Lightweight Composite Tanks for Liquid Hydrogen Storage

Bhavani Sankar
Peter Ifju
Department of Mechanical & Aerospace Engineering
University of Florida, Gainesville

Start Date = June 2002
Planned Completion = August 2006

Research Goals and Objectives

- Goal
  - To develop a lightweight composite material system for liquid hydrogen storage tanks
- Objectives
  - Develop and verify models to predict micro-cracking in fiber composite laminates
    - Micromechanics models for thermal stresses in the fiber and matrix phases
    - New experimental technique to measure CTE and thermal stresses
    - Develop and verify models for fracture and delamination at cryogenic conditions
  - Develop and verify models to predict gas permeability
    - Micro-mechanics based models for micro-crack density
    - Experiments to measure gas permeability
    - Models to predict gas permeability
  - Design methodology for LH2 tank based on the above results

Relevance to Current State-of-the-Art

- Currently composite tanks are not being used for LH2 storage because of micro-cracking and gas permeability issues. Although an impermeable liner can be added to the composite tank, debonding of the liner and subsequent leakage remains a problem. Hence a liner-less lightweight tank is still an urgent need for many weight critical applications.

Relevance to NASA

- NASA is aiming at reducing the cost of future launches by an order of magnitude and at the same time making future missions involving humans much safer. Fiber composites such as graphite/epoxy have high specific stiffness and specific strength and are finding applications in many aerospace structures. If the problem of micro-cracking and permeation can be solved, then these materials can also be used for LH2 storage systems.

Budget, Schedule and Deliverables

- Approximate Budget
  - 2002-03: $159K
  - 2003-04: $80K
  - 2004-05: $80K
  - 2005-06: $86K
- Schedule
  - 2002-03: Micromechanics and CTE measurements
  - 2003-04: Fracture mechanics models and experiments
  - 2004-05: Models for micro-crack density and permeability measurements
  - 2005-06: Modeling and measuring permeability under strain
- Deliverables
  - Permeability of various composite material systems
  - Models to predict thermal stresses, CTE, micro-crack density and permeability

Anticipated Technology End Use

- Design of lightweight fiber composite material system for cryogenic storage applications. The material system will have the following attributes:
  - minimum thermal stresses
  - Minimum amount of micro-cracking
  - Low gas permeability
- Design methodology for composite cryogenic storage systems

Accomplishments and Results

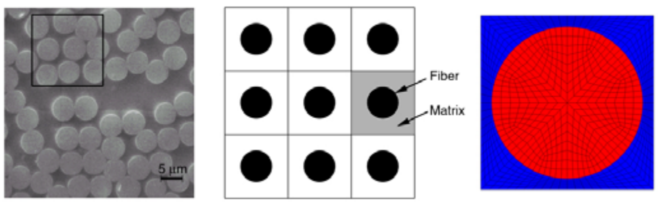
- Demonstrated micro-level thermal stresses are significant and has to be considered in addition to the ply-level thermal stresses in laminated composites at cryogenic temperatures
- Showed that residual stresses due to matrix shrinkage is significant at cryogenic temperatures and could affect safety-factor at cryogenic temperatures.
- Measured the fracture toughness of various material systems and showed that textile composites perform superbly at cryogenic conditions
- Measured the gas permeability of various laminates after cryo cycling and showed that (a) dispersing like plies is better than grouping them; (b) textile composites have low permeability even after cryo cycling
- Developed an efficient 3-D model to predict micro-crack density in laminates loaded bi-axially

Future Plans

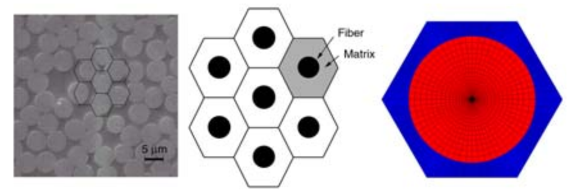
- Extend the micro-crack density prediction models to predict permeability
- Modify the permeability test set-up to measure permeability under strain
- Perform permeability tests on various laminate systems including textile composites and compare their performance under strain after cryo cycling

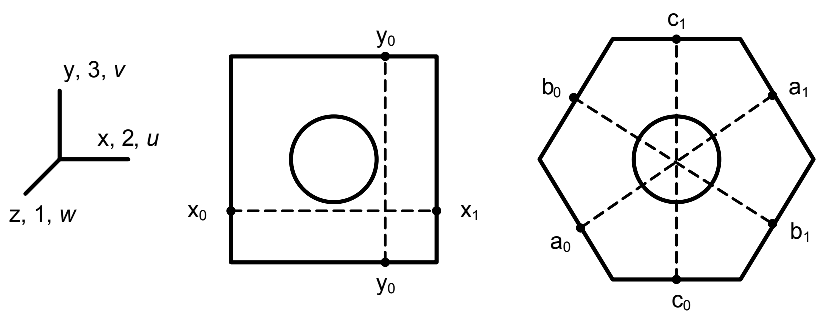
Micromechanics Models to Predict Thermal Stresses

Square Unit Cell



Hexagonal Unit Cell





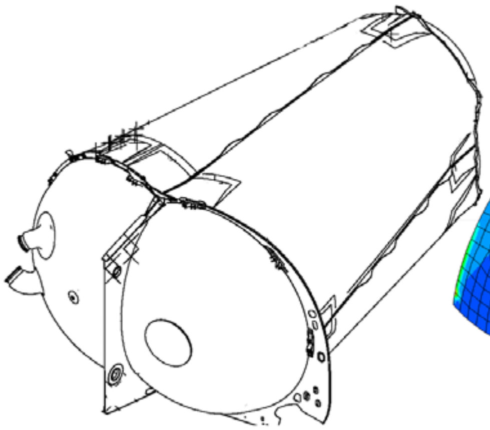
Periodic boundary condition for the square unit cell model subjected to individual strain cases

