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

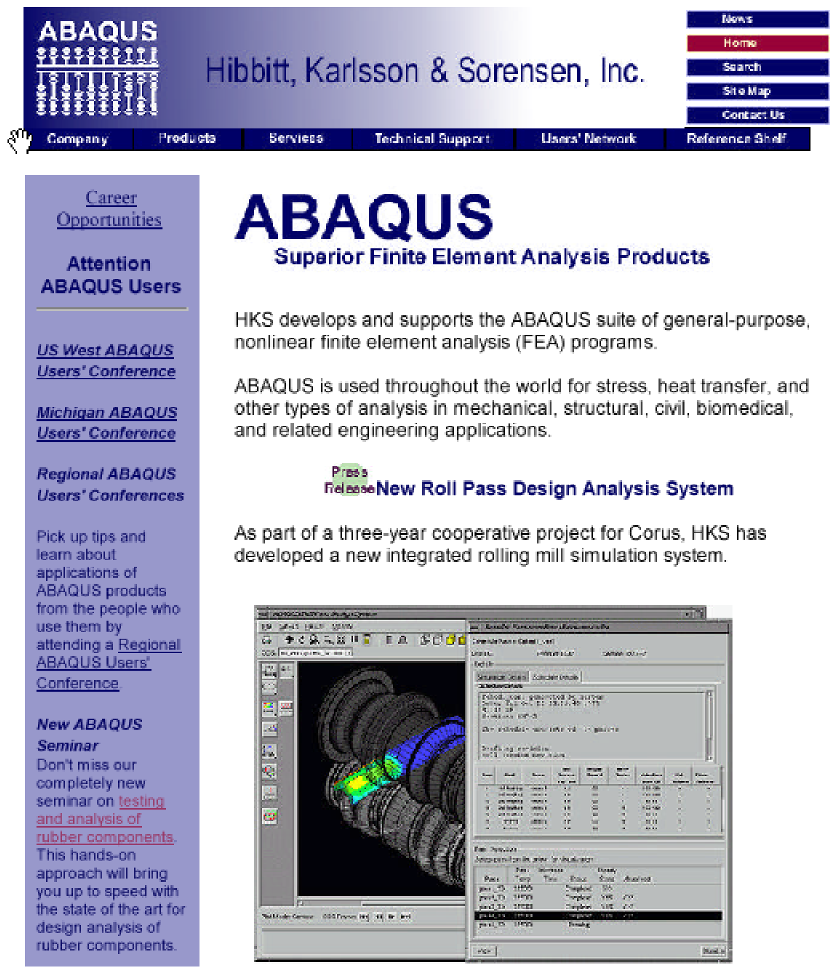
Headquarters in Pawtucket, RI

Local Office in Plymouth, MI

Suite of FEA software

Engineering Services including:

- Consulting
- Customization



www.abaqus.com

Motivation

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

What parts of FEA analysis are easy, well understood?

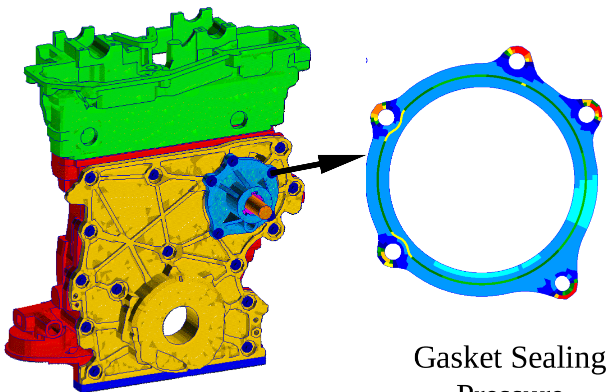
What parts are not?

Focus on issues surrounding:

- Material Behavior, test data, curve fitting
- Numerics, contact, elements, stabilization

