In order to minimize boil off of the liquid oxygen and liquid hydrogen and to prevent the formation of ice on its exterior surface, the Space Shuttle External Tank (ET) is insulated using various low-density, closed-cell polymeric foams. Improved analysis methods for these foam materials are needed to predict the foam structural response and to help identify the foam fracture behavior in order to help minimize foam shedding occurrences. This presentation describes a continuum based approach to modeling the foam thermo-mechanical behavior that accounts for the cellular nature of the material and explicitly addresses the effect of the internal cell gas pressure.

A porous media approach is implemented in a finite element frame work to model the mechanical behavior of the closed cell foam. The ABAQUS general purpose finite element program is used to simulate the continuum behavior of the foam. The soil mechanics element is implemented to account for the cell internal pressure and its effect on the stress and strain fields. The pressure variation inside the closed cells is calculated using the ideal gas laws. The soil mechanics element is compatible with an orthotropic materials model to capture the different behavior between the rise and in-plane directions of the foam.

The porous media approach is applied to model the foam thermal strain and calculate the foam effective coefficient of thermal expansion. The calculated foam coefficients of thermal expansion were able to simulate the measured thermal strain during heat up from cryogenic temperature to room temperature in vacuum. The porous media approach was applied to an insulated substrate with one inch foam and compared to a simple elastic solution without pore pressure. The porous media approach is also applied to model the foam mechanical behavior during subscale laboratory experiments. In this test, a foam layer sprayed on a metal substrate is subjected to a temperature variation while the metal substrate is stretched to simulate the structural response of the tank during operation. The thermal expansion mismatch between the foam and the metal substrate and the thermal gradient in the foam layer causes high tensile stresses near the metal/foam interface that can lead to delamination.
Porous Media Approach for Modeling Closed Cell Foam

Louis J. Ghosn
Senior Researcher
Ohio Aerospace Institute

and

Roy M. Sullivan
Material Research Engineer
NASA Glenn Research Center

43rd Annual Technical Meeting
Society of Engineering Science
August 13-16th, 2006
**SOFI Closed Cell Foam**

- 97% void filled with entrapped gases
- Polymeric cell walls
- Anisotropic properties
- Polymer out-gas upon heating:
  - weakens cell walls
  - creates additional internal pressures
  - results in a unique thermal expansion behavior

**Space Shuttle External Tank Foams**
- BX265
- NCFI
- PDL
Application of Porous Media Principles to Foam Thermo-mechanics

Generalized 3-D Constitutive Relations for Porous Media

\[
\sigma_{ij} = C_{ijkl} \left( e_{kl} - \alpha_{kk} T \Delta T \right) - \alpha_{ij}^P P
\]

- \( C_{ijkl} \): Elastic stiffness tensor
- \( P \): Cell internal pressure
- \( \alpha_{ij}^P \): Stress-Pressure coupling tensor
- \( \alpha_{kk}^T \): Coefficient of thermal expansions
- \( \Delta T = (T - T_{ref}) \): Change in temperature

Heat

Tank Wall

SOFI
SOFI Mechanical Properties
from FEA Unit Cell Model

\[ \nu = \frac{E_{11}}{2(1+\nu_{12})} \]  
\( (in 	ext{ – plane isotropic}) \)

\[ G_{31}^* = \frac{2G_{12}}{1+R} \]  
\( (Rise) \)

