A Micromechanics Finite Element Model for Studying the Mechanical Behavior of Spray-On Foam Insulation (SOFI)

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Proposed Abstract for the
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A micromechanics model has been constructed to study the mechanical behavior of spray-on foam insulation (SOFI) for the external tank. The model was constructed using finite elements representing the fundamental repeating unit of the SOFI microstructure. The details of the micromechanics model were based on cell observations and measured average cell dimensions discerned from photomicrographs. The unit cell model is an elongated Kelvin model (fourteen-sided polyhedron with 8 hexagonal and six quadrilateral faces), which will pack to a 100% density. The cell faces and cell edges are modeled using three-dimensional 20-node brick elements. Only one-eighth of the cell is modeled due to symmetry.

By exercising the model and correlating the results with the macro-mechanical foam behavior obtained through material characterization testing, the intrinsic stiffness and Poisson's Ratio of the polymeric cell walls and edges are determined as a function of temperature. The model is then exercised to study the unique and complex temperature-dependent mechanical behavior as well as the fracture initiation and propagation at the microscopic unit cell level.
A Micromechanics Finite Element Model for Studying the Mechanical Behavior of Spray-On Foam Insulation

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Micrographs of the Three Major NASA’s SOFI Materials

BX-265

PDL

NCFI
Classical Three-Dimensional Polyhedral Cells

Hexagonal Prism
8 faces, 18 edges
Packs to fill volume

Octahedron
8 faces, 12 edges

Rhombic dodecahedron
12 faces, 24 edges
Packs to fill volume

Pentagonal Dodecahedron
12 faces, 30 edges

Tetrakaidecahedron
14 faces, 36 edges
Packs to fill volume

Icosahedron
20 faces, 30 edges
• Average Cell Length (parallel to rise) – 218 μm
• Average Cell Width (perpendicular to rise) – 124 μm
  • Average measured # of faces = 12.4
  • Observed elongated cell structure
• Cells consist of thick edges and thin faces
Assumed Elongated Tetrakaidecahedron
BX-265

Packs to fill Volume

- $l_1 = 109 \, \mu m$
- $l_2 = 69 \, \mu m$
- $l_3 = 39 \, \mu m$
- $l_4 = 28 \, \mu m$

Rise Direction

218 $\mu m$

124 $\mu m$
BX-265 Cell Dimensions

- Edges are solid, triangular beams.

Triangular edges are 17 μm in width with average radii of 18 μm

Faces are thin membranes 0.1<t<1.0 μm
Symmetry

Top View
Normal to Rise

Cell Aspect Ratio
(Cell Length/Cell Width)

Rectangular section

Cell Length

Side View
Rise/In-plane

Square section

Cell Width
Finite Element Mesh for 1/8th Symmetry
Finite Element Mesh for 1/8th Symmetry

15195 Nodes
2948 21-Node Brick Elements
wall thickness 0.5 μm
17 μm triangular edges
with 18 μm radii of curvatures

Rise Direction

Half Wall Thickness
Fix in X
Full Wall Thickness

Fix in Y

Half Wall Thickness

Fix in Z
Along the bottom
Maximum Principal Stress for loading in the rise direction

BX-265

MSC.Ptran 2005 r2 08-Aug-06 17:43:07
Fringe: Static, Step2, TotalTime=3.5_2, Stress, Components, Max Principal, (NON-LAYERED)
Deform: Static, Step2, TotalTime=3.5_2, Deformation, Displacements, (NON-LAYERED)

Loading direction
In
Rise Direction
0.31 MPa applied Stress in Z

Poisson’s Effect

default_Fringe:
Max 38.54 @Nd 14338
Min .0207 @Nd 10835
default_Deformation:
Max 4.92-03 @Nd 11168
Maximum Principal Stress for in-plane loading
BX-265

MSC.Patran 2005 r2 08–Aug–06 17:35:35
Fringe: Static, Step2, TotalTime=3.5, Stress, Components, Max Principal, (NON=LAYERED)
Deform: Static, Step2, TotalTime=3.5, Deformation, Displacements.