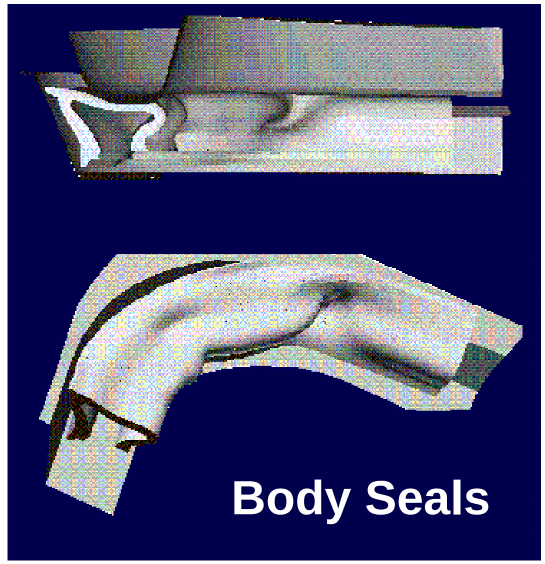
Comments on emerging capabilities

Motivation

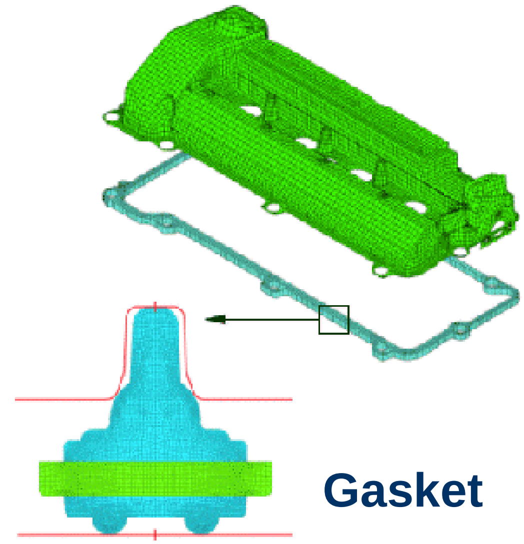


Water Pump Housing Assembly

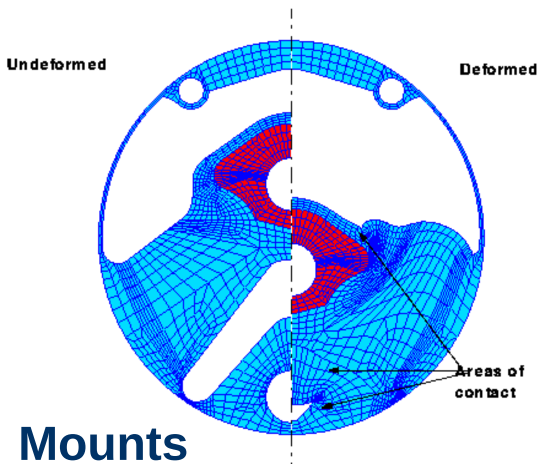
Assemblies



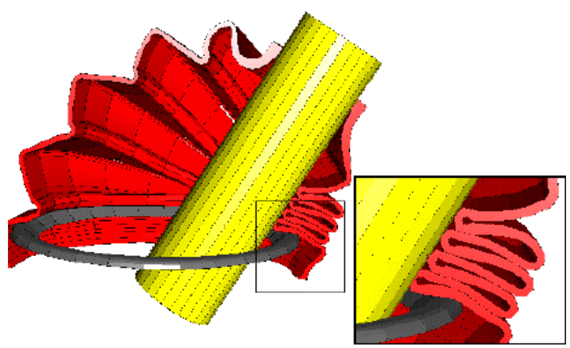
Body Seals



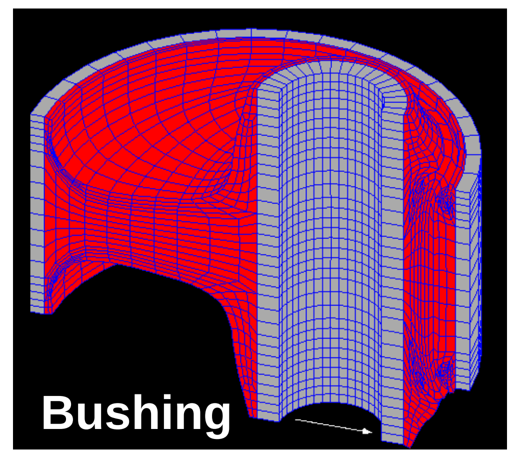
Gasket



Mounts



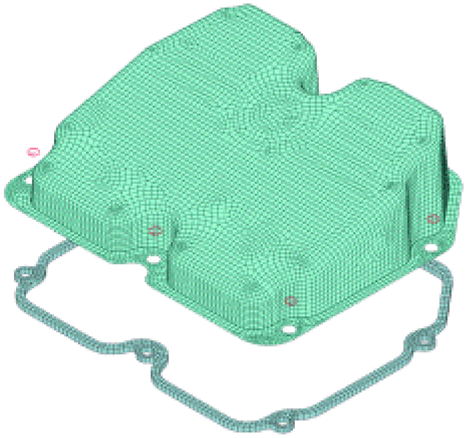
Boot

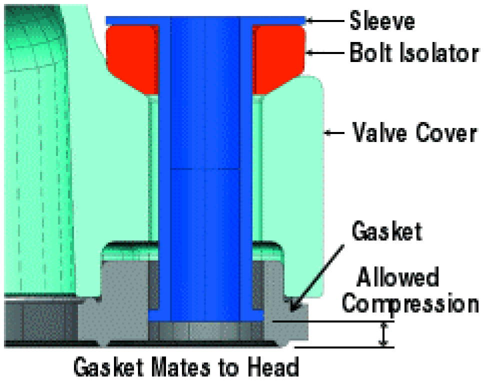


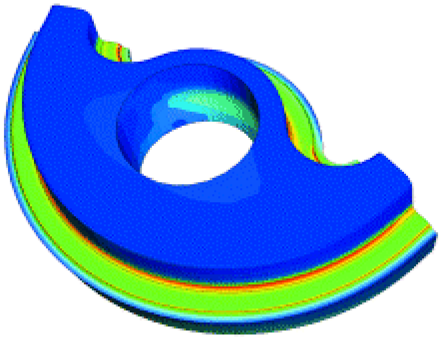
Bushing

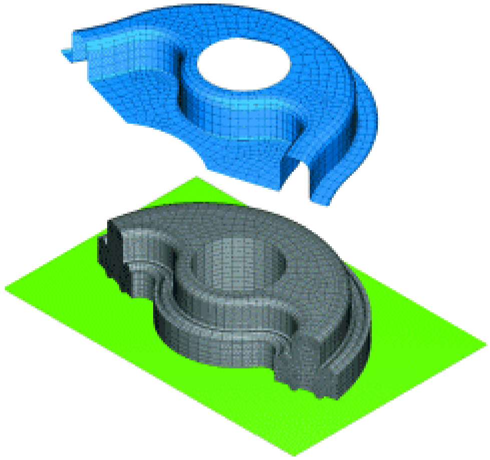
Motivation

Want to tackle complex 3D FE Analyses



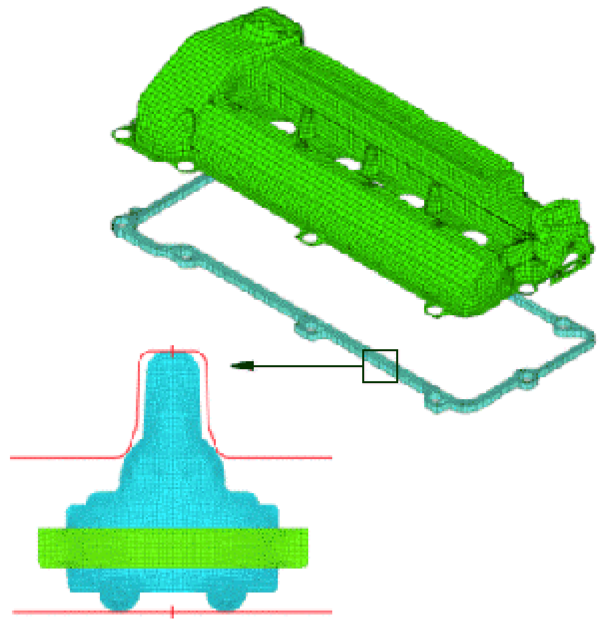


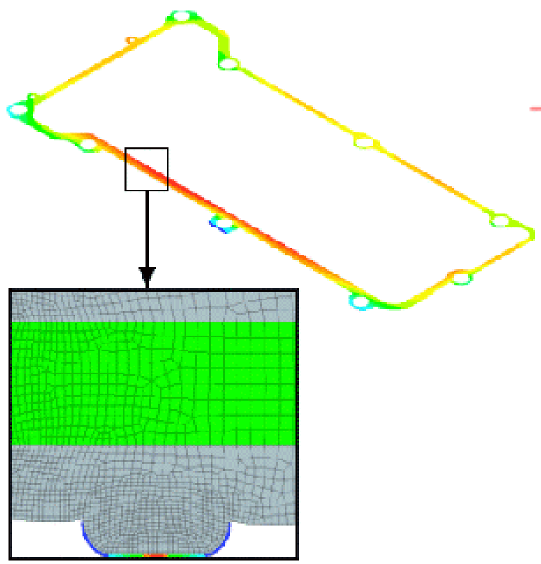


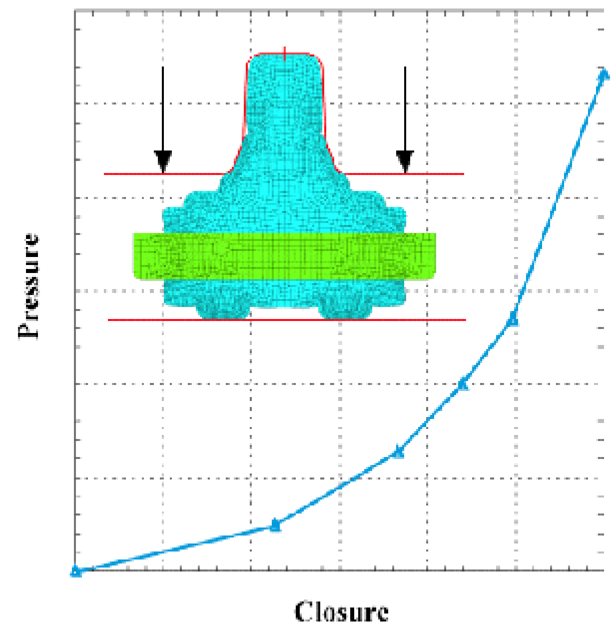


Motivation

Still need to simplify







FEA Technology
What's easy,
What's not?