*Ref. Gibson Ashby

<table>
<thead>
<tr>
<th></th>
<th>Temp (°C)</th>
<th>E11 (MPa)</th>
<th>E22 (MPa)</th>
<th>E33 (MPa)</th>
<th>nu12</th>
<th>nu13</th>
<th>nu32</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BX-265</strong></td>
<td>-251</td>
<td>10.97</td>
<td>10.97</td>
<td>39.89</td>
<td>0.488</td>
<td>0.143</td>
<td>0.520</td>
</tr>
<tr>
<td></td>
<td>-196</td>
<td>10.97</td>
<td>10.97</td>
<td>39.89</td>
<td>0.488</td>
<td>0.143</td>
<td>0.520</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>4.99</td>
<td>4.99</td>
<td>18.13</td>
<td>0.488</td>
<td>0.143</td>
<td>0.520</td>
</tr>
<tr>
<td><strong>NCFI</strong></td>
<td>-251</td>
<td>9.96</td>
<td>9.96</td>
<td>45.75</td>
<td>0.528</td>
<td>0.114</td>
<td>0.524</td>
</tr>
<tr>
<td></td>
<td>-196</td>
<td>9.96</td>
<td>9.96</td>
<td>45.75</td>
<td>0.528</td>
<td>0.114</td>
<td>0.524</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>4.53</td>
<td>4.53</td>
<td>20.80</td>
<td>0.528</td>
<td>0.114</td>
<td>0.524</td>
</tr>
<tr>
<td><strong>PDL</strong></td>
<td>-253</td>
<td>31.85</td>
<td>31.85</td>
<td>49.96</td>
<td>0.362</td>
<td>0.249</td>
<td>0.391</td>
</tr>
<tr>
<td></td>
<td>-196</td>
<td>25.03</td>
<td>25.03</td>
<td>39.26</td>
<td>0.362</td>
<td>0.249</td>
<td>0.391</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>12.74</td>
<td>12.74</td>
<td>19.99</td>
<td>0.362</td>
<td>0.249</td>
<td>0.391</td>
</tr>
</tbody>
</table>
Calibration of Thermal Expansion Coefficients

\[ e_{ij} = P S_{ijkl} \alpha_{kl}^P + \alpha_{ii}^T \Delta T \]

Assuming \( \alpha_{ij}^P = [I] \)

\[ \varepsilon_{11} = (p_{cell} - p_{ext}) \frac{1 - \nu_{12} - \nu_{13}}{E_{11}} + \alpha_{11}^T (T - T_{ref}) \]

\[ \varepsilon_{22} = (p_{cell} - p_{ext}) \frac{1 - \nu_{21} - \nu_{23}}{E_{22}} + \alpha_{22}^T (T - T_{ref}) \]

\[ \varepsilon_{33} = (p_{cell} - p_{ext}) \frac{1 - \nu_{31} - \nu_{32}}{E_{33}} + \alpha_{33}^T (T - T_{ref}) \]

Solving for \( \alpha_{kk}^T \) yields:

\[ \alpha_{11}^T = \frac{\varepsilon_{11}}{T - T_{ref}} - \frac{p_{cell} - p_{ext}}{T - T_{ref}} \cdot \frac{1 - \nu_{12} - \nu_{13}}{E_{11}} \]

\[ \alpha_{22}^T = \frac{\varepsilon_{22}}{T - T_{ref}} - \frac{p_{cell} - p_{ext}}{T - T_{ref}} \cdot \frac{1 - \nu_{21} - \nu_{23}}{E_{22}} \]

\[ \alpha_{33}^T = \frac{\varepsilon_{33}}{T - T_{ref}} - \frac{p_{cell} - p_{ext}}{T - T_{ref}} \cdot \frac{1 - \nu_{31} - \nu_{32}}{E_{33}} \]
Flow Chart for Pore Pressure Analysis Approach

- Finite Element Mesh of Foam Application
- ABAQUS FE Thermal Analysis Solution
  - Nodal temperatures: Temperature Distributions in the Foam
- Pore Pressure Subroutine
  - Nodal internal cell gas pressures: Pressure Distributions in the Foam
- ABAQUS FE Porous Media Analysis Solution
  - Solid Skeleton Stress Distribution
Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613
Porous-Media applied to thermal-strain experiment

Rise

Symmetry planes

In-plane

Rise displacement

In-plane displacement

Note

- Use the 1-atm thermal strain for calibrating the Porous-Media CTE
- Verify the CTE and pore pressure using the vacuum data
## Calibrated SOFI CTE

