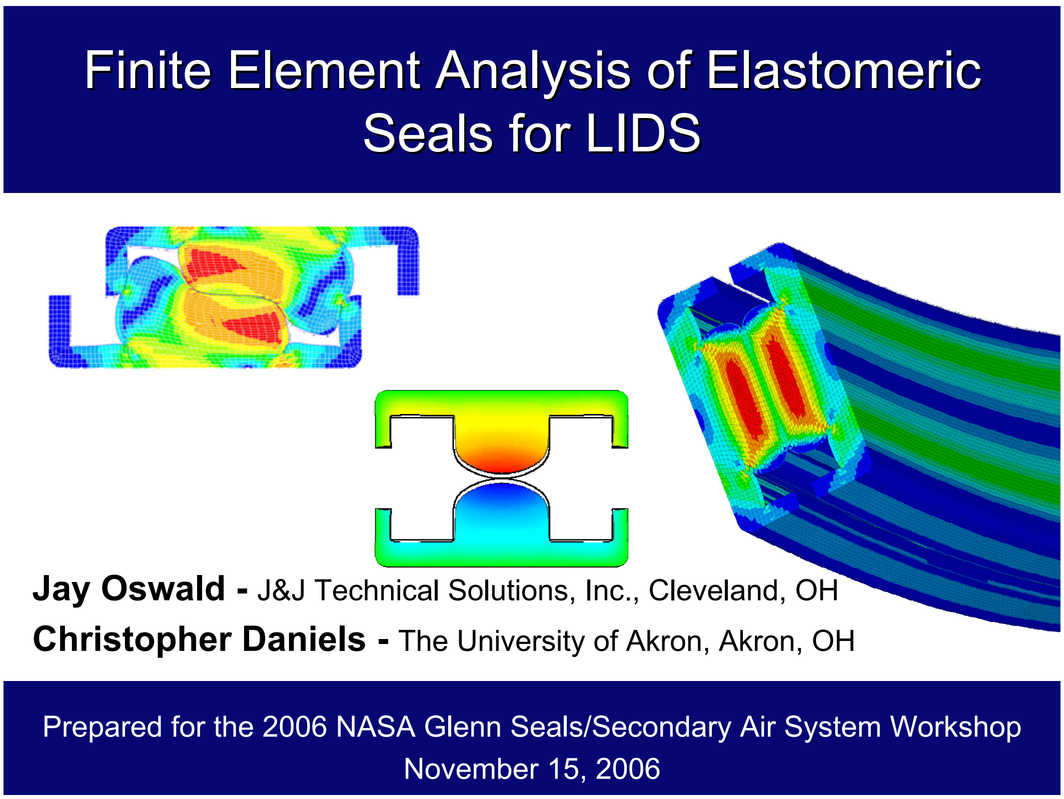
FINITE ELEMENT ANALYSIS OF ELASTOMERIC SEALS FOR LIDS

Jay J. Oswald
J&J Technical Solutions, Inc.
Cleveland, Ohio

Christopher C. Daniels
University of Akron
Akron, Ohio



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:

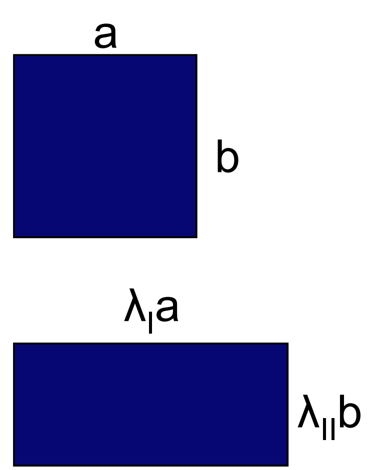
W = cε:ε

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

Hyperelasticity:

W = f(I_1,I_2,I_3)

or **W = f(λ_I, λ_{II}, λ_{III})**



$$\sigma_{ij} = \frac{\partial W}{\partial \varepsilon_{ij}}$$

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

$$I_1 = \lambda_I^{\,2} + \lambda_{II}^{\,2} + \lambda_{III}^{\,2}$$

$$I_2 = \lambda_I^{\,2}\lambda_{II}^{\,2} + \lambda_{II}^{\,2}\lambda_{III}^{\,2} + \lambda_{III}^{\,2}\lambda_{II}^{\,2}$$

$$I_3 = \lambda_I^{\,2}\lambda_{II}^{\,2}\lambda_{III}^{\,2} = 1 + \left(\frac{\Delta V}{V}\right)^2 = J^2$$