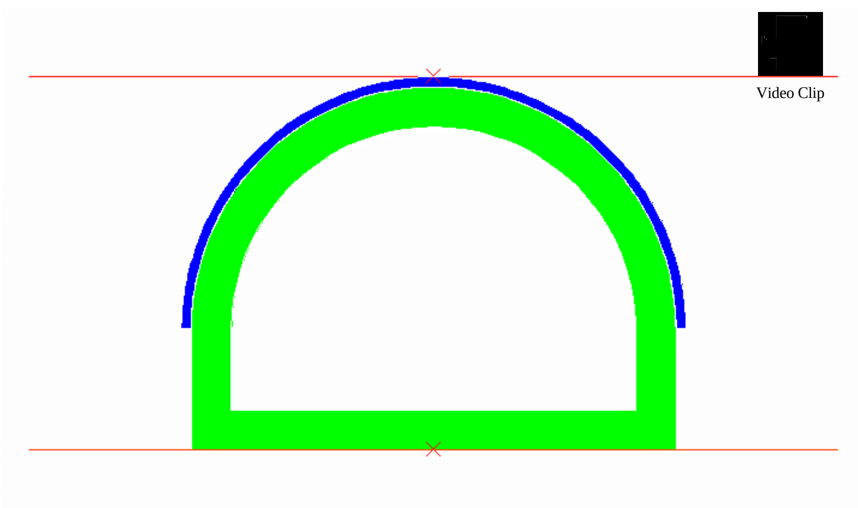
FEA Technology

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

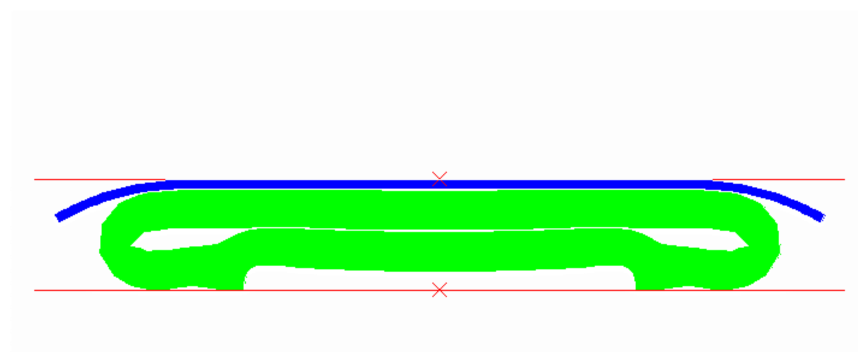


Fix Base

Video Clip

Tie Pieces

Video Clip



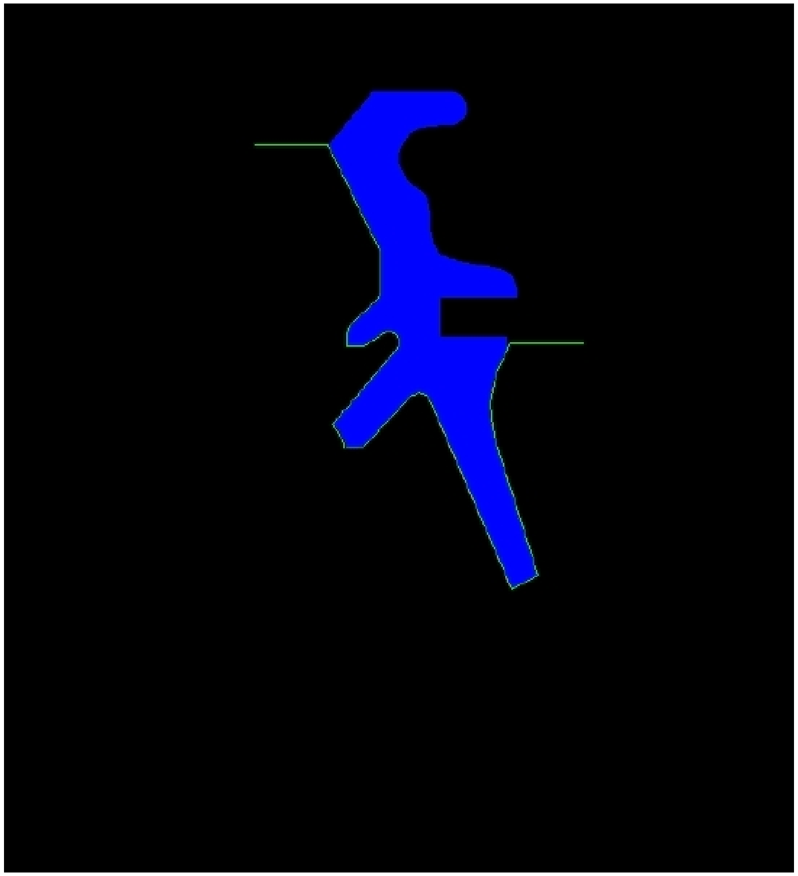
FEA Technology

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

Single deformable body

Single rigid body

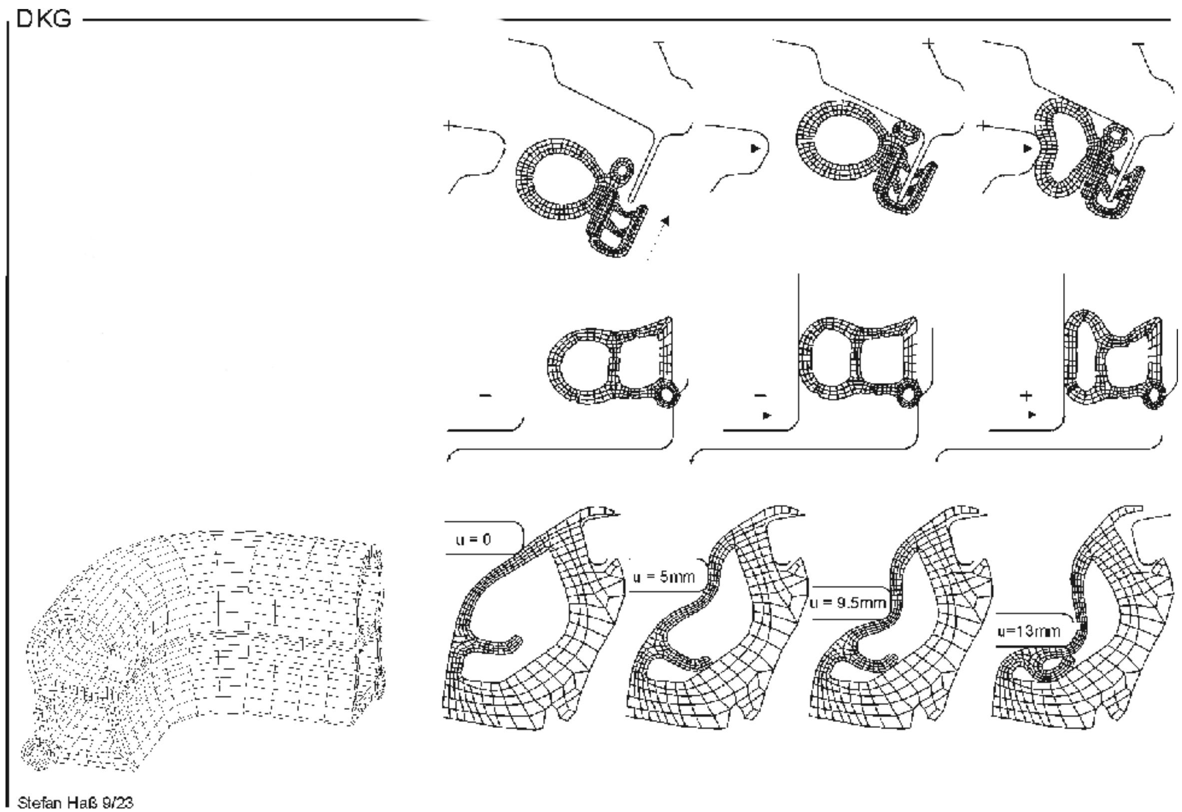
Self-Contact during pull-out



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

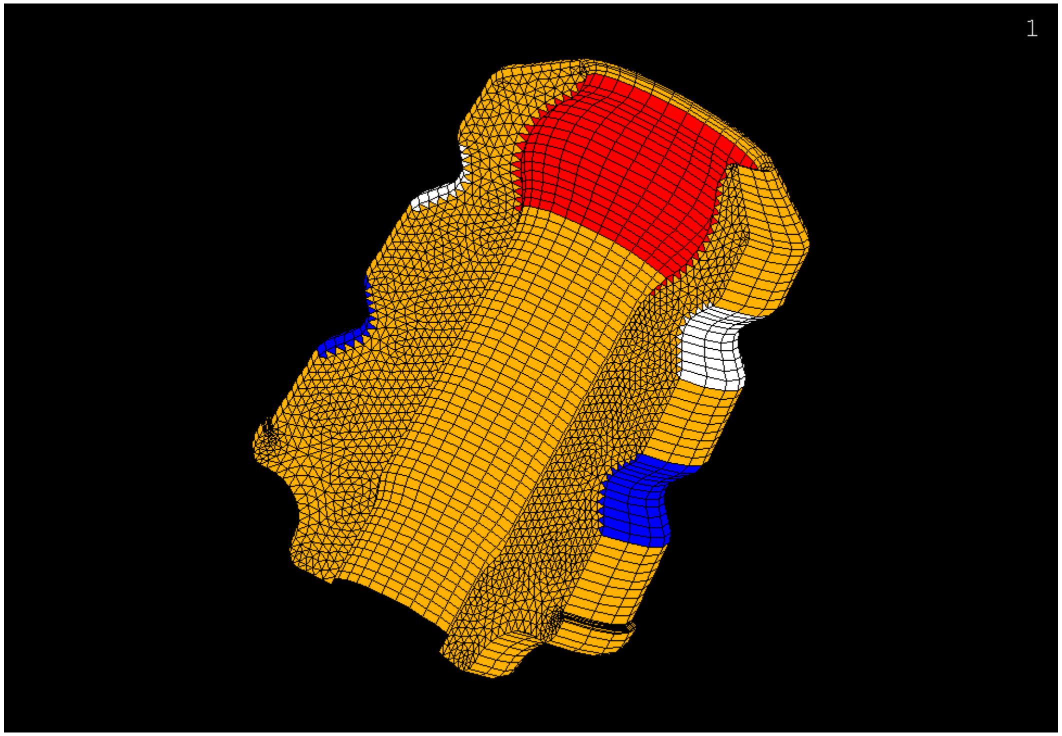
Self-Contact

Interference Fit

Hyperfoam Material

See Example Manual II

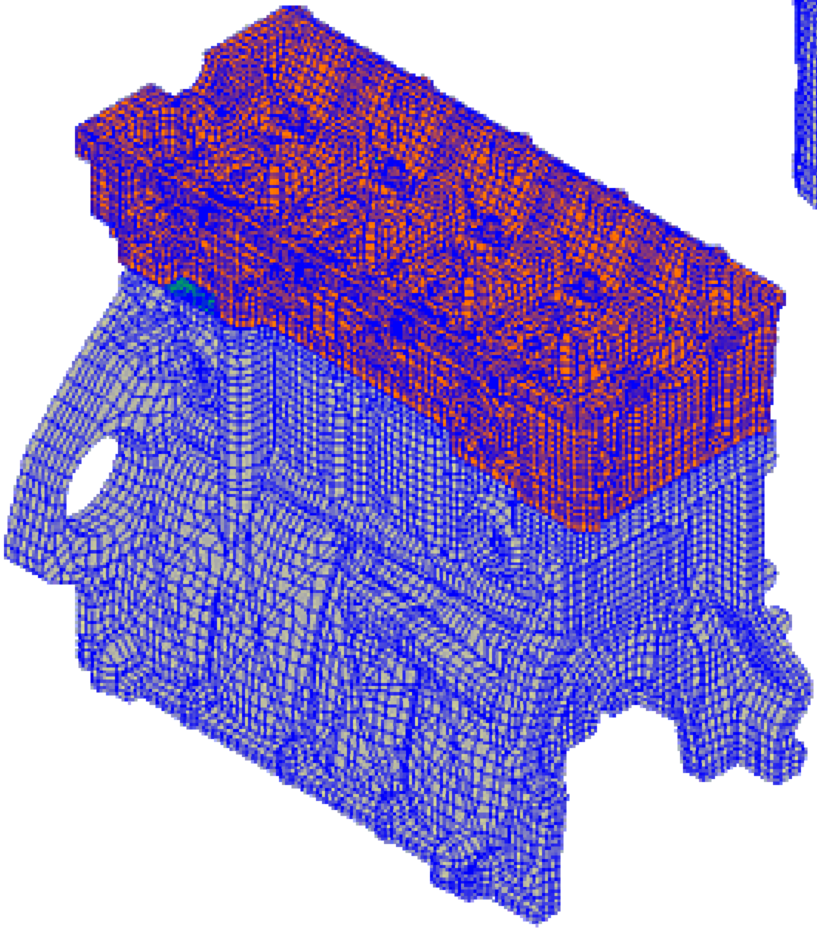
page 4.2.25-1

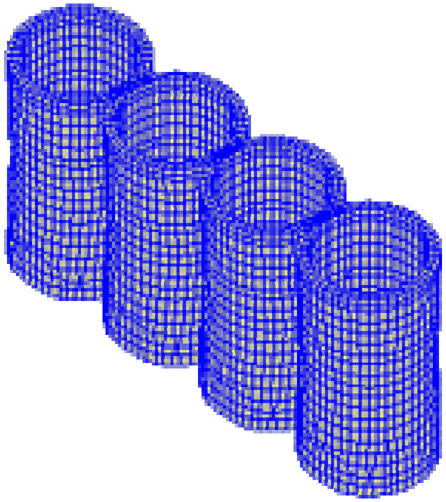


FEA Technology