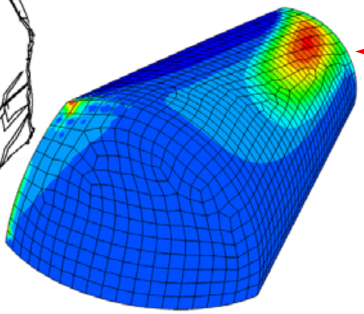
$\varepsilon_x=1$	$\varepsilon_y=1$	$\varepsilon_z=1$	$\gamma_{xy}=1$	$\gamma_{xz}=1$	$\gamma_{yz}=1$
$u_{x1}-u_{x0}=L$ $v_{y1}-v_{y0}=0$ $w_{z1}-w_{z0}=0$	$u_{x1}-u_{x0}=0$ $v_{y1}-v_{y0}=L$ $w_{z1}-w_{z0}=0$	$u_{x1}-u_{x0}=0$ $v_{y1}-v_{y0}=0$ $w_{z1}-w_{z0}=t$	$v_{x1}-v_{x0}=0.5L$ $u_{y1}-u_{y0}=0.5L$ $w_{z1}-w_{z0}=0$	$w_{x1}-w_{x0}=L$ $u_{z1}-u_{z0}=0$	$w_{y0}+w_{y1}=L$ $v_{z1}-v_{z0}=0$

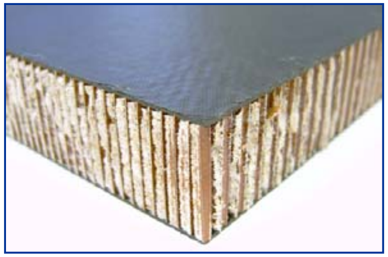
Periodic boundary condition for the hexagonal unit cell model subjected to individual strain cases

Multi-Scale Modeling

Pressure = 57 PSI, Temperature = 50K. The tank was modeled using finite elements. The macro-level strains were calculated using the FE analysis.



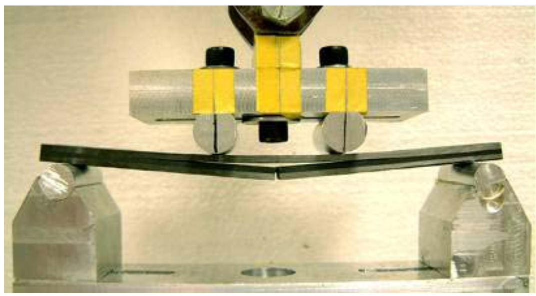




- Inner facesheet 0.066 in. thick – 13 plies [$45/90_3/-45/0_3/-45/90_3/45$]
- Core 1.5 in. thick honeycomb Korex 3/16 – 3.0
- Outer facesheet 0.034 in. thick – 7 plies [65/0/-65/90/-65/0/65]

Fracture Test at Room and Cryogenic Temperature

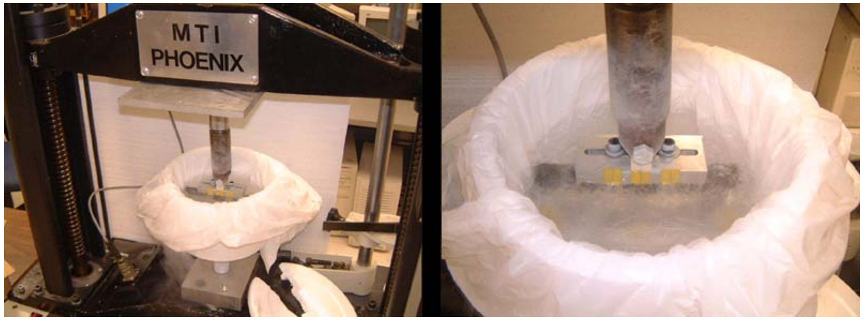
Four-point bending experimental setup



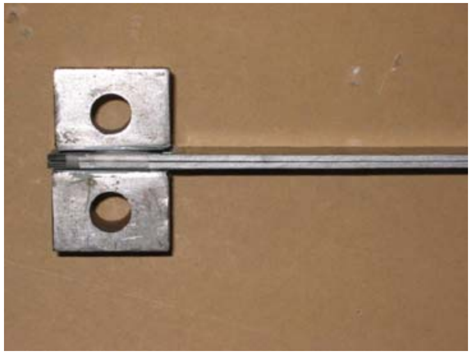
Dimensions of composite specimens [0/90/0]