$\lambda_I, \lambda_{II}, \lambda_{III}$: 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)

$$W = \sum_{i+j=1}^{N} C_{ij} \left(\bar{I}_1 - 3\right)^i \left(\bar{I}_2 - 3\right)^j + \sum_{k=1}^{N} \frac{1}{d_k} \left(J - 1\right)^{2k}$$

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

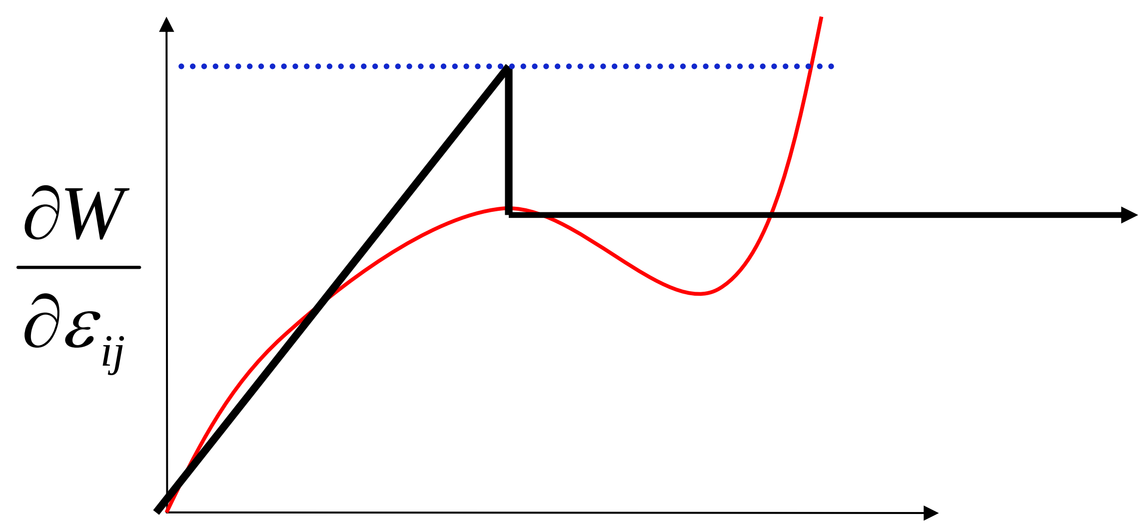
$1/d_1 \approx 200{,}000$ $\qquad$ $c_{1,0} \approx 40$

Constraints on the work function

Zero strain must have zero energy ($W(0) = 0$)

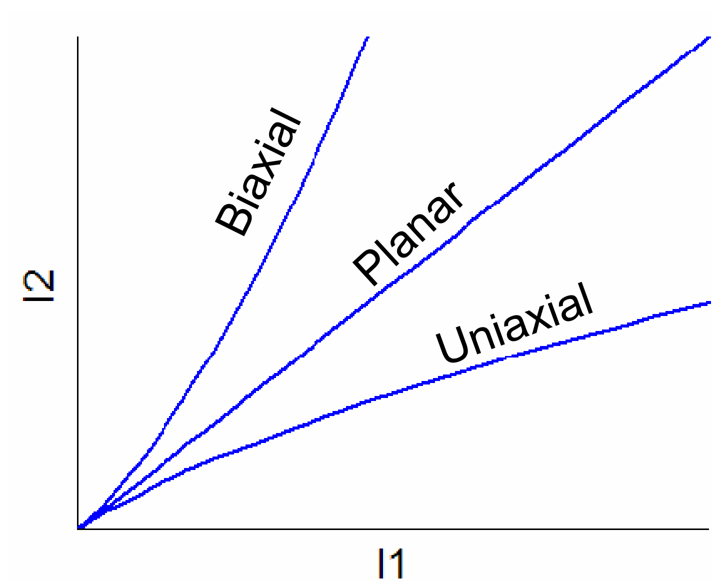
Zero strain must have zero stress ($W'(0) = 0$)