In-Plane Loading direction
0.31 MPa applied stress in X

Poisson’s Effect

MPa

X

Y

Z
Calibration of BX-265 Stress/Strain Curve

BX-265 @ room temperature

Experimental data courtesy of LMSSC External Tank Return to Flight, Fracture Toughness: Phase 2 (Kristin Morgan)
Effects of Solid Poisson’s’ Ratio on the Foam Stress/Strain Curve

BX-265 @ room temperature

Solid Poisson’s Ratios
0.2/0.3/0.4

Rise Direction

2.11 (Numerical Calibrated Cell Aspect Ratio)
Solid Poisson’s Ratio 0.3, E_s = 2.0GPa

Experimental data courtesy of LMSSC External Tank Return to Flight, Fracture Toughness: Phase 2 (Kristin Morgan)
Calibration of BX-265 Stress/Strain Curve (-320 F)

BX-265 @ -195.6 C

- Rise Direction
- y = 39.892x
- y = 10.974x
- in-plane
- Solid Poisson’s Ratio 0.3, $E_s = 4.4$ GPa

Experimental data courtesy of LMSSC External Tank Return to Flight, Fracture Toughness: Phase 2 (Kristin Morgan)
Calibration of BX-265 Stress/Strain Curve (-420 F)

BX-265 @ -251 C

Rise Direction

\[ y = 39.892x \]

in-plane

\[ y = 10.974x \]

2.11 (Numerical Calibrated Cell Aspect Ratio)
Solid Poisson’s Ratio 0.3, \( E_s = 4.4 \text{GPa} \)

Experimental data courtesy of LMSSC External Tank Return to Flight, Fracture Toughness: Phase 2 (Kristin Morgan)
Calibration of NCFI Stress/Strain Curve (RT)

NCFI-24-124 @ room temperature

\[ y = 20.796x \]

\[ y = 4.5269x \]

Rise Direction

in-plane

2.36 (Numerical Calibrated Cell Aspect Ratio)
Solid Poisson’s Ratio 0.3, \( E_s = 2.0 \text{GPa} \)

Strain, mm/mm

Stress, MPa

Experimental data courtesy of LMSSC External Tank Return to Flight, Fracture Toughness: Phase 2 (Kristin Morgan)
Calibration of NCFI Stress/Strain Curve (-320 F)

**NCFI-24-124 @ -195.6 C**

- **y = 45.752x**
- **y = 9.9588x**

**Rise Direction**

- 33-Min
- 33-Mid
- 33-Max
- 11-Min
- 11-Mid
- 11-Max

In-plane

2.36 (Numerical Calibrated Cell Aspect Ratio)
Solid Poisson’s Ratio 0.3, $E_s = 4.4GPa$

Experimental data courtesy of LMSSC External Tank Return to Flight, Fracture Toughness: Phase 2 (Kristin Morgan)
Calibration of NCFI Stress/Strain Curve (-420 F)

NCFI-24-124 @ -251 C

Stress, MPa vs. Strain, mm/mm

In-plane:
y = 9.959x

Rise Direction:
y = 45.752x

2.36 (Numerical Calibrated Cell Aspect Ratio)
Solid Poisson’s Ratio 0.3, E_s = 4.4GPa

Experimental data courtesy of LMSSC External Tank Return to Flight, Fracture Toughness: Phase 2 (Kristin Morgan)
Calibration of PDL Stress/Strain Curve (RT)

PDL-1034 @ room temperature

\[ y = 12.741x \]
\[ y = 19.985x \]

Stress, MPa

Strain, mm/mm

Rise Direction

in-plane

Experimental data courtesy of LMSSC External Tank Return to Flight, Fracture Toughness: Phase 2 (Kristin Morgan)
Calibration of PDL Stress/Strain Curve (-320 F)

PDL-1034 @ -195.6 C

Stress, MPa

Strain, mm/mm

Rise Direction

y = 39.255x

y = 25.026x

1.25 (Numerical Calibrated Cell Aspect Ratio)
Solid Poisson’s Ratio 0.3, $E_s = 2.75$ GPa