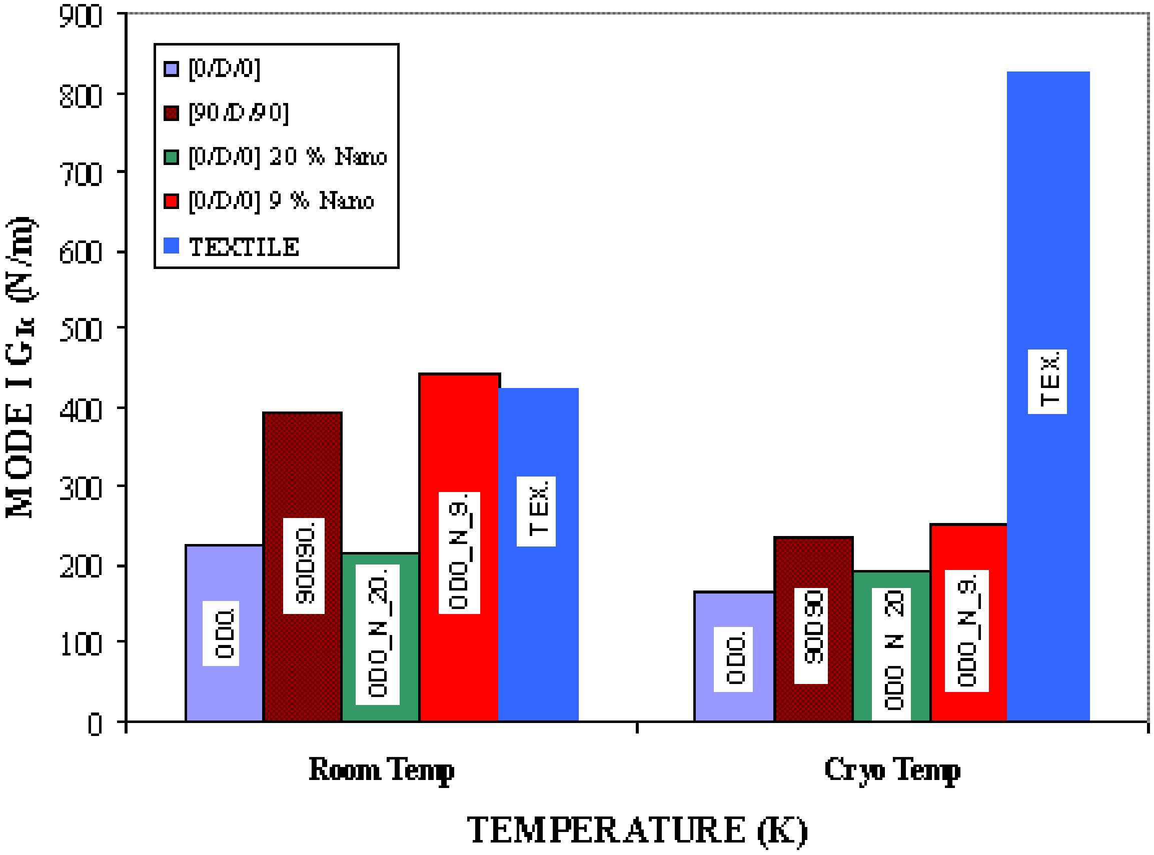
Specimen	Length (mm)	Width (mm)	Layer Thickness	
			Top and bottom layer, 0º (mm)	Mid layer, 90º (mm)
1	145.4	18.6	2.4	1.8
2	146.2	18.7	2.4	2.4
3	145.7	18.8	2.4	3.0