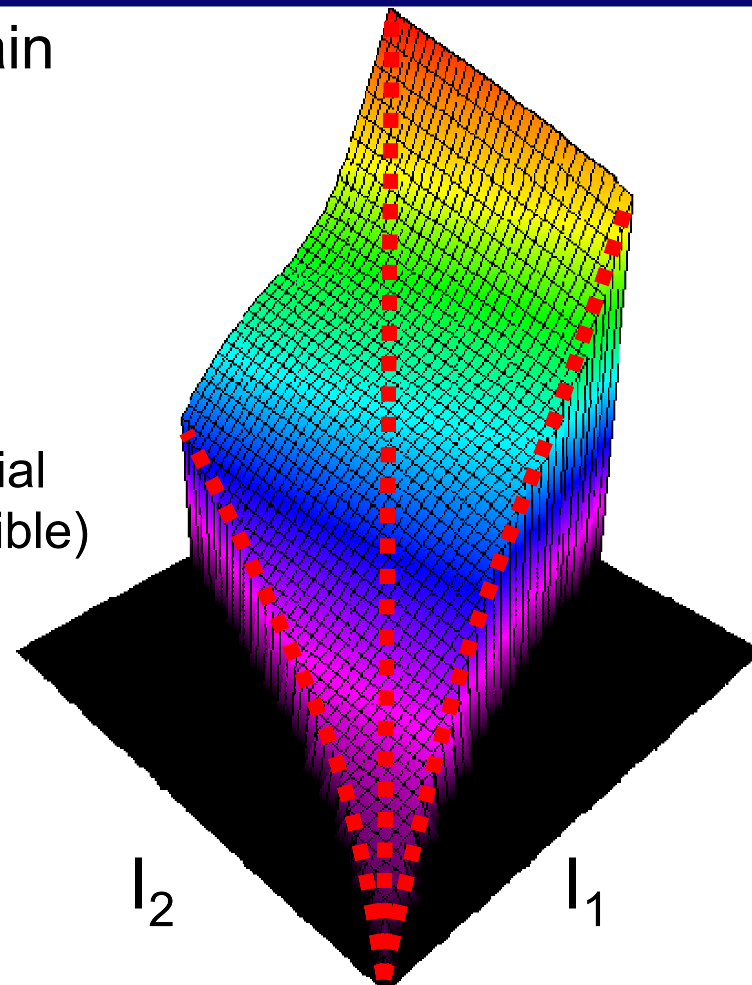
Second derivative must be positive ($W''(\varepsilon) > 0$ for all ε)



Determining W

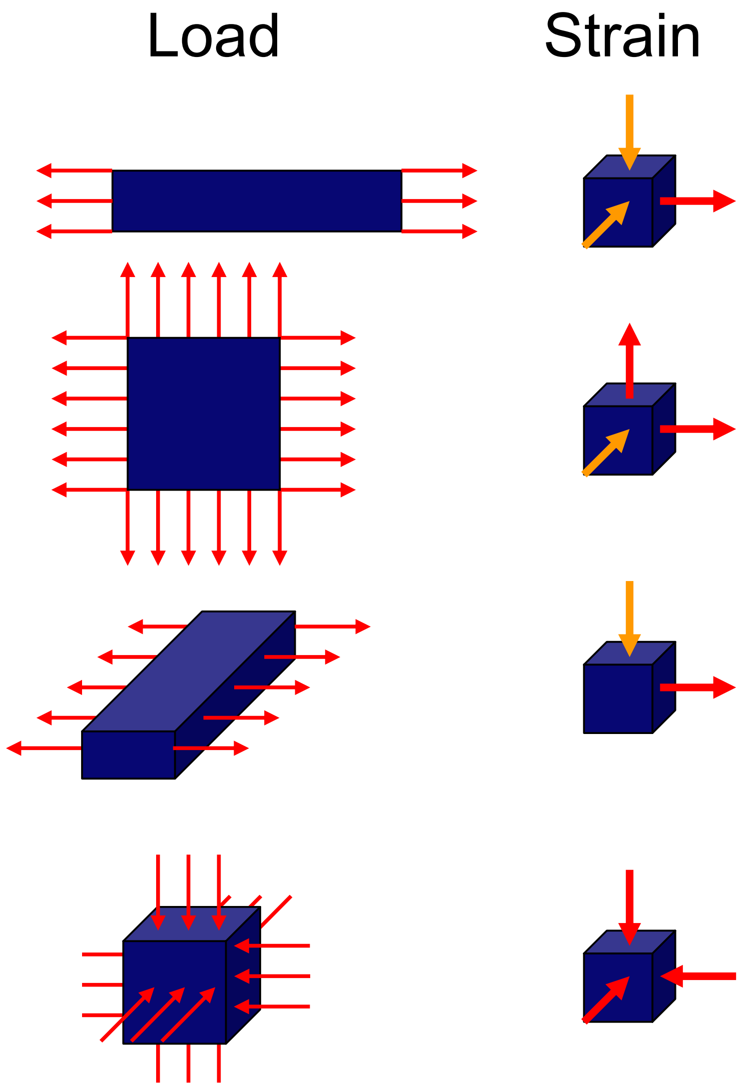
- Fit W to experimental stress-strain states
  - Three basic strain modes
    - Uniaxial tension
    - Biaxial tension
    - Planar tension
  - All deformation falls between uniaxial and biaxial – (I3 = 1 → incompressible)