Engine Sealing, Gasket Elements

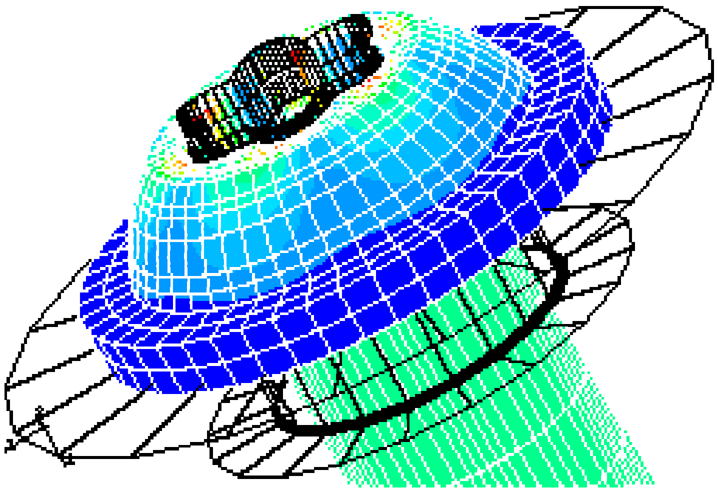
Four cylinder
engine assembly
(block/gasket/head)



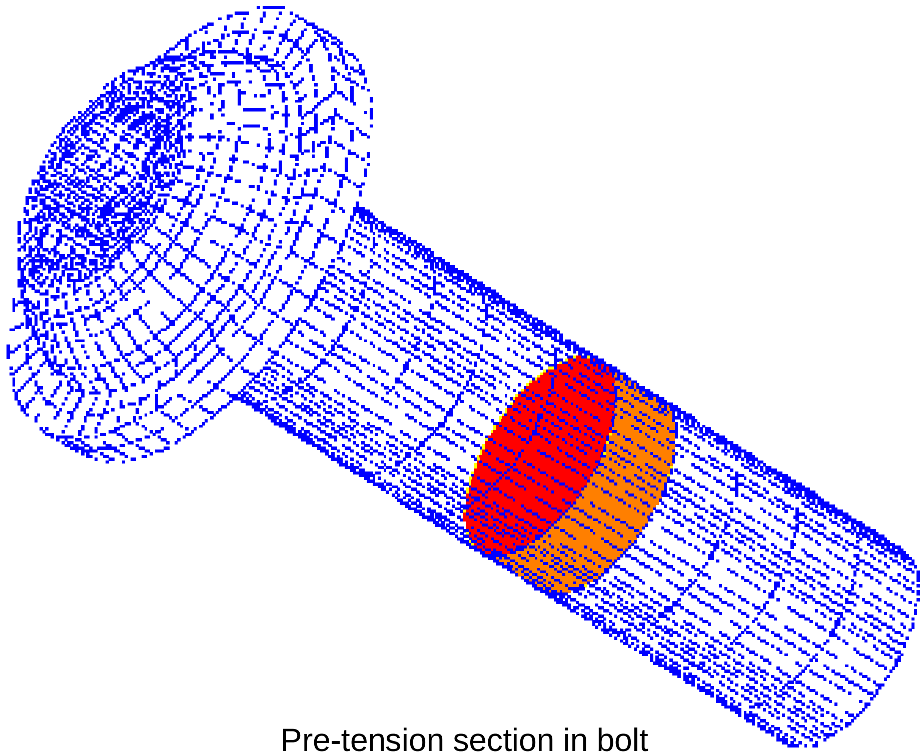


FEA Technology

* PRE-TENSION SECTION



Bolt with rigid flange and tool



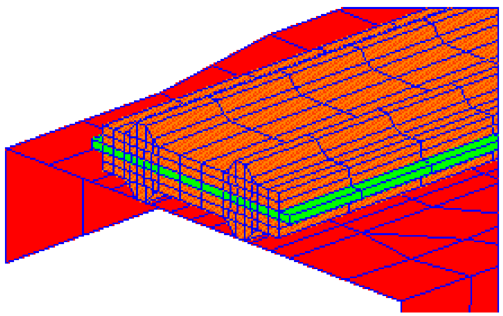
Pre-tension section in bolt

FEA Technology

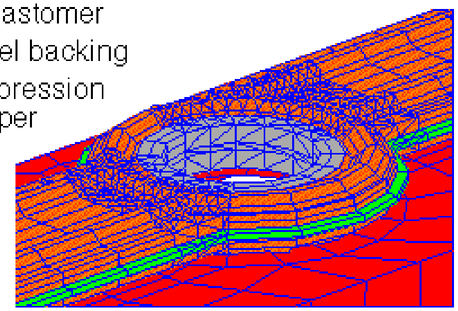
Engine Sealing, Gasket Elements

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

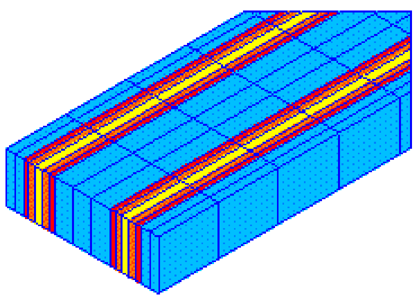
Solid element mesh of seal:

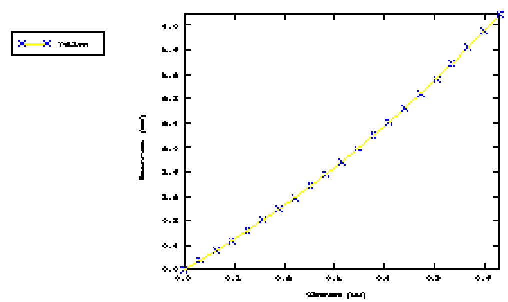


orange - elastomer
green - steel backing
gray - compression stopper



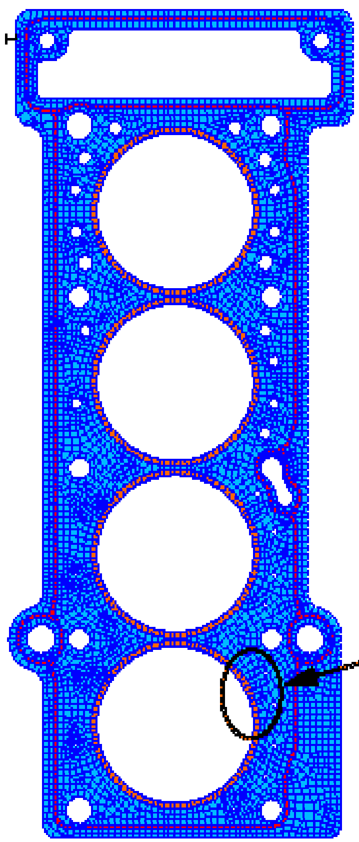
Gasket element mesh of seal:

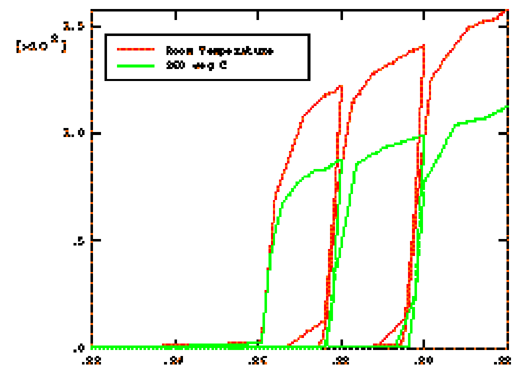


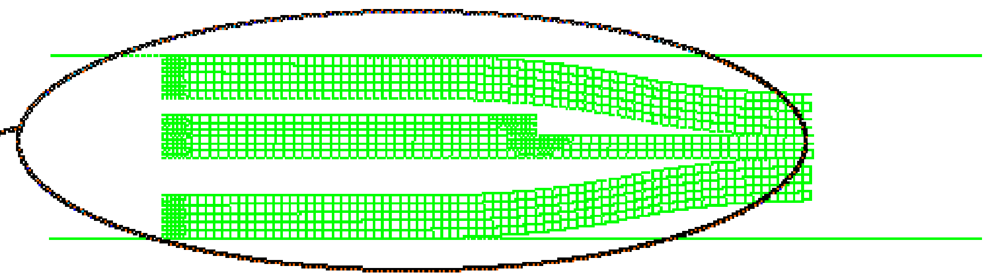


FEA Technology

Engine Sealing, Gasket Elements, Pressure Closure Specification

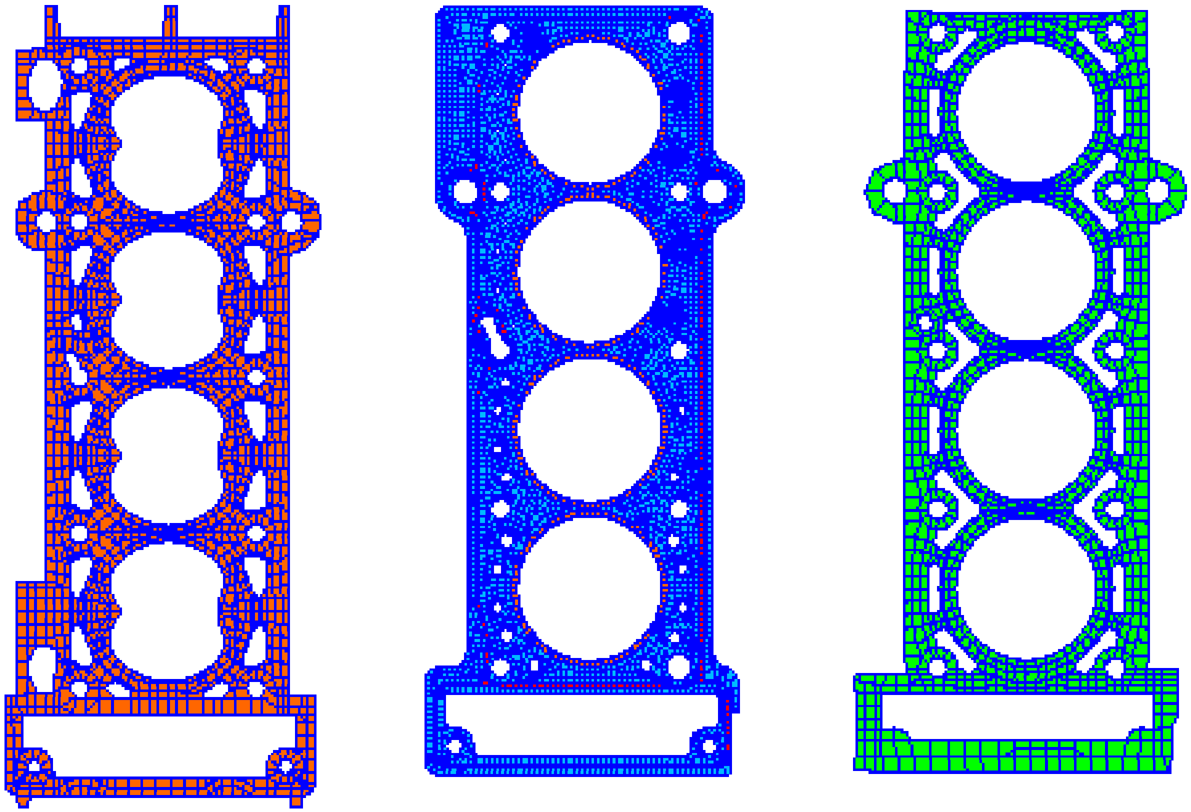






FEA Technology

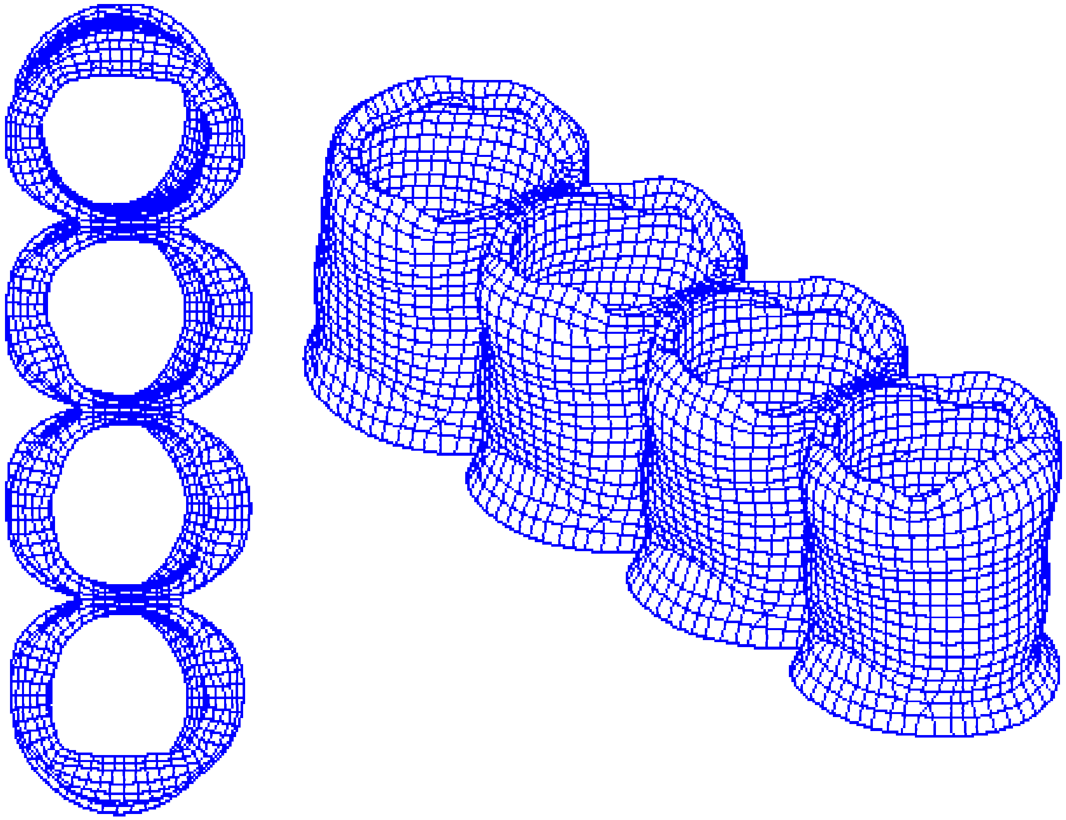
∗CONTACT PAIR with mismatched meshes



Head surface Gasket surface Block surface

FEA Technology

4th-order mode due to bolt pattern is clearly visible (cloverleaf)