Four-point bending experimental setup at cryogenic temperature

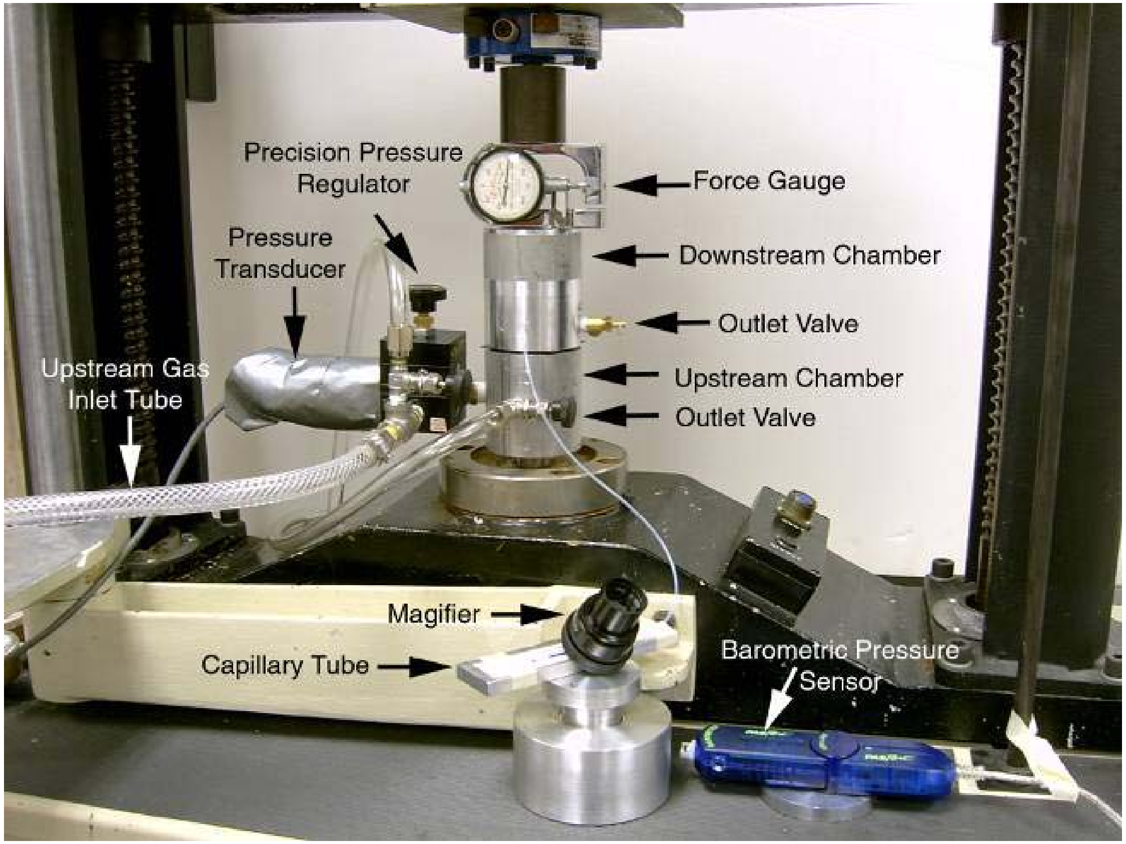


Delamination fracture toughness of different material systems

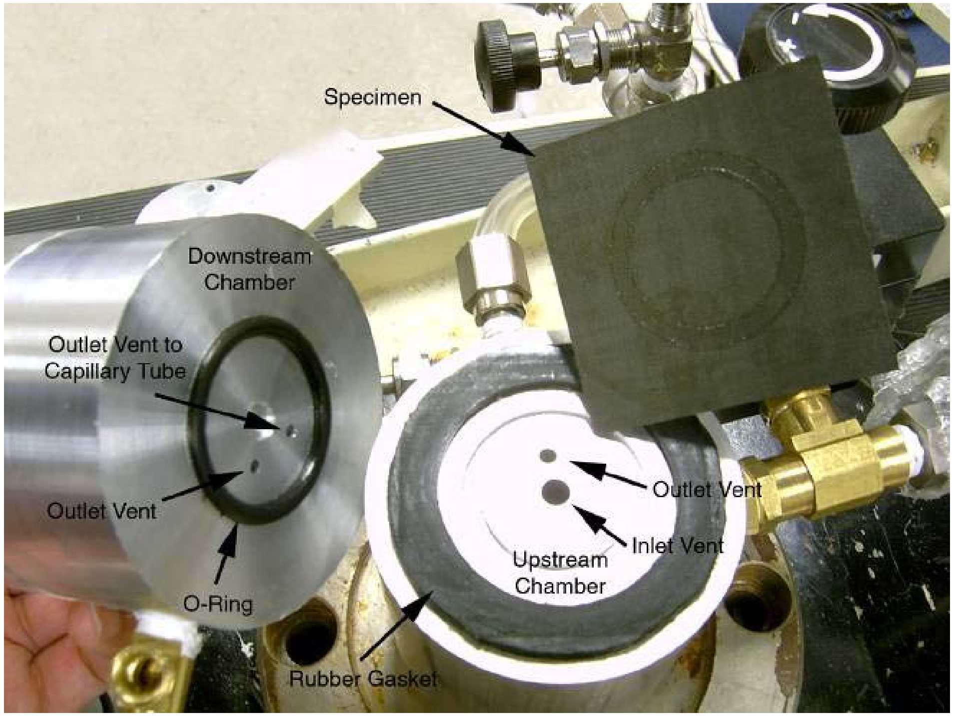




Permeability Test Facility

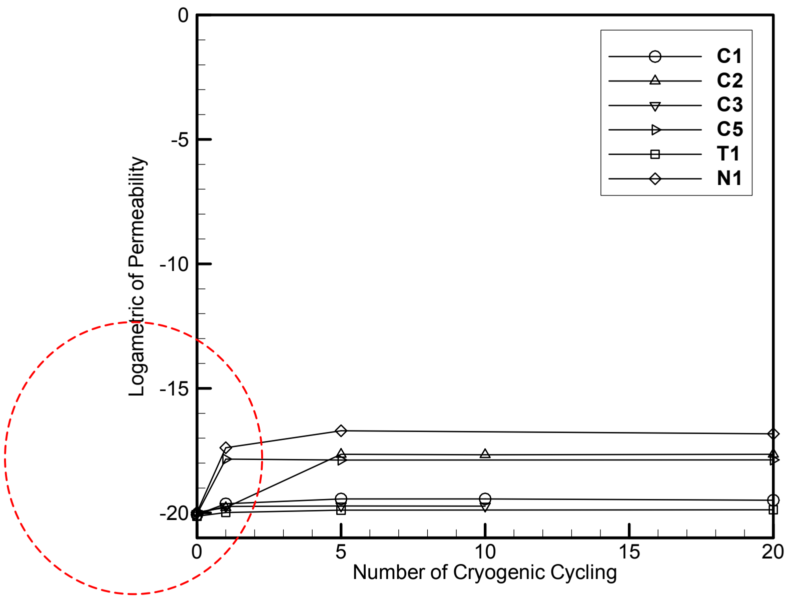


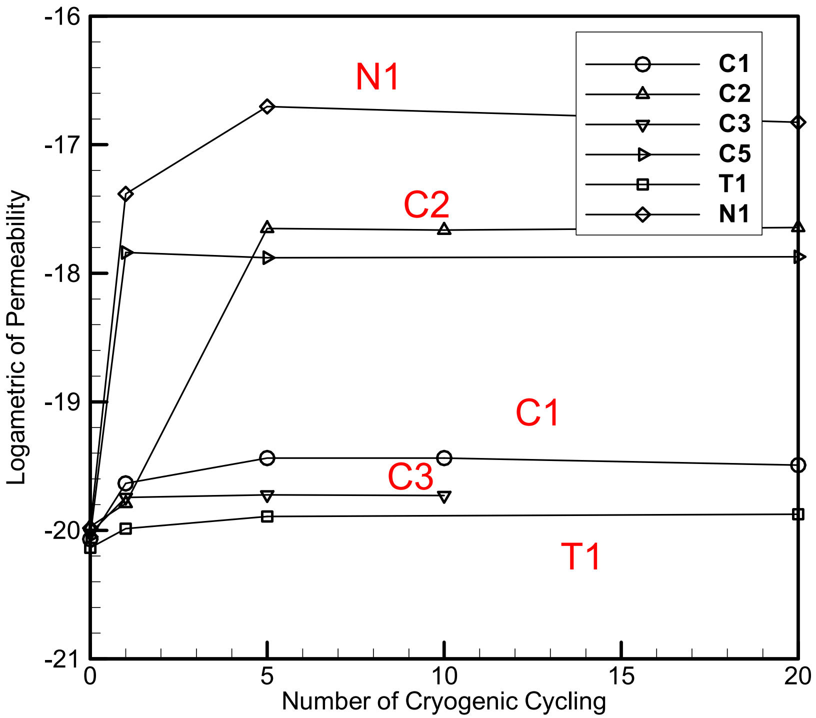
Gas Transmission Cell



O-ring Inner Diameter = 38 mm

Permeability of Various Composite Materials Systems

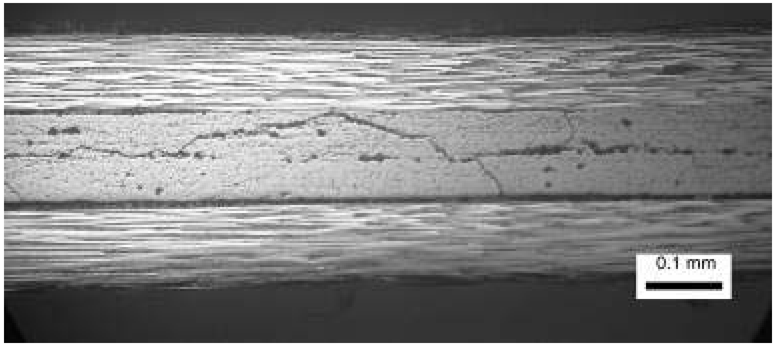