Energy density function of a hyperelastic material

Basic strain states of a nearly incompressible material



	Stretch Ratios
Uniaxial	$\lambda_I = \frac{1}{\lambda_{II}^2} = \frac{1}{\lambda_{III}^2}$
Biaxial	$\lambda_I = \lambda_{II} = \frac{1}{\sqrt{\lambda_{III}}}$
Planar	$\lambda_I = \frac{1}{\lambda_{II}}, \lambda_{III} = 1$
Volumetric	$\lambda_I = \lambda_{II} = \lambda_{III} < 1$

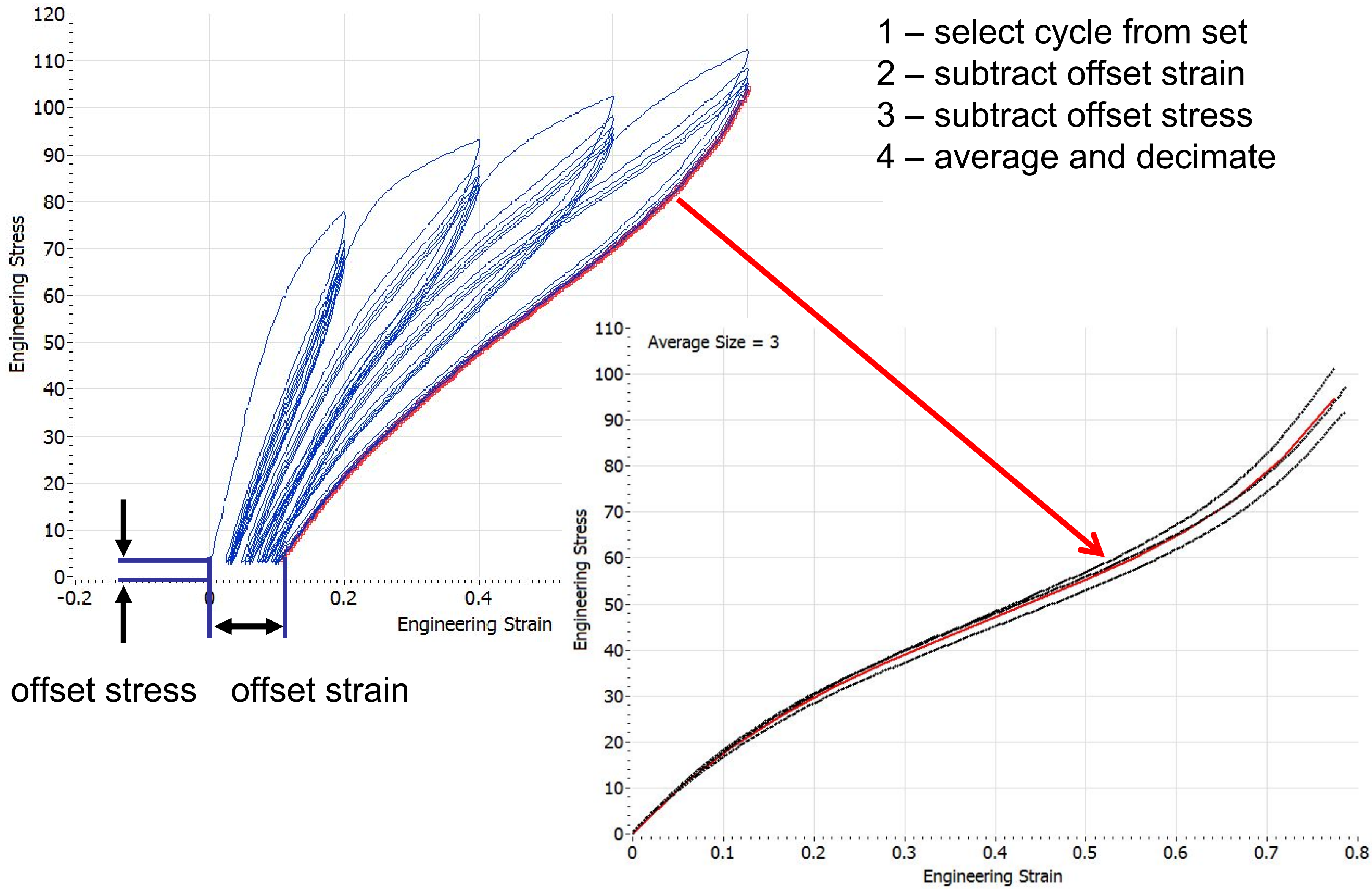
Material Tests Performed

- 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

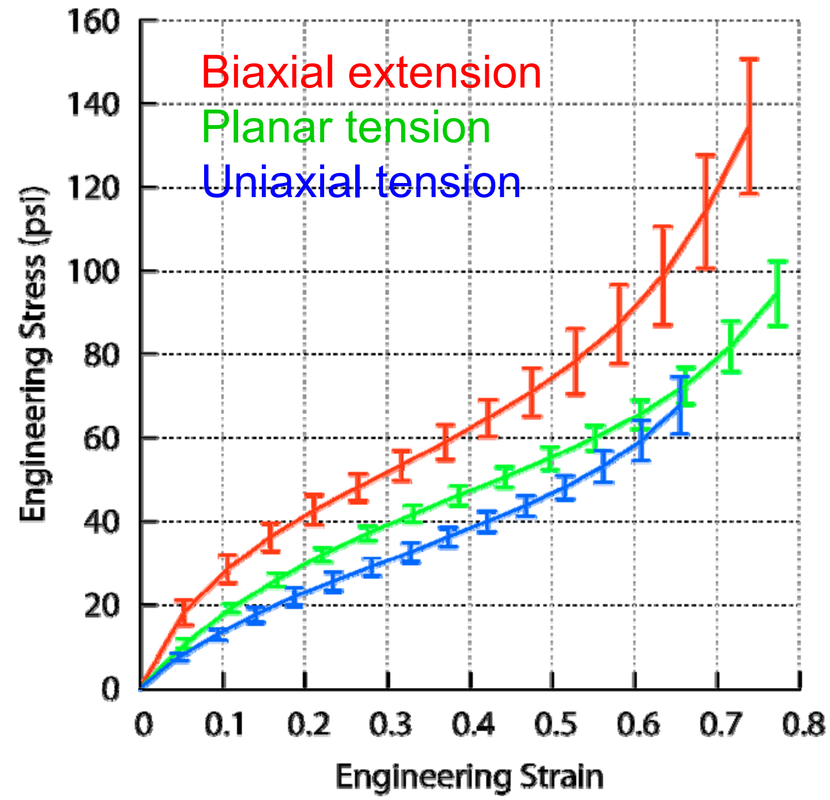
Data Processing

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



Processed data from 40 durometer elastomer (-50 ºC)

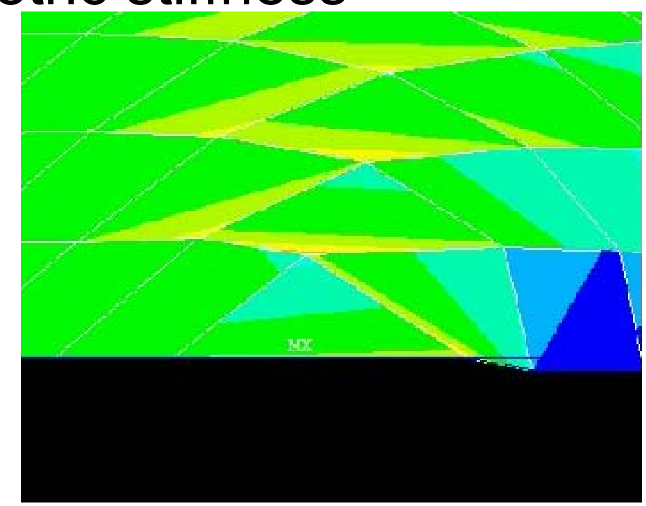
The strain energy density is the area under the curve for each deformation