Experimental data courtesy of LMSSC External Tank Return to Flight, Fracture Toughness: Phase 2 (Kristin Morgan)
Calibration of PDL Stress/Strain Curve (-420 F)

PDL-1034 @ -251 C

- **Rise Direction**
  - $y = 49.961x$
  - $y = 31.852x$

- **in-plane**

1.25 (Numerical Calibrated Cell Aspect Ratio)
Solid Poisson’s Ratio 0.3, $E_s = 3.5$ GPa

Experimental data courtesy of LMSSC External Tank Return to Flight, Fracture Toughness: Phase 2 (Kristin Morgan)
<table>
<thead>
<tr>
<th></th>
<th>Length (μm)</th>
<th>Width (μm)</th>
<th>Aspect Ratio</th>
<th>Poisson's Ratio</th>
<th>Modulus, $E_s$ (GPa) @ -195.6°C</th>
<th>Modulus, $E_s$ (GPa) @ -195.6°C</th>
<th>Modulus, $E_s$ (GPa) @ RT</th>
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<tbody>
<tr>
<td><strong>Calibrated</strong></td>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>BX-265</td>
<td>262</td>
<td>124</td>
<td>2.11</td>
<td>0.3</td>
<td>2.0</td>
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<td>NCFI</td>
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<td>100</td>
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<td>PDL</td>
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<td>0.3</td>
<td>1.4</td>
<td>2.75</td>
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<td><strong>Measured</strong></td>
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</tr>
<tr>
<td>BX-265</td>
<td>218</td>
<td>124</td>
<td>1.76</td>
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</tr>
</tbody>
</table>

## Foam Effective Elastic Properties

### BX-265

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>E11 (MPa)</th>
<th>E22 (MPa)</th>
<th>E33 (MPa)</th>
<th>$\nu_{12}$</th>
<th>$\nu_{13}$</th>
<th>$\nu_{23}$</th>
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</thead>
<tbody>
<tr>
<td>-251</td>
<td>10.97</td>
<td>10.97</td>
<td>39.89</td>
<td>0.488</td>
<td>0.143</td>
<td>0.143</td>
</tr>
<tr>
<td>-196</td>
<td>10.97</td>
<td>10.97</td>
<td>39.89</td>
<td>0.488</td>
<td>0.143</td>
<td>0.143</td>
</tr>
<tr>
<td>24</td>
<td>4.99</td>
<td>4.99</td>
<td>18.13</td>
<td>0.488</td>
<td>0.143</td>
<td>0.143</td>
</tr>
</tbody>
</table>

### NCFI

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>E11 (MPa)</th>
<th>E22 (MPa)</th>
<th>E33 (MPa)</th>
<th>$\nu_{12}$</th>
<th>$\nu_{13}$</th>
<th>$\nu_{23}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-251</td>
<td>9.96</td>
<td>9.96</td>
<td>45.75</td>
<td>0.528</td>
<td>0.114</td>
<td>0.114</td>
</tr>
<tr>
<td>-196</td>
<td>9.96</td>
<td>9.96</td>
<td>45.75</td>
<td>0.528</td>
<td>0.114</td>
<td>0.114</td>
</tr>
<tr>
<td>24</td>
<td>4.53</td>
<td>4.53</td>
<td>20.80</td>
<td>0.528</td>
<td>0.114</td>
<td>0.114</td>
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</table>

### PDL

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>E11 (MPa)</th>
<th>E22 (MPa)</th>
<th>E33 (MPa)</th>
<th>$\nu_{12}$</th>
<th>$\nu_{13}$</th>
<th>$\nu_{23}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-253</td>
<td>31.85</td>
<td>31.85</td>
<td>49.96</td>
<td>0.362</td>
<td>0.249</td>
<td>0.249</td>
</tr>
<tr>
<td>-196</td>
<td>25.03</td>
<td>25.03</td>
<td>39.26</td>
<td>0.362</td>
<td>0.249</td>
<td>0.249</td>
</tr>
<tr>
<td>24</td>
<td>12.74</td>
<td>12.74</td>
<td>19.99</td>
<td>0.362</td>
<td>0.249</td>
<td>0.249</td>
</tr>
</tbody>
</table>
UTS of NCFI at RT