### BX-265

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>$\alpha_{11}$ (1/C)</th>
<th>$\alpha_{22}$ (1/C)</th>
<th>$\alpha_{33}$ (1/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-253</td>
<td>5.90E-05</td>
<td>5.90E-05</td>
<td>3.68E-05</td>
</tr>
<tr>
<td>-196</td>
<td>6.90E-05</td>
<td>6.90E-05</td>
<td>4.23E-05</td>
</tr>
<tr>
<td>-73</td>
<td>8.94E-05</td>
<td>8.94E-05</td>
<td>5.32E-05</td>
</tr>
<tr>
<td>24</td>
<td>1.65E-04</td>
<td>1.65E-04</td>
<td>9.96E-05</td>
</tr>
<tr>
<td>93</td>
<td>2.40E-04</td>
<td>2.40E-04</td>
<td>1.46E-04</td>
</tr>
</tbody>
</table>

### NCFI 24-124

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>$\alpha_{11}$ (1/C)</th>
<th>$\alpha_{22}$ (1/C)</th>
<th>$\alpha_{33}$ (1/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-253</td>
<td>4.92E-05</td>
<td>4.92E-05</td>
<td>3.72E-05</td>
</tr>
<tr>
<td>-196</td>
<td>6.29E-05</td>
<td>6.29E-05</td>
<td>4.59E-05</td>
</tr>
<tr>
<td>-73</td>
<td>6.34E-05</td>
<td>6.34E-05</td>
<td>6.23E-05</td>
</tr>
<tr>
<td>24</td>
<td>7.80E-05</td>
<td>7.80E-05</td>
<td>8.21E-05</td>
</tr>
<tr>
<td>93</td>
<td>9.26E-05</td>
<td>9.26E-05</td>
<td>1.02E-04</td>
</tr>
<tr>
<td>149</td>
<td>2.03E-04</td>
<td>2.03E-04</td>
<td>1.93E-04</td>
</tr>
</tbody>
</table>

### PDL-1034

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>$\alpha_{11}$ (1/C)</th>
<th>$\alpha_{22}$ (1/C)</th>
<th>$\alpha_{33}$ (1/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-253</td>
<td>4.61E-05</td>
<td>4.61E-05</td>
<td>4.12E-05</td>
</tr>
<tr>
<td>-196</td>
<td>5.67E-05</td>
<td>5.67E-05</td>
<td>5.14E-05</td>
</tr>
<tr>
<td>-73</td>
<td>7.02E-05</td>
<td>7.02E-05</td>
<td>6.40E-05</td>
</tr>
<tr>
<td>24</td>
<td>1.35E-04</td>
<td>1.35E-04</td>
<td>1.40E-04</td>
</tr>
<tr>
<td>93</td>
<td>1.99E-04</td>
<td>1.99E-04</td>
<td>2.16E-04</td>
</tr>
<tr>
<td>149</td>
<td>4.76E-04</td>
<td>4.76E-04</td>
<td>5.63E-04</td>
</tr>
</tbody>
</table>
Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613
Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613
CTE, PDL-1034
in-plane

Picture of a graph showing thermal strain against temperature for different series.

Porous Media Verification (vacuum)

Vacuum

Pull Vacuum

Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613
Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613
CTE, BX-265
in-plane

Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613
CTE BX265
rise direction

Data courtesy of E. Stokes: Thermal expansion of three ET Polyurethane and Polyisocyanurate foams 11613
High Temperature Thermal Strain

Thermal Expansion BX-265

Data from B. A. Lerch (NASA GRC)
Thermogravimetric Analysis of Pulverized BX-265

\[ P = \sum p_i = \sum \tilde{\rho}_i RT \]

\[ \tilde{\rho}_i \] is the molar density of the \( i^{\text{th}} \) gas in the cells, given by

\[ \tilde{\rho}_i = \tilde{\rho}_i^0 + \int_t ^{\infty} \frac{d\rho_{i,s}}{dt} dt \]

Initial Gas

Gas species

Gained from the foam
Cell Pressure vs Temperature

Pressure, MPa

Temperature, C

Water
Air
Total
Calibrated High temperature BX-265 CTE

CTE (1/C)

