FEA of Elastomers and Gaskets in ABAQUS
Tod Dalrymple
HKS Michigan

ASTM
Finite Element Analysis
Focus Event
Who is Hibbitt, Karlsson & Sorensen, Inc.

The makers of the ABAQUS Finite Element Analysis Software

Focus is nonlinear FEA

Worldwide Company

Headquarters in Pawtucket, RI

Local Office in Plymouth, MI

Suite of FEA software

Engineering Services including:
  Consulting
  Customization

www.abaqus.com

Copyright 2000 Hibbitt, Karlsson & Sorensen, Inc.
Motivation

What is the state of the FEA technology for elastomers and gaskets?

What parts of FEA analysis are easy, well understood?

What parts are not?

Focus on issues surrounding:

Material Behavior, test data, curve fitting

Numerics, contact, elements, stabilization

Comments on emerging capabilities
Motivation

Water Pump Housing Assembly

Gasket Sealing Pressure

Assemblies

Body Seals

Gasket

Mounts

Boot

Bushing

Copyright 2000 Hibbitt, Karlsson & Sorensen, Inc.

ASTM FEA Focus Event
Motivation

Want to tackle complex 3D FE Analyses
Motivation

Still need to simplify
FEA Technology
What’s easy,
What’s not?
FEA Technology

Simple Problem – Compression of a 2-Piece Elastomer Arch

Complex Deformations, watch out for folds, element inside-out

Easy to perform 2D analyses, design studies

Easy to vary contact conditions, friction, tie bodies
**FEA Technology**

Pull-out analysis of a seal, again very straightforward to perform

- Single deformable body
- Single rigid body
- Self-Contact during pull-out
**FEA Technology**

Weather strip Analysis – 2D CLD analyses easy and routine

3D installation - can be complex due to imperfection sensitive buckling
**FEA Technology**

Jounce Bumper, Axisymmetric analysis

Very large deformations, high element distortions, use triangles

Self-Contact

Interference Fit

Hyperfoam Material

See Example Manual II page 4.2.25-1
FEA Technology

Engine Sealing, Gasket Elements

Four cylinder engine assembly (block/gasket/head)
FEA Technology

*PRE-TENSION SECTION

Bolt with rigid flange and tool

Pre-tension section in bolt
FEA Technology

Engine Sealing, Gasket Elements

Can solve problems routinely that used to be one-of-kind monsters

Solid element mesh of seal:
- orange - elastomer
- green - steel backing
- gray - compression stopper

Gasket element mesh of seal:
FEA Technology

Engine Sealing, Gasket Elements, Pressure Closure Specification
FEA Technology

*CONTACT PAIR with mismatched meshes

Head surface  Gasket surface  Block surface
FEA Technology

4th-order mode due to bolt pattern is clearly visible (cloverleaf)
Elastomer Behavior
Material Modeling
Elastomers are composed of long chains of entangled molecules

Large reversible, nearly incompressible deformation

Initially isotropic, but molecules orient themselves when strained

Stiffness proportional to cross-link density
Modeling Elastomer Behavior

Markedly nonlinear Stress-Strain response

Highly Temperature dependent Stress-Strain response

Molecule on molecule frictional sliding that manifests as:

- Hysteresis
- Damping
- Strain-Rate Dependency
- Viscoelasticity

Damage due to mechanical breaking of chain to chain bonds

Damage due to chemicals, ozone

Stress-Strain response sensitive to processing - % Cure
Modeling Elastomer Behavior

Load/unload test data showing damage at three successive strain levels

Also shows Hysteresis Loops (after damage reaches limit)

Note permanent set too

Red – Strain to 20%
Blue – Strain to 50%
Black – Strain to 100%
**Modeling Elastomer Behavior**

What material aspects do you **want** to capture?

What material aspects **can** you capture?

State of technology – you can’t have it all!

- Ignore frictional sliding effects, consider as nonlinear reversible
- Use hyperelastic material model to capture nonlinearity
- Test at temperature extremes, use multiple models
- Precondition to encapsulate mechanical damage
- Precondition to encapsulate chemical damage

Test your real part, curve fit to one of several rubber models
Modeling Elastomer Behavior

We understand the relative stiffness in different modes of deformation.

We know curve fitting to just one test can be dangerous!
Modeling Elastomer Behavior

We can construct short-time or long-time stress-strain response
Modeling Elastomer Behavior

To create the best elastomer material model, ones needs:

To understand the FEA material models
To understand the testing required
To correlate the material model and the experimental data before embarking on FEA of the real components!

HKS, in conjunction with Axel Products, Inc. has developed a course that combines this test and analysis understanding and taught in the test lab.