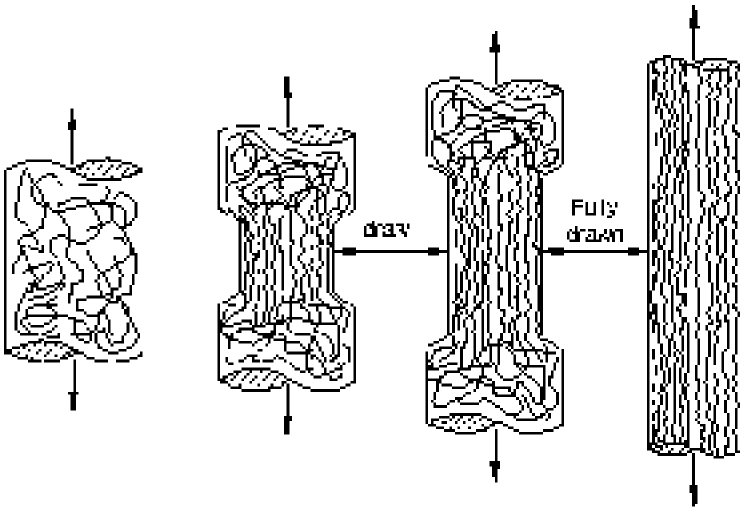


Elastomer Behavior
Material Modeling

Modeling Elastomer Behavior

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

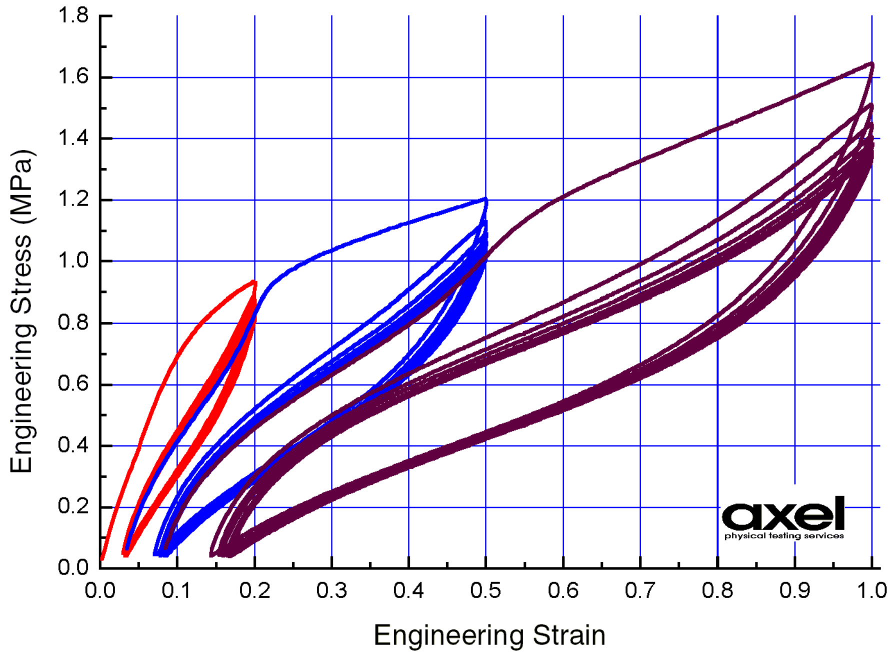
Also shows Hysteresis Loops (after damage reaches limit)

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!

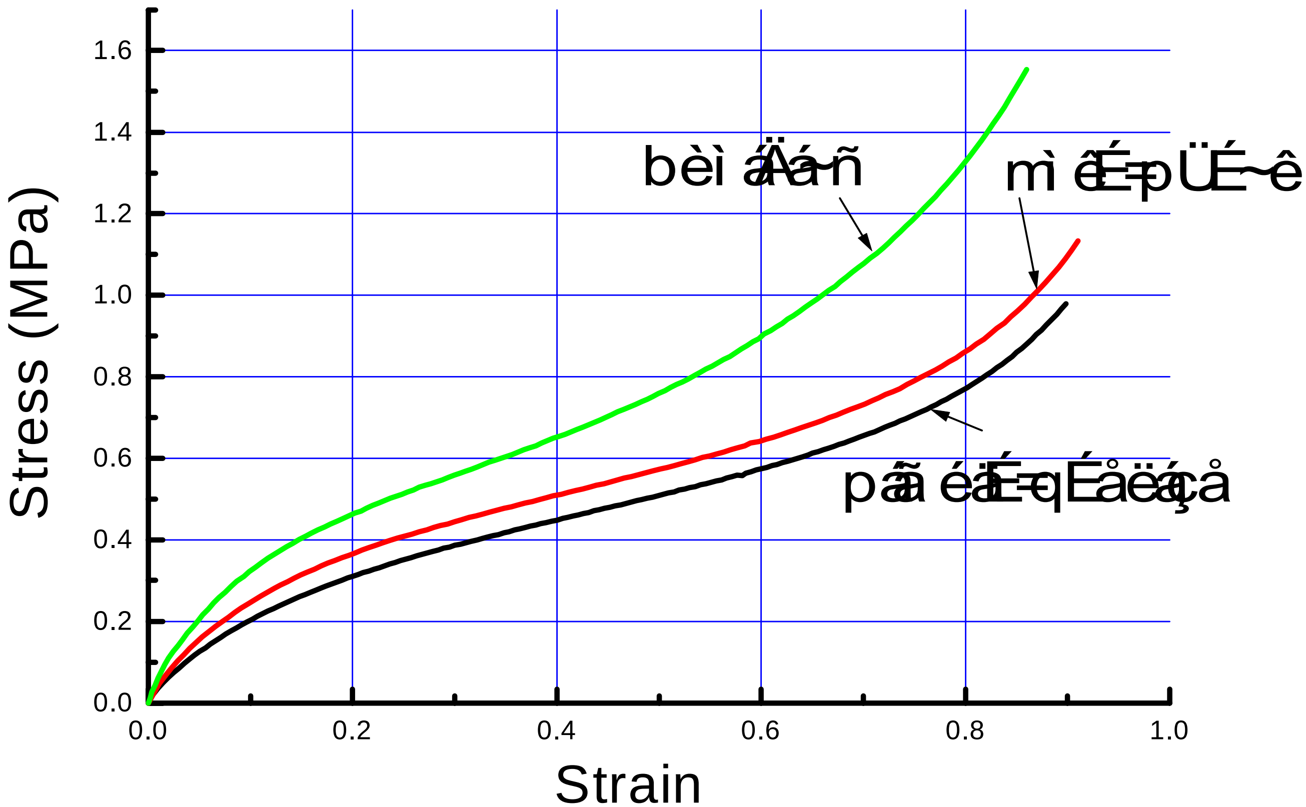
- Ignore frictional sliding effects, consider as nonlinear reversible
- Use hyperelastic material model to capture nonlinearity
- Test at temperature extremes, use multiple models
- Precondition to encapsulate mechanical damage
- Precondition to encapsulate chemical damage

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

Modeling Elastomer Behavior

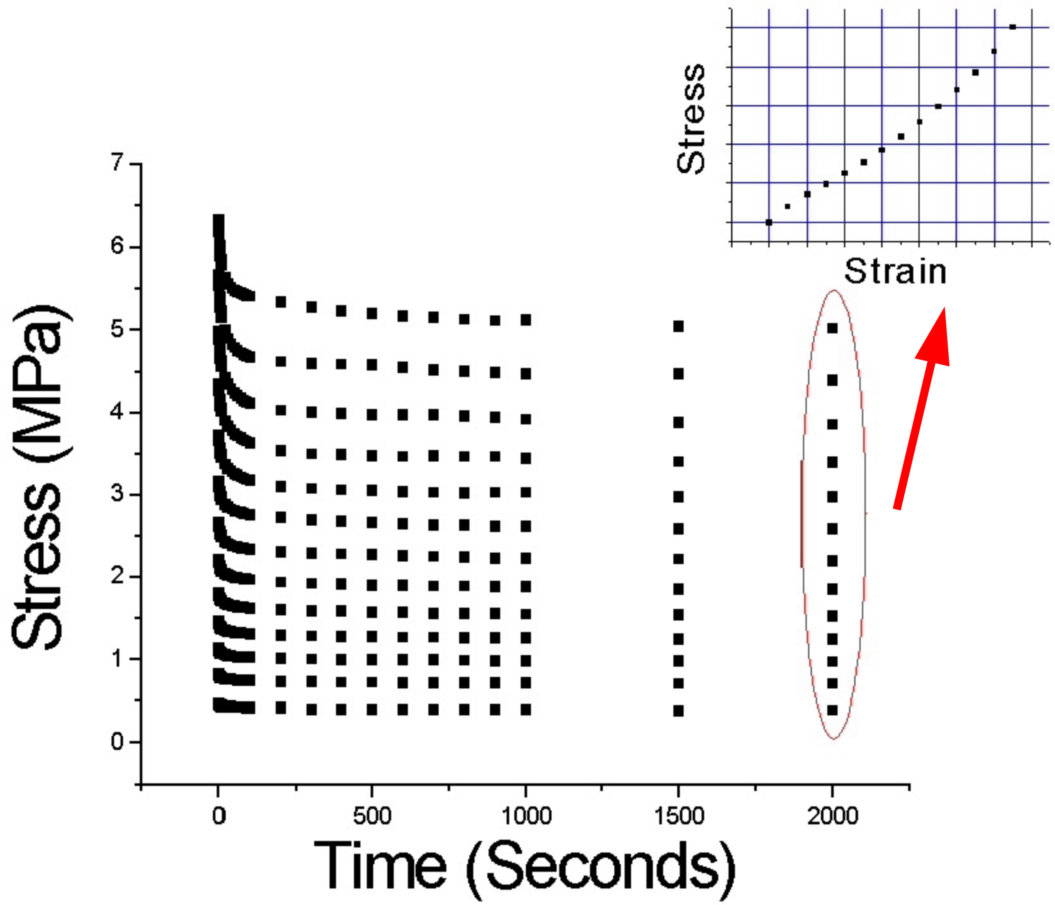
We understand the relative stiffness in different modes of deformation