Temperature, C

-1E-03 -8E-04 -6E-04 -4E-04 -2E-04 0E+00 2E-04 4E-04 6E-04 8E-04 1E-03

0 50 100 150 200

In-Plane (Air Only)
Rise (Air Only)
In-Plane (Vaporr & Air)
Rise (Vapor & Air)
Simple Example to Determine the Advantage of the Porous Media Formulation

25.4mm NCFI

2.54mm Ti64 Substrate

-250 C

-18 C
Foam through thickness stress profiles

Simple Elastic Solution
Foam through thickness stress profiles

Porous Media Solution

Stress, MPa

Normalized distance from bottom, Y/t

Pore Pressure, MPa

NCFI Strength Range

XX
YY
ZZ
Pore-Pressure

1 atm
Comparison of the stress distribution between the two methods

8% decrease in XX & ZZ stresses

Open symbol → porous-media
Closed symbol → simple elastic

Increases in YY stresses due to the reduction of the cell pore pressure with decrease temperature

NCFI Strength Range
Thermal Gradient with Substrate Stress

25.4mm NCFI

2.54mm Ti64 Substrate

-250 C

150 MPa

-18 C

150 MPa
Foam through thickness stress profiles

Porous Media Solution with Substrate Stress (150 MPa)

- Normalized distance from bottom, Y/t
- Stress, MPa
- Pore Pressure, MPa

NCFI Strength Range
Foam through thickness stress profiles

7% increase in XX stress

Open symbol → Thermal Gradient
Closed symbol → Thermal Gradient + Substrate Pull

Localized stress variation in the YY direction

NCFI Strength Range

Stress, MPa

Normalized distance from bottom, Y/t
Modeling the Cryoflex specimen

NCFI, BX-265 or Hybrid BX-PDL

Al-2195-T8 (for Lo2 tank) or Ti-6-4 for (Lh2 tank)
Temperature Profile for Gradient Test

Lh2 test, with Ti substrate
-18°C
5 cm (1.99”)

Lo2 test, with Al-2195-T substrate
-250°C
9.2 cm (3.59”)
1.27 cm (0.5”)

Symmetry
LH2 Gradient (@-17.8°C to -245°C, 950 MPa)
No Slit, No Pore Pressure

NCFI Strength Range

Distance from substrate, mm

Stress, MPa

XX
YY
ZZ
XY
XZ
YZ
LH2 Gradient (@-17.8C to -245C, 950MPa)
No Slit, With Pore Pressure

With the $\sigma_{xx}$ well in the failure zone
Only 1 out 12 specimens failed
LH2 Immersion (@-185C, 122MPa)
No Slit, With Pore Pressure

With the $\sigma_{xx}$ well below the failure zone
10 out 10 specimens failed
Transversely isotropic material, Hyper-elliptic failure function

\[ a_1 \left( \sigma_{11}^2 + \sigma_{22}^2 \right) + a_3 \left( \sigma_{33}^2 \right) + a_4 \left( \sigma_{11} \cdot \sigma_{22} \right) + a_5 \left( \sigma_{11} \sigma_{33} + \sigma_{22} \sigma_{33} \right) + a_7 \left( \sigma_{11} + \sigma_{22} \right) + a_9 \sigma_{33} \]

\[ + \left( 2a_1 - a_4 \right) \sigma_{12}^2 + a_{11} \left( \sigma_{13}^2 + \sigma_{23}^2 \right) = 1 \]
Summary

• The porous media approach was applied to three ET SOFI materials.
• The Anisotropic CTE tensors were derived to provide with good results for the strain variation as a function of temperature in vacuum.
• A high temperature CTE was derived based on TGA data showing an in-plane negative CTE.
• The implementation of the porous media into ABAQUS was outlined.
• The stress distribution of the cryoflex specimens were determined for the immersion and gradient tests.
• The maximum stress calculated was inconsistent with the experimentally observed failures.

Future Work

• Investigate the soundness of a negative in-plane CTE for BX-265
• Develop a failure criteria for the cryoflex specimen based on the experimental observation and FEA results