., "Through-Laminate Damage in Cryogenically Cycled Polymer Composites," AIAA-2004-1771, 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Palm Springs, California, Apr. 19-22, 2004.
14. Bechel, V., "Permeability and Damage in Unloaded Cryogenically Cycled PMCs," AIAA-2005-2156, 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference , Austin, Texas, April 18-21, 2005.

15. Bechel, V. Negilski, M. and James, J., "Limiting the Permeability of Composites for Cryogenic Application," *Composites Science and Technology*, 2006 (to be published).
16. Gates, T. S., Grenoble, R.W. and Whitley, K. S. "Permeability and life-time durability of polymer matrix composites for cryogenic fuel tanks," AIAA 2004-1859, 45th AIAA/ASME/ASCE/AHS/ASC SDM conference, Palm Spring, CA; 2004.
17. Roy, S., Utturkar, A. and Nair, A., "Modeling and characterization of permeability and damage of graphite/epoxy at cryogenic temperature," AIAA 2005-2088,46th AIAA/ASME/ASCE/AHS/ASC SDM conference, Austin, TX, 2005.
18. Nairn, J. A. and Hu, S., "Matrix Microcracking", *Damage Mechanics of Composite Materials*, Elsevier Science, R. Talreja, ed., 1994, Chapter 6.
19. Nairn, J. A., "Matrix Microcracking in Composites," *Polymer Matrix Composites*, Elsevier Science, R. Talreja and J. A, Manson eds., 2001, Chapter 13.
20. Nairn, J. A., Hu, S., Liu, S., and Bark, J.S. *Proceedings. of the First NASA Advanced Composite Tech. Conference*, Seattle, WA. 1990.
21. Nairn, J. A., "The Strain Energy Release Rate of Composite Microcracking: A Variational Approach", *Journal of Composite Materials*, No. 23, 1989.
22. Nairn, J. A., "Applications of Finite Fracture Mechanics for Predicting Fracture Events in Composites", 5th International. Conference on Deformation and Fracture of Composites, London, U.K., 1999.