NCFI 24-124: Round 7" Dogbone Specimen

- **Rise**
  - Average UTS at SATP = 0.42 MPa
  - Average UTS under vacuum = 0.45 MPa

- **In-Plane**
  - Average UTS at SATP = 0.185 MPa
  - Average UTS under vacuum = 0.137 MPa

Exp. data courtesy of Kristin Morgan

Symbols data LMSSC External Tank Return to Flight, Fracture Toughness: Phase 2 (Kristin Morgan)
Maximum Principal Stress for loading in the rise direction
NCFI (1 atm)

Unit Cell Loading In Rise Direction

Rise at 1-atm @ 0.42 MPa applied stress

MSC.Patran 2005 r2 29-Jun-06 10:34:06
Fringe: Static, Step2, Total Time = 2, Stress, Components, Max Principal, (NON-LAYERED)

163 MPa (23.6Ksi)
Maximum Principal Stress for loading in the in-plane direction 
NCFI (1 atm)

Unit Cell Loading In-Plane direction

182 MPa (26.4 Ksi)

In-Plane 1-atm @ 0.186 MPa external load
Maximum Principal Stress for loading in the rise direction

NCFI (Vacuum Test)

Unit Cell Loading In Rise Direction

Rise mid-cell in vacuum @ 0.45 MPa external load

205 MPa (29.7Ksi)
Maximum Principal Stress for loading in the rise direction
NCFI (Vacuum Test)

141 MPa
(20.5 Ksi)

Unit Cell
Loading
In-Plane direction
vacuum

In-Plane mid-cell in vacuum
@ 0.127 MPs external load
<table>
<thead>
<tr>
<th>NCFI, UTS</th>
<th>Applied Stress</th>
<th>Max. Principal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa</td>
<td>MPa</td>
</tr>
<tr>
<td>Rise</td>
<td>SATM</td>
<td>0.42</td>
</tr>
<tr>
<td>In-Plane</td>
<td>SATM</td>
<td>0.186</td>
</tr>
<tr>
<td>Rise</td>
<td>Vacuum</td>
<td>0.45</td>
</tr>
<tr>
<td>In-Plane</td>
<td>Vacuum</td>
<td>0.127</td>
</tr>
</tbody>
</table>

Loading in Rise Direction
Without cell walls (Open Cell)

Max. Principal, 443MPa
Open Cell Structure For Failure Analysis

$2L_2 \sin \theta$

$\sqrt{2L_2 \cos \theta + L_4}$

Simplify model (Only Edges)

In-Plane
Equilibrium and Structural Analysis of Frames yields

\[ N = \sigma_{zz} \sin \theta \left[ \frac{\sqrt{2} L_2 \cos \theta + L_4}{2} \right]^2 \]

\[ M = \sigma_{zz} L_2 \cos \theta \left[ \frac{\sqrt{2} L_2 \cos \theta + L_4}{4} \right]^2 \]

\[ N = \sigma_{yy} L_2 \cos \theta \sin \theta \left[ 2 L_2 \cos \theta + \sqrt{2} L_4 \right] \]

\[ M = \frac{\sigma_{yy} L_2^2 \sin^2 \theta \left[ 2 L_2 \cos \theta + \sqrt{2} L_4 \right]}{2} \]
Strength of Materials approach for calculating the maximum stress at the outer fiber of an axial and flexural of the edges

\[
\sigma_{\text{max}} = \frac{N}{A} + \frac{Mr}{I}
\]

Where
- \( A \) = edge x-area
- \( I \) = edge moment of Inertia
- \( r \) = distance to outer fiber