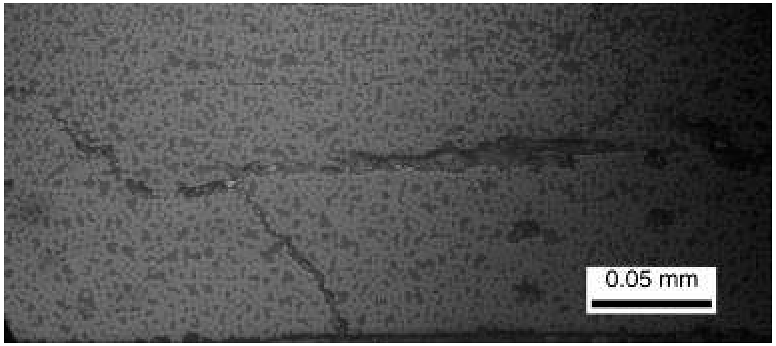


C1,C2,C3 are laminated composite specimens.
T1 is a textile composite specimen.
N1 is a laminated composite specimen embedded with nano-particles.

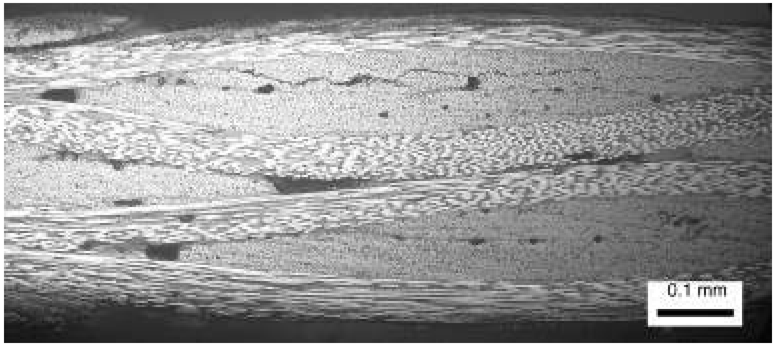
Optical Microscopic Analysis of Laminated and Textile Composite Specimens

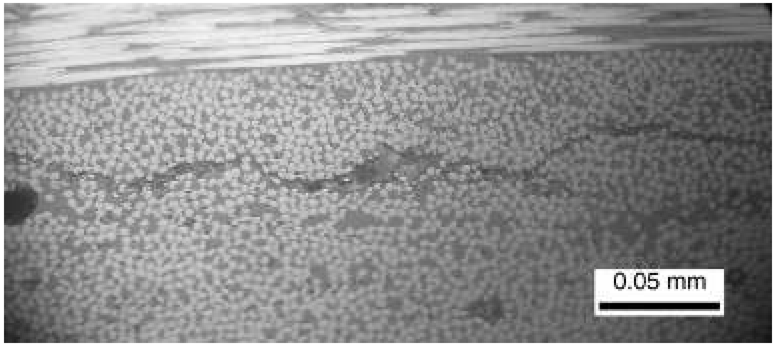
(After Cryogenic Cycling)





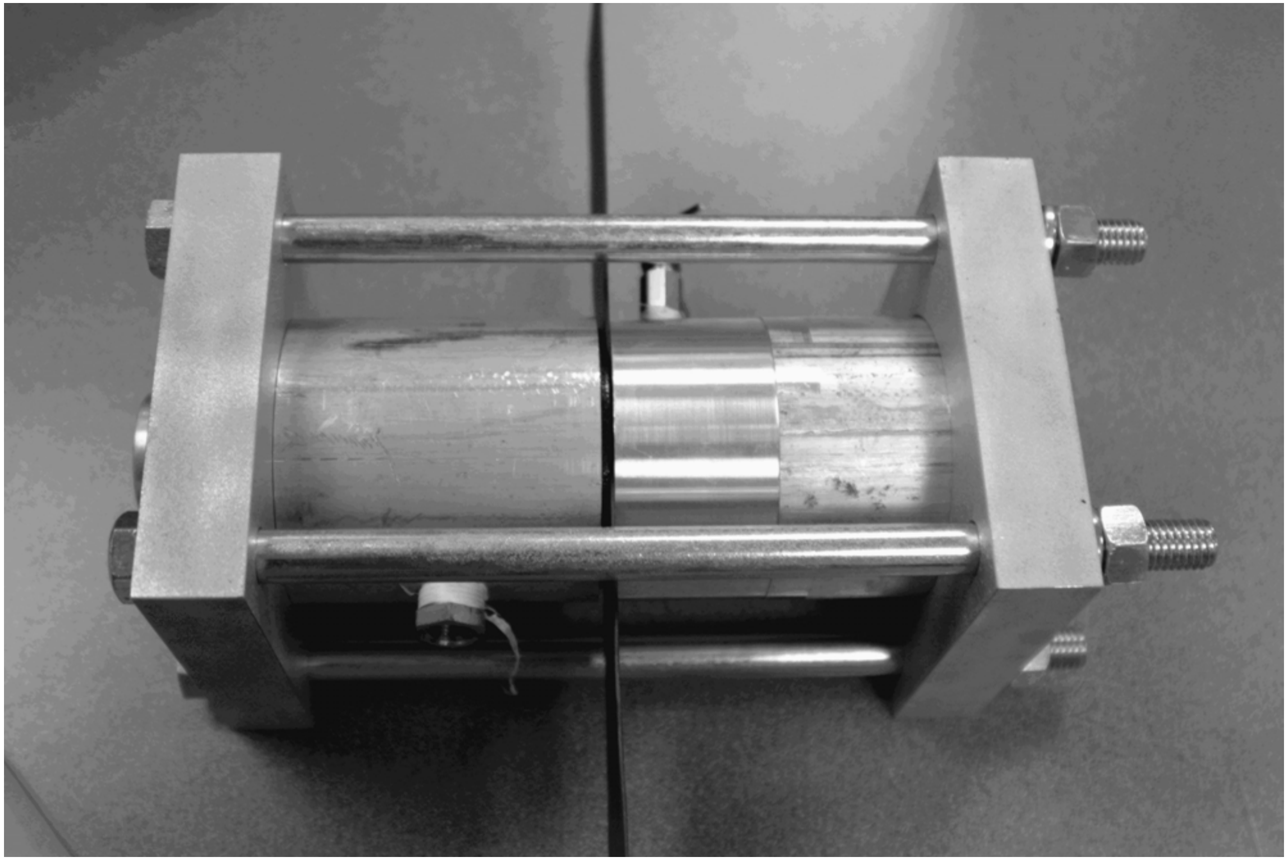
In laminated composites cracks
connect through plies