Testing and Analysis of Elastomers with ABAQUS
Modeling Elastomer Behavior

The hyperelastic material curve fitting capability allows you to compare different hyperelastic models with the test data.
Modeling Elastomer Behavior

Physically motivated models

Arruda-Boyce
Van der Waals

Phenomenological models

Polynomial (order N) \( \geq 2N \)
  Mooney-Rivlin (1\textsuperscript{st} order) 2
  Reduced polynomial (independent of \( \bar{I}_2 \)) N
  Neo-Hookean (1\textsuperscript{st} order) 1
  Yeoh (3\textsuperscript{rd} order) 3
  Ogden (order N) 2N

Material parameters
(deviatoric behavior)

2
4
Modeling Elastomer Behavior

Advanced Topic – Viscoelasticity

Some users incorporate this routinely

Viscoelastic model: linear viscoelasticity

Bergström-Boyce model: nonlinear viscoelasticity

![Graph showing stress-strain behavior of Chloroprene Rubber (15 pph)]
Modeling Elastomer Behavior

Advanced Topic – Damage, Strain softening, Mullins effect

Currently can only be modeled in ABAQUS using a UMAT\textsuperscript{1}

\textsuperscript{1}Häusler, Sckuhr, and Weiß, “Enhancement of the Freudenberg Material Model for Elastomers to Account for the Mullins Effect,” 2000 ABAQUS Users’ Conference.
Modeling Elastomer Behavior

Advanced Topic: Porous rubbers, or elastomeric foams

Large volumetric deformations – very compressible
Tensile and compressive deformation mechanisms differ at large strains
Numerical Issues, Contact Behavior, Instabilities
Numerics, Contact

Contact occurs routinely in elastomer analyses

Imperative to understand Contact Master-Slave relationships

Only Slave Nodes are checked for contact!

Incorrect

Master surface placed on fine mesh $\Rightarrow$
Gross penetration into slave surface.

Correct

Master surface placed on coarse mesh $\Rightarrow$
Minimal penetration into slave surface.
Numerics, Contact

Contact is complex and heuristic

2D Contact very robust and pretty easy

3D Contact has many more opportunities to go astray

Lots of contact “rules”, these will help you build robust models

Still need to constrain free motions in statics

Master surface smoothing has large affect on convergence
Numerics, Stability

Geometric Local Instability – local buckling, wrinkling, folds, etc.

Is it really element inside-out problem? Mesh with Tri/Tet’s locally

Emerging /Standard capability – Stabilization *static, stabilize

Try *dynamics in Abaqus/Standard

Try Abaqus/Explicit dynamics

Contact Driven Buckling/Collapse Problems

Use *static, stabilize
Numerics, Abaqus/Explicit

For tough 3D elastomer and contact problems try Abaqus/Explicit

Abaqus/Explicit solves a dynamics problem resolving wave propagation

Originally used just for highly dynamic events – explosions, crash

Used extensively in sheet forming to solve quasi-static problems

Beginning to use Explicit method to solve rubber quasi-static problems

Syntax very similar to Abaqus/Standard

Learn about time scaling and mass scaling techniques
Numerics, Abaqus/Explicit

Bushing Insertion, Twist, Translate done with Abaqus/Explicit

ABAQUS/Explicit Analysis of a Rubber Bushing
Cut-Away View of 360 Degree Model

Step 1: Insert
Step 2: Twist
Step 3: Translate

Courtesy of Barry Controls and ABAQUS Solutions Northeast, LLC
Numerics, Abaqus/Explicit

Solution-Dependent Adaptivity

Mesh adaptivity is based on solution variables as well as minimum element distortion.

Elements concentrate in areas where they are needed.

Adaptation is based on boundary curvature.

Initial configuration

Video Clip

Uniform adaptivity

Solution-dependent adaptivity
Emerging Capabilities, Design Sensitivity Analysis
# Emerging Capability: Design Sensitivity Analysis

**ABAQUS/Design implements both total and incremental DSA**

<table>
<thead>
<tr>
<th>Total DSA</th>
<th>Incremental DSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suitable for history-independent problems</td>
<td>Suitable for history-dependent problems</td>
</tr>
<tr>
<td>Need only do DSA for increments of interest</td>
<td>Must perform DSA every increment</td>
</tr>
<tr>
<td>Only elements whose properties and/or node coordinates are design-dependent must be DSA enabled</td>
<td>All elements in structure must be DSA enabled</td>
</tr>
<tr>
<td></td>
<td>More expensive than total formulation</td>
</tr>
</tbody>
</table>
Example Problem: Engine Mount (half model)

- Rubber isolator
- Fold-point
- Bump-stop
- Engine bracket
- Lower-arm
Engine Mount: Design Parameters

Material property

Mooney-Rivlin $C_{10}$ modulus

($C_{01}$ modulus is made dependent on $C_{10}$, $C_{01} = 1/3 C_{10}$)

Shape variations controlled by:

Bump-stop dimension

Lower-arm dimension

Fold-point dimension
Results: History of Sensitivities of Vertical Displacement

- Bump-stop
- Material
- Fold-point
- Lower-arm

Copyright 2000 Hibbitt, Karlsson & Sorensen, Inc.

ASTM FEA Focus Event
FEA of Elastomers and Gaskets in ABAQUS

Tod Dalrymple
HKS Michigan

ASTM
Finite Element Analysis Focus Event