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

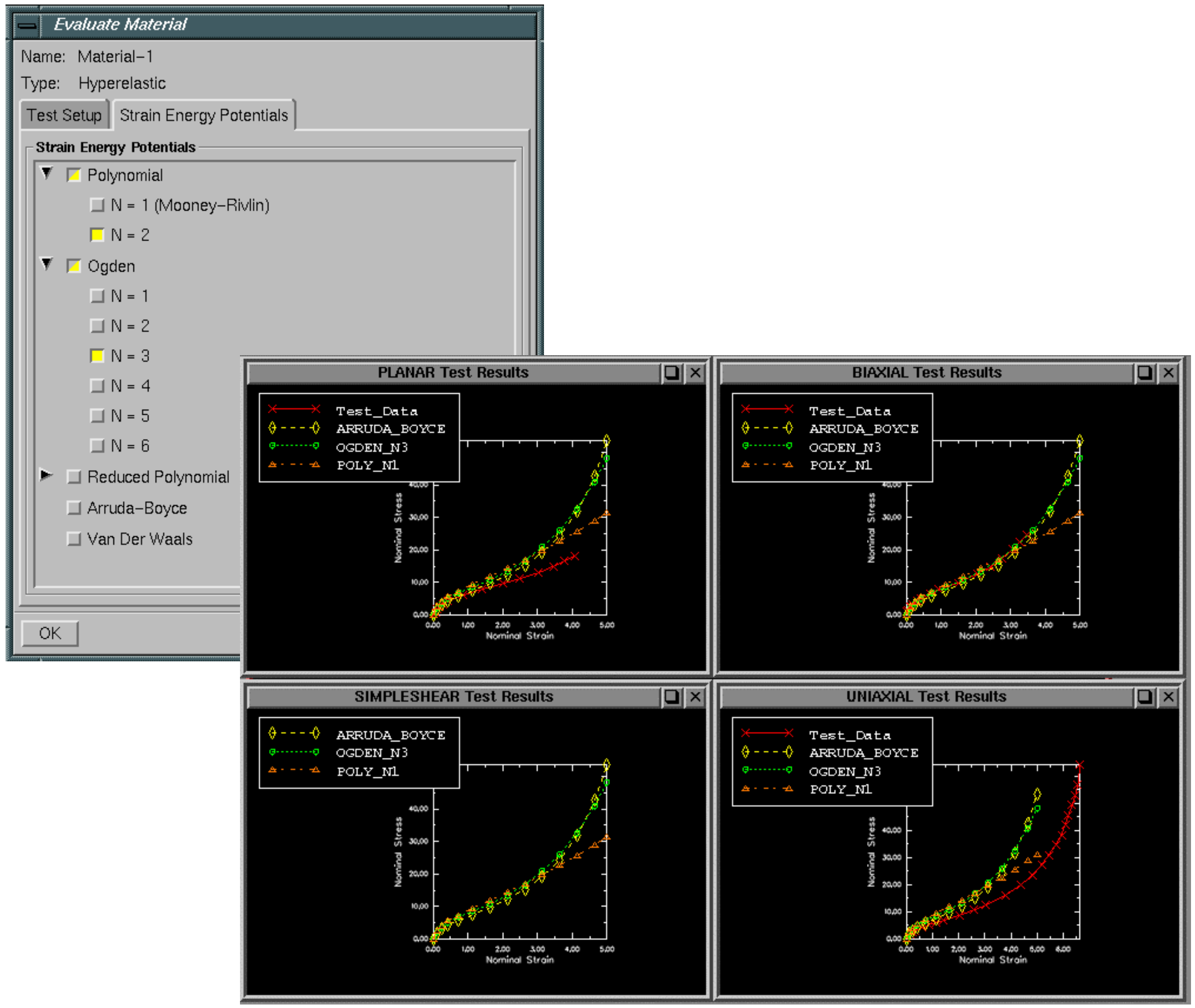
To correlate the material model and the experimental data before embarking on FEA of the real components!

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

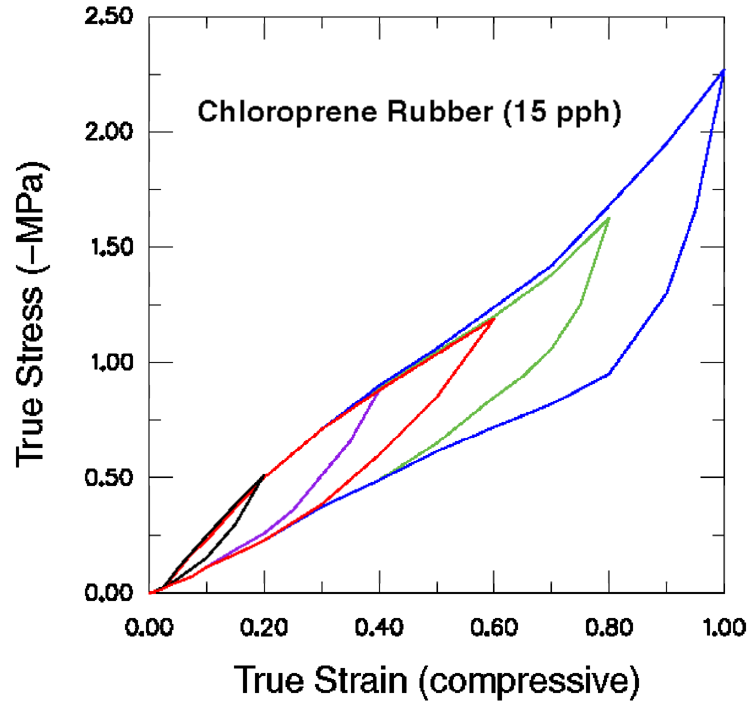
Physically motivated models	**Material parameters (deviatoric behavior)**
Arruda-Boyce	2
Van der Waals	4
Phenomenological models	
Polynomial (order N)	≥ 2N
Mooney-Rivlin (1st order)	2
Reduced polynomial (independent of $\bar{I}_2$)	N
Neo-Hookean (1st order)	1
Yeoh (3rd order)	3
Ogden (order N)	2N

Modeling Elastomer Behavior

Advanced Topic – Viscoelasticity

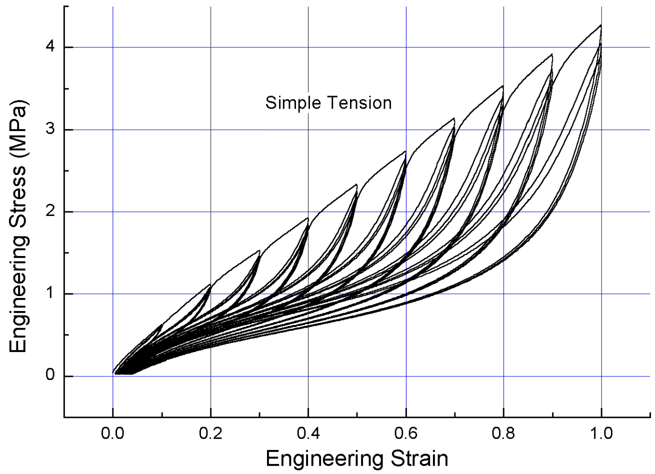
Some users incorporate this routinely

- Viscoelastic model: linear viscoelasticity
- Bergström-Boyce model: nonlinear viscoelasticity