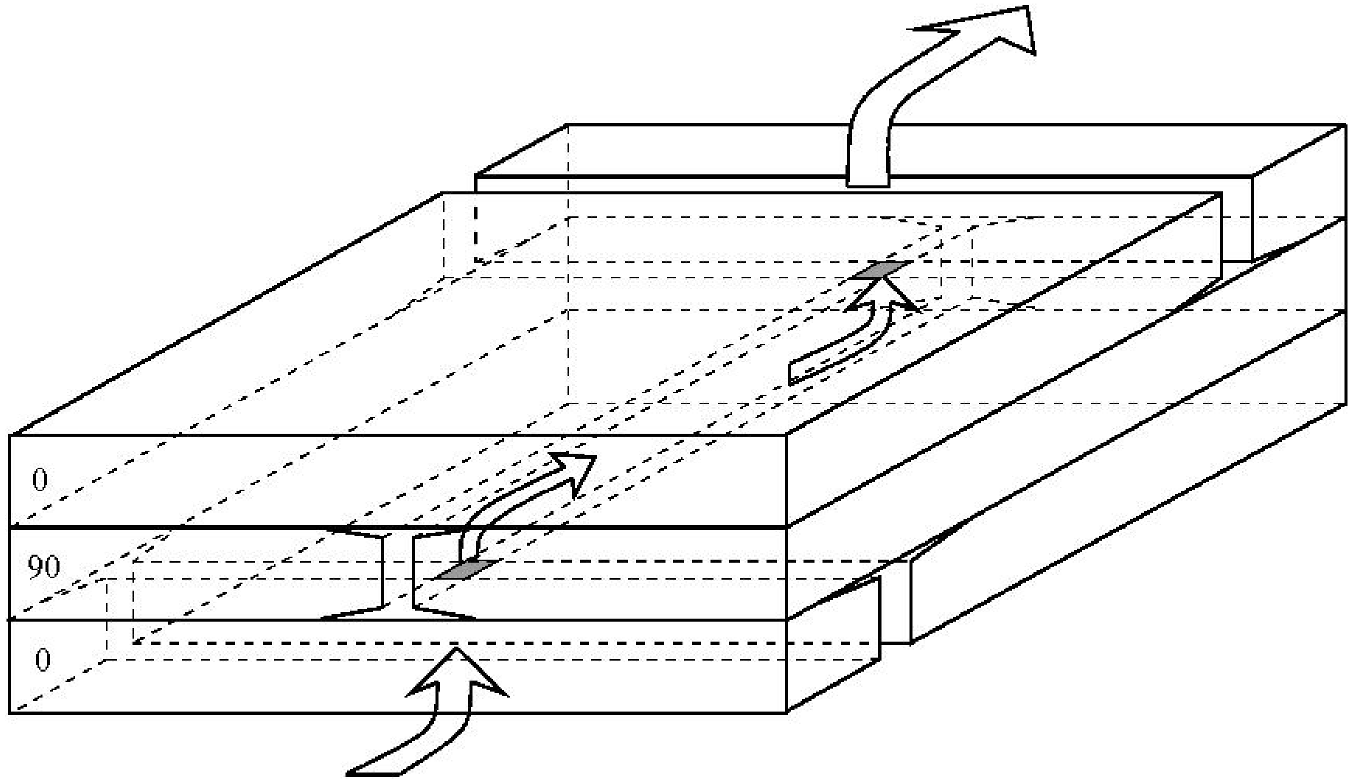


In textile composites cracks
are restricted to yarns and plies

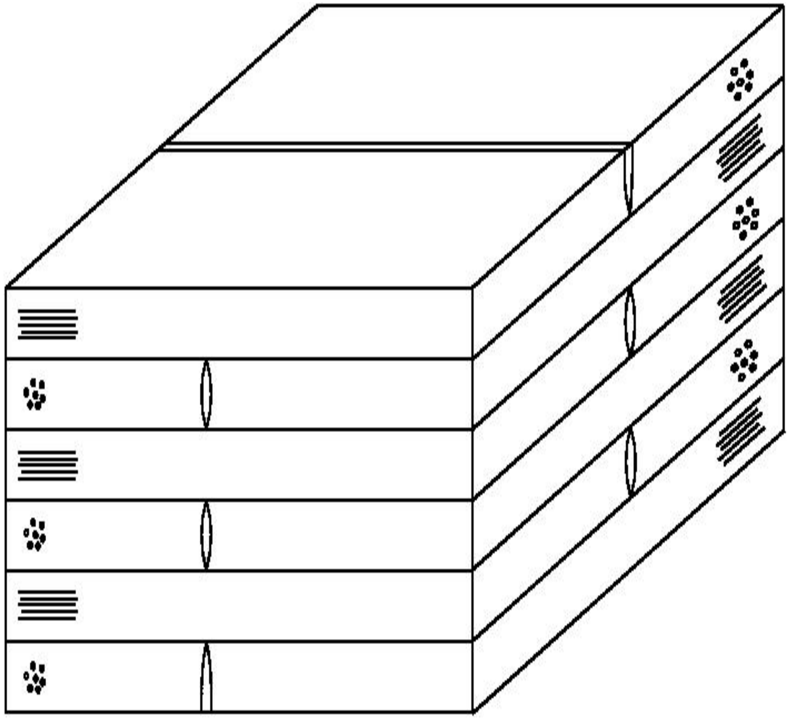
Modified set up to measure permeability under strain

