FINITE ELEMENT ANALYSIS OF ELASTOMERIC SEALS FOR LIDS

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Finite Element Analysis of Elastomeric Seals for LIDS

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Objectives & Motivation

Objective
• Create a means of evaluating seals w/o prototypes

Motivation
• Cost
  – Prototype 54” seal ~$100k per seal pair
  – FEA license + high end workstation ~ $30k per year
• Development time
  – 6 months lead time for a new seal design
  – Many designs per day (solution time <1 minute)
• Understanding
  – Difficult to experimentally measure strains, contact pressure profile, stresses, displacements
Part I

Hyperelastic Material Modeling
Special Properties of Hyperelastic Materials

- Fully or nearly incompressible
  - Bulk modulus typically 100-1000x shear modulus
  - Poisson's ratio approaches 0.5
- Problems in displacement-based FEA formulation
- Requires B-bar or mixed u-P formulation
- Huge elastic range of deformation
  - Strains > 80% are (mostly) recoverable
- Analysis should account for nonlinear geometry and material properties
Hyperelasticity vs. Linear Elasticity

**Linear elasticity:**
\[ W = c \varepsilon : \varepsilon \]

(which is like: \( E = \frac{1}{2} k \Delta x^2 \))

**Hyperelasticity:**
\[ W = f(I_1, I_2, I_3) \]

or \( W = f(\lambda_1, \lambda_\text{II}, \lambda_\text{III}) \)

\[ \sigma_{ij} = \frac{\partial W}{\partial \varepsilon_{ij}} \]

Definition of second Piola-Kirchhoff stress from strain energy density and Green-Lagrange strain

\[ I_1 = \lambda_1^2 + \lambda_\text{II}^2 + \lambda_\text{III}^2 \]

\[ I_2 = \lambda_1^2 \lambda_\text{II}^2 + \lambda_\text{II}^2 \lambda_\text{III}^2 + \lambda_\text{III}^2 \lambda_\text{II}^2 \]

\[ I_3 = \lambda_1^2 \lambda_\text{II}^2 \lambda_\text{III}^2 = 1 + \left( \frac{\Delta V}{V} \right)^2 = J^2 \]

\( \lambda_1, \lambda_\text{II}, \lambda_\text{III} \) : principal stretch ratios

\( I_1, I_2, I_3 \) : strain invariants

\( J \) : Jacobian (volume ratio)
Some forms of the work function

Polynomial models: (Mooney-Rivlin, Neo-Hookean)

\[ W = \sum_{i+j=1}^{N} C_{i,j} (I_1 - 3)^i (I_2 - 3)^j + \sum_{k=1}^{N} \frac{1}{d_k} (J - 1)^{2k} \]

Yeoh model: \( j=0 \), neglects second strain invariant

- For plane strain Yeoh is equivalent to general polynomial form because \( I_1 = I_2 \)

Comparison of lowest order terms for a 50 durometer material

\[ 1/d_1 \approx 200,000 \quad c_{1,0} \approx 40 \]
Constraints on the work function

Zero strain must have zero energy \((W(0) = 0)\)
Zero strain must have zero stress \((W'(0) = 0)\)
Second derivative must be positive \((W''(\varepsilon) > 0 \text{ for all } \varepsilon)\)
Determining $W$

- Fit $W$ to experimental stress-strain states
  - Three basic strain modes
    - Uniaxial tension
    - Biaxial tension
    - Planar tension
  - All deformation falls between uniaxial and biaxial – ($I_3 = 1 \rightarrow$ incompressible)

Energy density function of a hyperelastic material
Basic strain states of a nearly incompressible material

<table>
<thead>
<tr>
<th>Load</th>
<th>Strain</th>
<th>Stretch Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniaxial</td>
<td><img src="image1" alt="Uniaxial Load" /> <img src="image2" alt="Uniaxial Strain" /></td>
<td>$\lambda_1 = \frac{1}{\lambda_{II}^2} = \frac{1}{\lambda_{III}^2}$</td>
</tr>
<tr>
<td>Biaxial</td>
<td><img src="image3" alt="Biaxial Load" /> <img src="image4" alt="Biaxial Strain" /></td>
<td>$\lambda_1 = \lambda_{II} = \frac{1}{\sqrt{\lambda_{III}}}$</td>
</tr>
<tr>
<td>Planar</td>
<td><img src="image5" alt="Planar Load" /> <img src="image6" alt="Planar Strain" /></td>
<td>$\lambda_1 = \frac{1}{\lambda_{II}}, \lambda_{III} = 1$</td>
</tr>
<tr>
<td>Volumetric</td>
<td><img src="image7" alt="Volumetric Load" /> <img src="image8" alt="Volumetric Strain" /></td>
<td>$\lambda_1 = \lambda_{II} = \lambda_{III} &lt; 1$</td>
</tr>
</tbody>
</table>
Material Tests Performed

- **Materials**: XELA-SA-401, S0899-50, S0383-70
  - 40, 50, 70 durometer hardness

- **Test parameters**
  - Various temperatures
    - -50, 23, 50, & 125 ºC
  - 3 specimens per test
  - Uniaxial, planar, biaxial tension & volumetric
    - 20, 40, 60, 80 % strain increments

- **Other properties**:  
  - Coefficient of friction (elastomer on elastomer), thermal conductivity, heat capacity, density, emissivity, absorptivity

This data will be published soon in a NASA technical publication.
Data Processing

1 – select cycle from set
2 – subtract offset strain
3 – subtract offset stress
4 – average and decimate
Processed Material Data

Uncertainty based off student’s t distribution from multiple specimens

Results can be curve fitted to determine material property constants

This can be done as a function of temperature

The strain energy density is the area under the curve for each deformation

Processed data from 40 durometer elastomer (-50 °C )
Part II

Finite Element Analysis of Seals
Hints for Elastomeric FEA

1) Stay away from triangular elements
   • Elements with 2 displacement BC will have only 1 degree of freedom due to incompressibility

2) Low order elements converge easiest 4-node brick works well

3) Sliding contact may require non-symmetric stiffness matrices for large friction coefficients

4) Watch corners for element distortion

5) u-P element formulation is most stable

6) Check for stability of material models

Severe element edge distortion
Analyses did not converge
Types of FEA models of LIDS seals

Aligned seal – contact pressure

Tolerance studies

Misaligned seal
Principal strains

Gaskoseal adhesion analysis with cohesive elements at contact
Seal Thermal Analyses

- CTE of elastomers is very high
  - 350×10^{-6} °C^{-1}
  - Al: 24×10^{-6} °C^{-1}

Comparison of compression at 25°C (front) and 125°C (back). Contours are axial stress.

Y displacement of seals with 100°C rise in temperature, black outline indicates original geometry.
Summary

• Need 4 experimental strain states to
  – choose energy density function
  – fit material constants
  – determine compressibility of material

• Hyperelastic material present new challenges

• FEA analyses for LIDS
  – Force vs. displacement and pressure contours
    • Aligned & misaligned cases
  – Thermal expansion
  – Tolerance studies
  – Adhesion analysis
Further reading/information

• ANSYS gives excellent background for element technology/hyperelasticity
  – Nonlinear element technology
    • http://www.ansys.com/assets/tech-papers/nonlinear-element-tech.pdf
  – Hyperelasticity
    • http://www.tsne.co.kr/board/download.asp?strFileName=conflong_hyperel.pdf&dr=ansys

• Future publications of material properties, analysis, etc. will be posted on
  http://www.grc.nasa.gov/WWW/structuralseal