Leads to the relation between the maximum stress in the struts and the average applied stress in the z and y directions:

\[
\sigma_{zz} = \frac{\sigma_{\text{max}}}{\sin \theta + \frac{L_2 r \cos \theta}{2A} \left(\sqrt{2}L_2 \cos \theta + L_4\right)^2}
\]
\[
\sigma_{yy} = \frac{\sigma_{\text{max}}}{\frac{L_2 \cos \theta \sin \theta}{A} + \frac{L_2 r \sin^2 \theta}{2I} \left(2L_2 \cos \theta + \sqrt{2}L_4\right)}
\]

Calculating the average cell strain and stress can also lead to determining the effective cell modulus in two directions:

\[
E_z = \frac{24EI \sin \theta}{L_2^2 \cos^2 \theta + \frac{12I \sin^2 \theta}{AL_2^2} \left(\sqrt{2}L_2 \cos \theta + L_4\right)^2}
\]
\[
E_y = \frac{12EI}{2L_2^3 \sin^2 \theta + L_4^3 + \frac{12I}{A} \left(2L_2 \cos^2 \theta + L_4\right) L_2 \sin \theta}
\]
Ratio of the Stiffness in the z- and y-directions is

\[
\frac{E_z}{E_y} = \frac{2\sin^2 \theta \left( 2L_2 \sin^2 \theta + L_4^3 + \frac{12I}{A} \left( 2L_2 \cos^2 \theta + L_4 \right) \right)}{L_2 \left[ \cos^2 \theta + \frac{12I}{AL_2^2} \right] \left[ \sqrt{2L_2 \cos \theta + L_4} \right]^2}
\]

Assuming \( L_2 \) and \( L_4 \) are 69 \( \mu m \) and 28 \( \mu m \), respectively, we can plot the stiffness ratio versus inclination angle.

Measured stiffness ratio for BX-265 at room temperature

\[
\frac{E_z}{E_y} = \frac{18MPa}{5MPa} = 3.6
\]

Strut cross-section has small influence on stiffness ratio versus inclination angle

Results indicate that the inclination angle for BX-265 is \( \sim 55^\circ \)
Ratio of strengths in z- and y-directions is

\[
\frac{\sigma_z}{\sigma_y} = \frac{4L_2 \sin \theta \left[ 2I \cos \theta + L_2 rA \sin \theta \right]}{\left[ 2I \sin \theta + L_2 rA \cos \theta \right] \left[ 2L_2 \cos \theta + \sqrt{2L_4} \right]}
\]

From experimental tensile test specimen the measured ratio of the rise to in-plane strengths is approximately 1.6.

Results indicate that the inclination angle is 47°
Substituting $L_2$, $L_4$, and the inclination angle into the previous equations for foam modulus and foam strengths and solving for the polymer (strut) modulus and polymer (strut) strengths, we get

<table>
<thead>
<tr>
<th></th>
<th>Polymer (Strut) Modulus, MPa (ksi)</th>
<th>Polymer (Strut) Strength, MPa (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Using $\theta = 55^\circ$</td>
<td>Using $\theta = 47^\circ$</td>
</tr>
<tr>
<td><strong>Circular x-section</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R=5 \ \mu m$</td>
<td>21,500 (3,120)</td>
<td>603 (87.5)</td>
</tr>
<tr>
<td>$R=10 \ \mu m$</td>
<td>1,450 (210)</td>
<td>76 (11)</td>
</tr>
<tr>
<td>$R=20 \ \mu m$</td>
<td>111 (16)</td>
<td>10 (1.5)</td>
</tr>
<tr>
<td><strong>Triangular x-section</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$h=17 \ \mu m$</td>
<td>7,300 (1,059)</td>
<td>393 (57)</td>
</tr>
</tbody>
</table>
Summary

• SOFI microstructure were successfully modeled as elongated Tetrakaidecahedron closed cell
• Elastic modulus and Poisson’s ratios were estimated from the unit cell model
• The estimation of the polymer solid strength and stiffness was attempted by FEA and Frame models.
• Frame model yields similar results as the finite element model if a circular cross-section with a radius of 10 mm is used.

Future Work

• Refine the FEA model (Nonlinearity) to improve on the failure stress estimates
• Review the modeling of a unit cell in vacuum