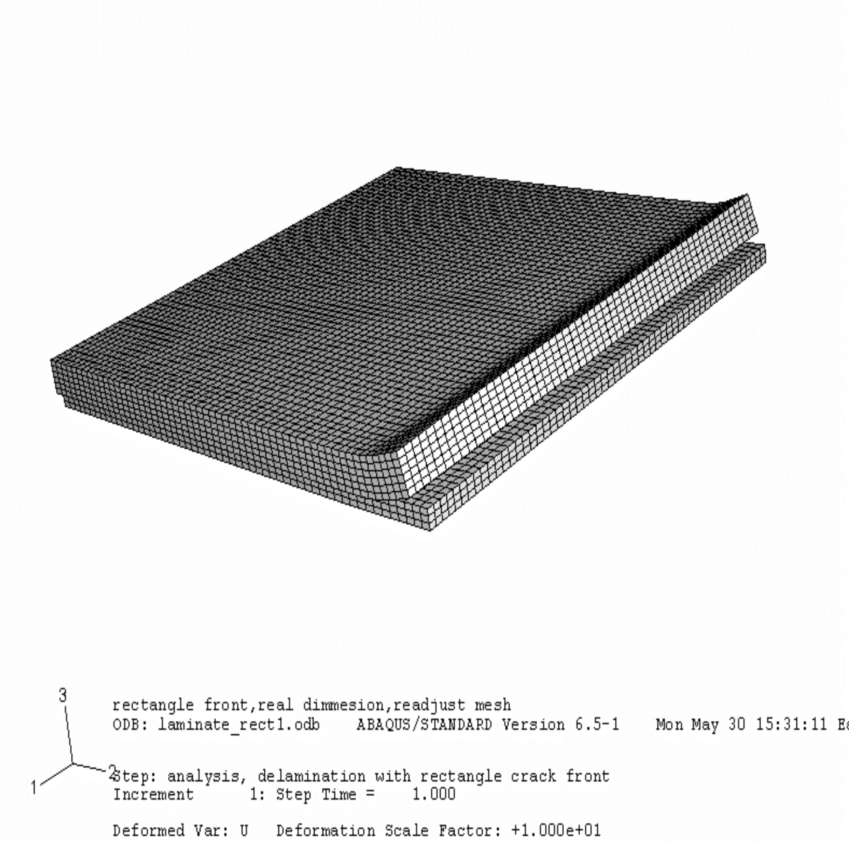


Modeling Permeability in Composite Laminates

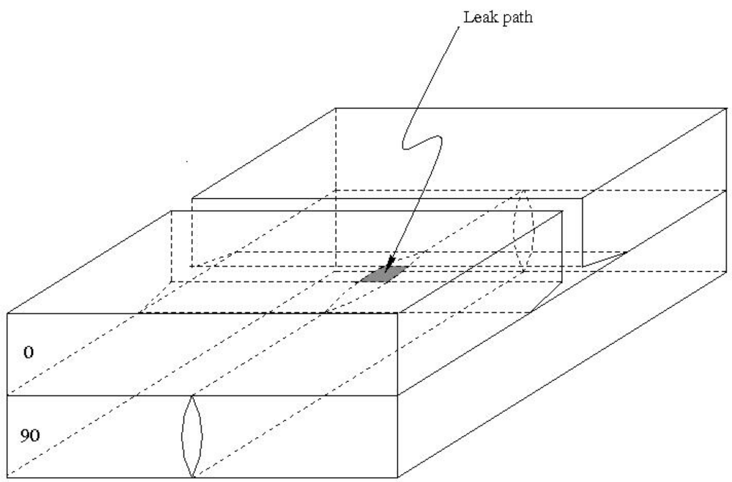


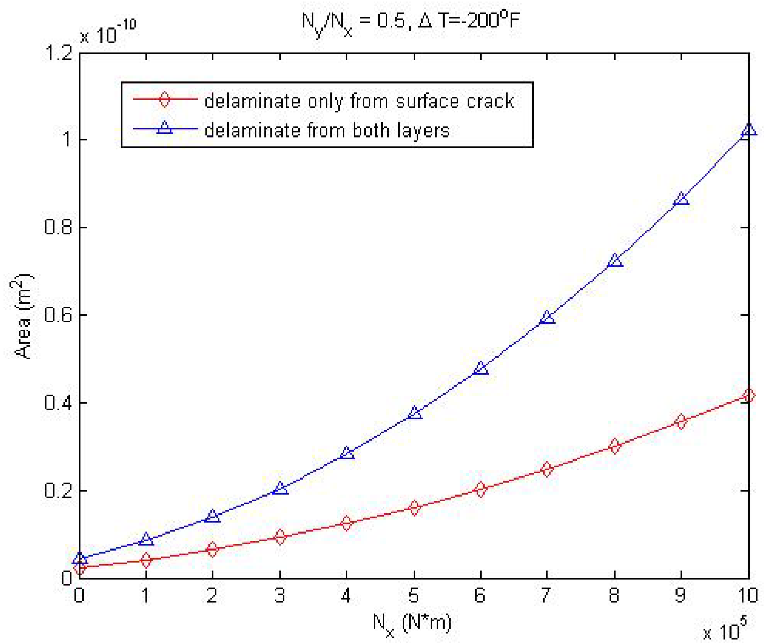
3-D Finite Element Model

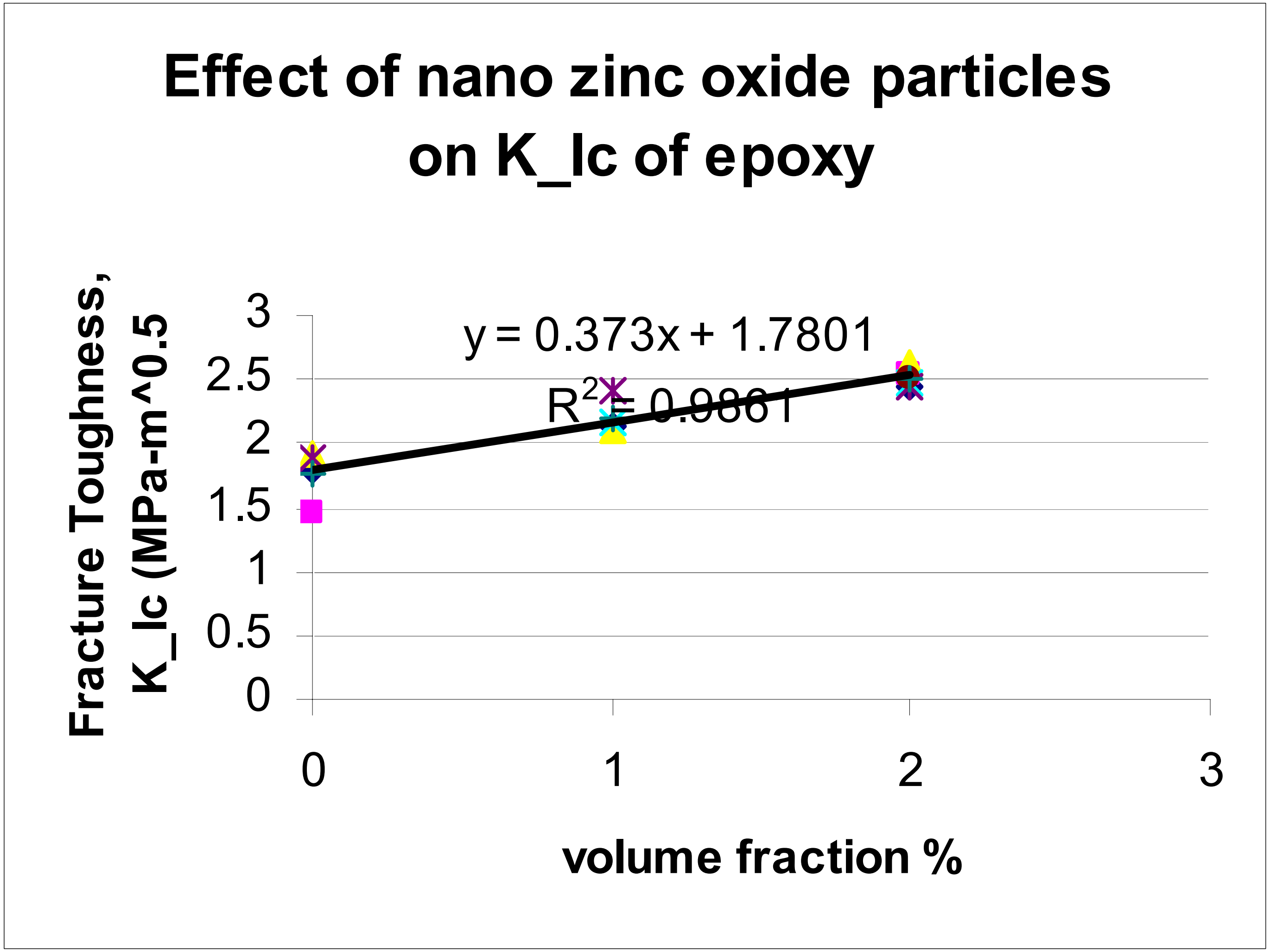




Crack surface area as a function load






Effect of nano zinc oxide particles on K_Ic of epoxy
Fracture Toughness, K_Ic (MPa-m^0.5)
3
2.5
2
1.5
1
0.5
0
y = 0.373x + 1.7801
R2 = 0.9861
0
1
2
3
volume fraction %

Students Graduated/Current

- Doctoral Students
  - Sukjoo Choi (May 2005, Post Doctoral Associate at Texas A&M)
  - Jianlong Xu (expected May 2007)
- Master Students (with thesis)
  - Sujith Kalarikkal (August 2004, with Research Applications, Inc., San Diego)
  - Won-Jong Noh (August 2004, with Hyundai Motors)
  - James VanPelt (expected May 2007)

Archival Publications

- Lim, W.-K., S.-Y. Choi and B.V. Sankar (2001) "Biaxial Load Effects on Crack Extension in Anisotropic Solids", *Engineering Fracture Mechanics*, 68(4):403-416.
- Choi, S., B.V. Sankar. “Fracture toughness of carbon foam”, *Journal of Composite Materials*, 37(23):2101-2116, 2003.
- Choi, S. and B.V. Sankar, 2005, “A Micromechanical method to predict the fracture toughness of cellular materials”, *International Journal of Solids & Structures* 42 (2005) 1797-1817.