Part II

Finite Element Analysis of Seals

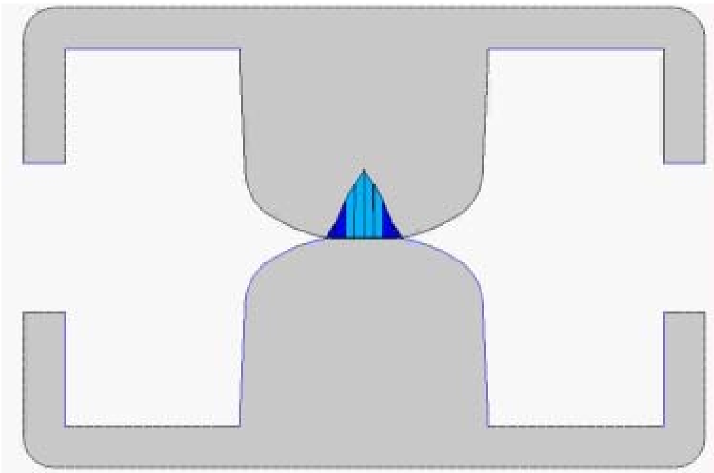
Hints for Elastomeric FEA

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

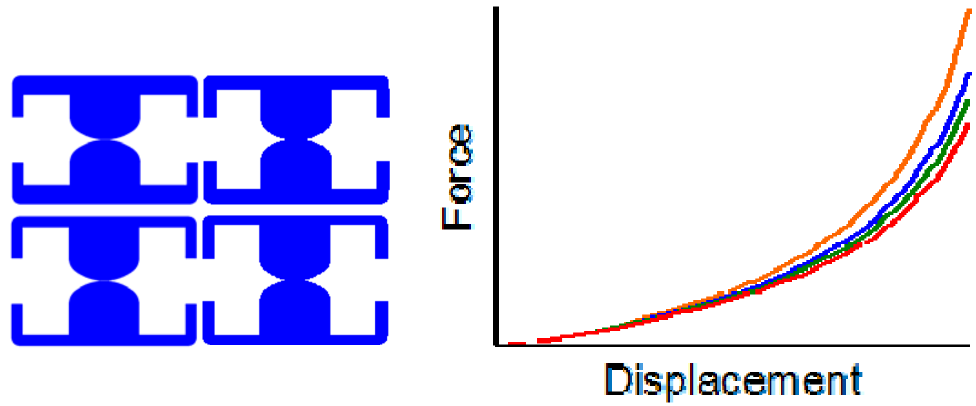


Severe element edge distortion
Analyses did not converge

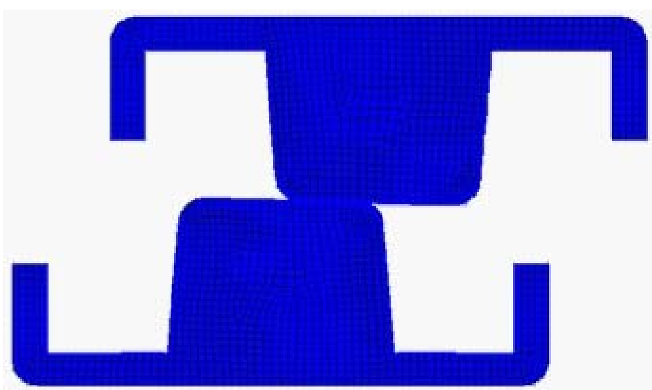
Types of FEA models of LIDS seals



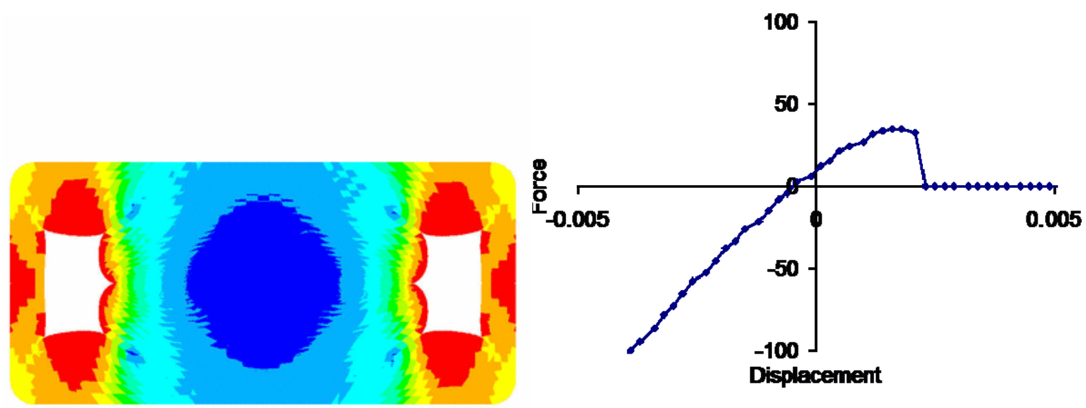
Aligned seal – contact pressure



Tolerance studies



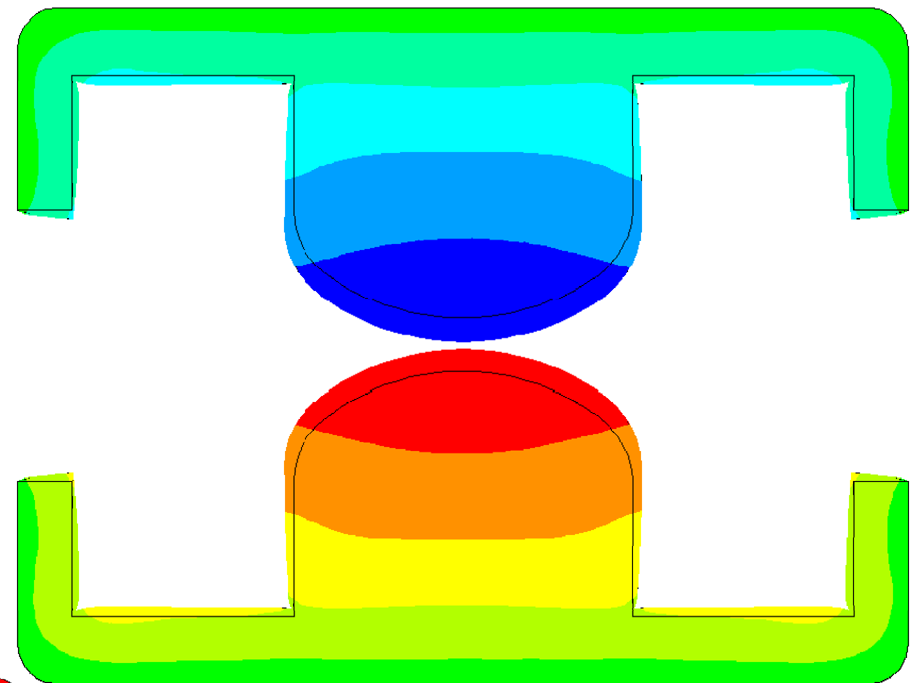
