Lightweight Composite Tanks for Liquid Hydrogen Storage

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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 linerless 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

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

<table>
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<tr>
<th>$\varepsilon_x=1$</th>
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Periodic boundary condition for the hexagonal unit cell model subjected to individual strain cases

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</table>
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]

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Top and bottom layer, 0º (mm)</th>
<th>Mid layer, 90º (mm)</th>
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</thead>
<tbody>
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<td>2.4</td>
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<td>146.2</td>
<td>18.7</td>
<td>2.4</td>
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<tr>
<td>3</td>
<td>145.7</td>
<td>18.8</td>
<td>2.4</td>
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</tr>
</tbody>
</table>

Four-point bending experimental setup at cryogenic temperature
Delamination fracture toughness of different material systems

![Graph showing delamination fracture toughness of different material systems](image)
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.

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Optical Microscopic Analysis of Laminated and TextileComposite 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$\cdot$m$^{0.5}$)

Volume fraction %

$y = 0.373x + 1.7801$

$R^2 = 0.9861$
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