- Choi, S. And B.V. Sankar, “A micromechanics method to predict the micro-cracking of the LH2 composite tank at cryogenic temperature”, Proceedings of the 5th International Congress on Thermal Stresses and related Topics, TS 2003, Blacksburg, VA, 8-11 June 2003, pp. WM441-444.
- Choi, S., B.V. Sankar, “Micromechanical Analysis of Composite Laminates at Cryogenic Temperatures”, *J. Composite Materials (in press)*
- Choi, S., B.V. Sankar. “Thermal stresses in a composite pressure vessel at cryogenic temperatures”, *Developments in Theoretical and Applied Mechanics,* Proceedings of the 22nd Southeastern Conference in Theoretical and Applied Mechanics (SECTAM), August 15-17, 2004, Center for Advanced Materials, Tuskegee University, Tuskegee, Alabama, pp. 587-596.
- Kalarikkal, S., B.V. Sankar, P.G. Ifju, “Effect of Cryogenic Temperature on the Fracture Toughness of Graphite/Epoxy Composites”. *ASME Journal of Engineering Materials and Technology* (in press)
- Grau, DL, XS Qiu, BV Sankar. "Relation between interfacial fracture toughness and mode-mixity in honeycomb core sandwich composites", *J. Sandwich Structures & Materials* (in press)