Misaligned seal
Principal strains



Gaskoseal adhesion analysis with
cohesive elements at contact

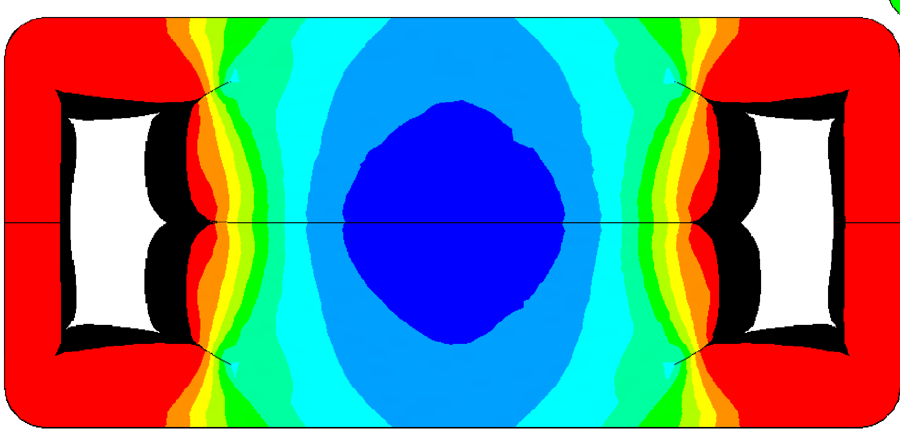
Seal Thermal Analyses

- CTE of elastomers is very high
  - $350 \times 10^{-6}\ ^{o}C^{-1}$
  - Al: $24 \times 10^{-6}\ ^{o}C^{-1}$



Y displacement of seals with 100ºC rise in temperature, black outline indicates original geometry

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



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