Modeling Elastomer Behavior

Advanced Topic – Damage, Strain softening, Mullins effect

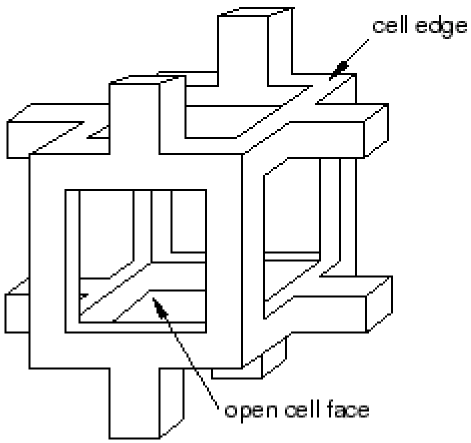


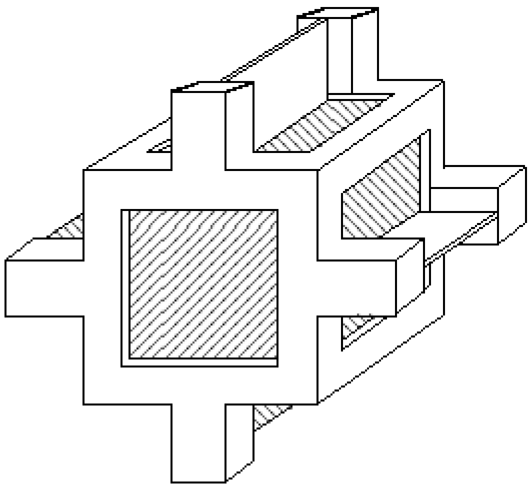
Currently can only be modeled in ABAQUS using a **`UMAT`**[1]

[1]Häusler, Sckuhr, and Weiβ, “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

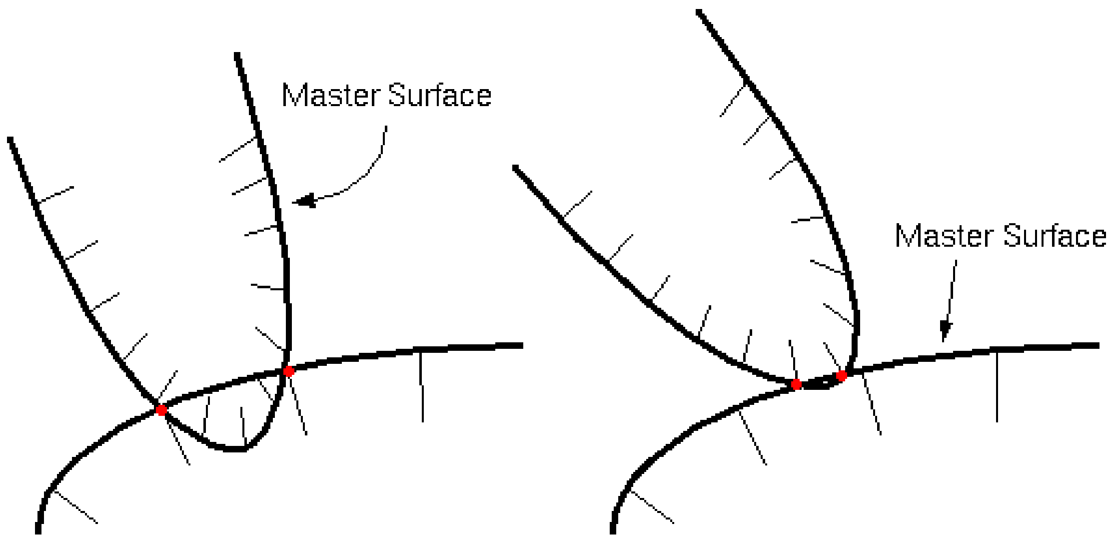
Numerical Issues, Contact Behavior, Instabilities

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 ⇒
Gross penetration into slave surface.

Correct

Master surface placed on coarse mesh ⇒
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`**

3D Arch

Video Clip

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

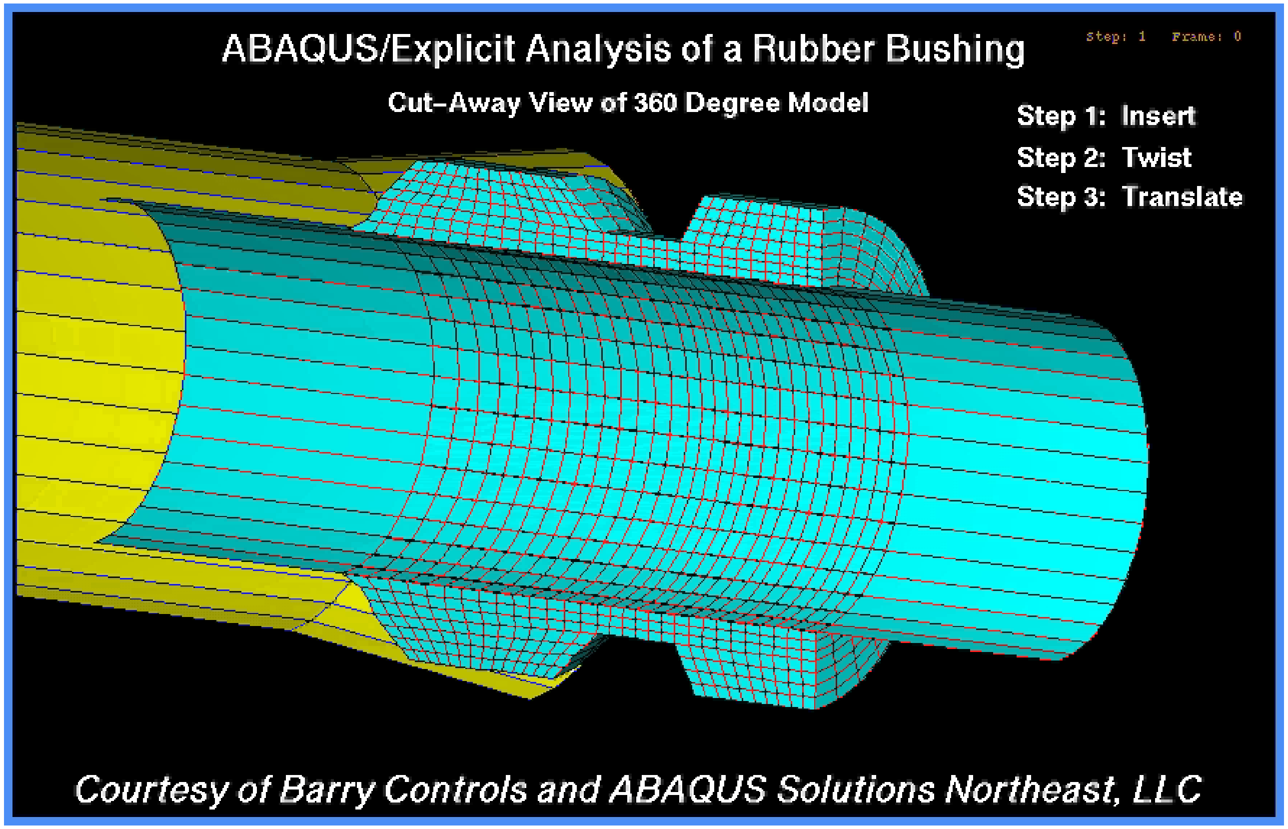
Beginning to use Explicit method to solve rubber quasi-static problems

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



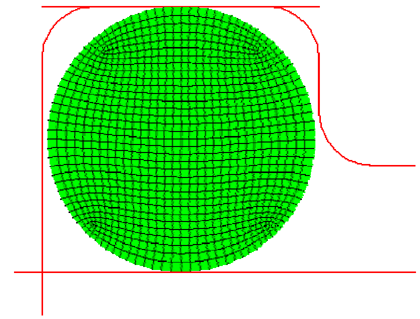
Numerics, Abaqus/Explicit

Solution-Dependent Adaptivity

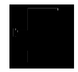
Mesh adaptivity is based on solution variables as well as minimum element distortion

Elements concentrate in areas where they are needed

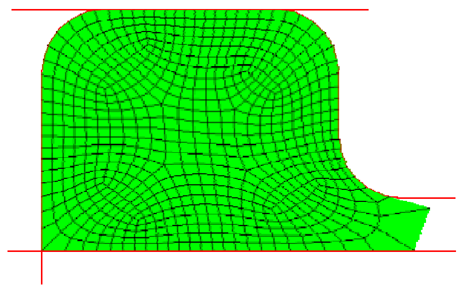
Adaptation is based on boundary curvature



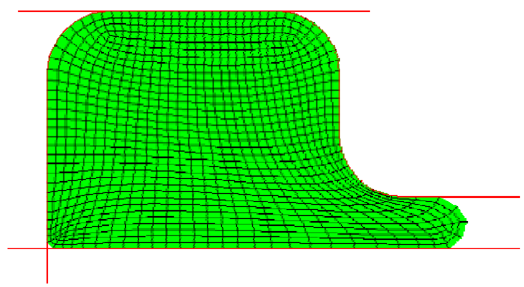
Initial configuration



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

Total DSA

Suitable for history-independent problems

Need only do DSA for increments of interest

Only elements whose properties and/or node coordinates are design-dependent must be DSA enabled

Incremental DSA

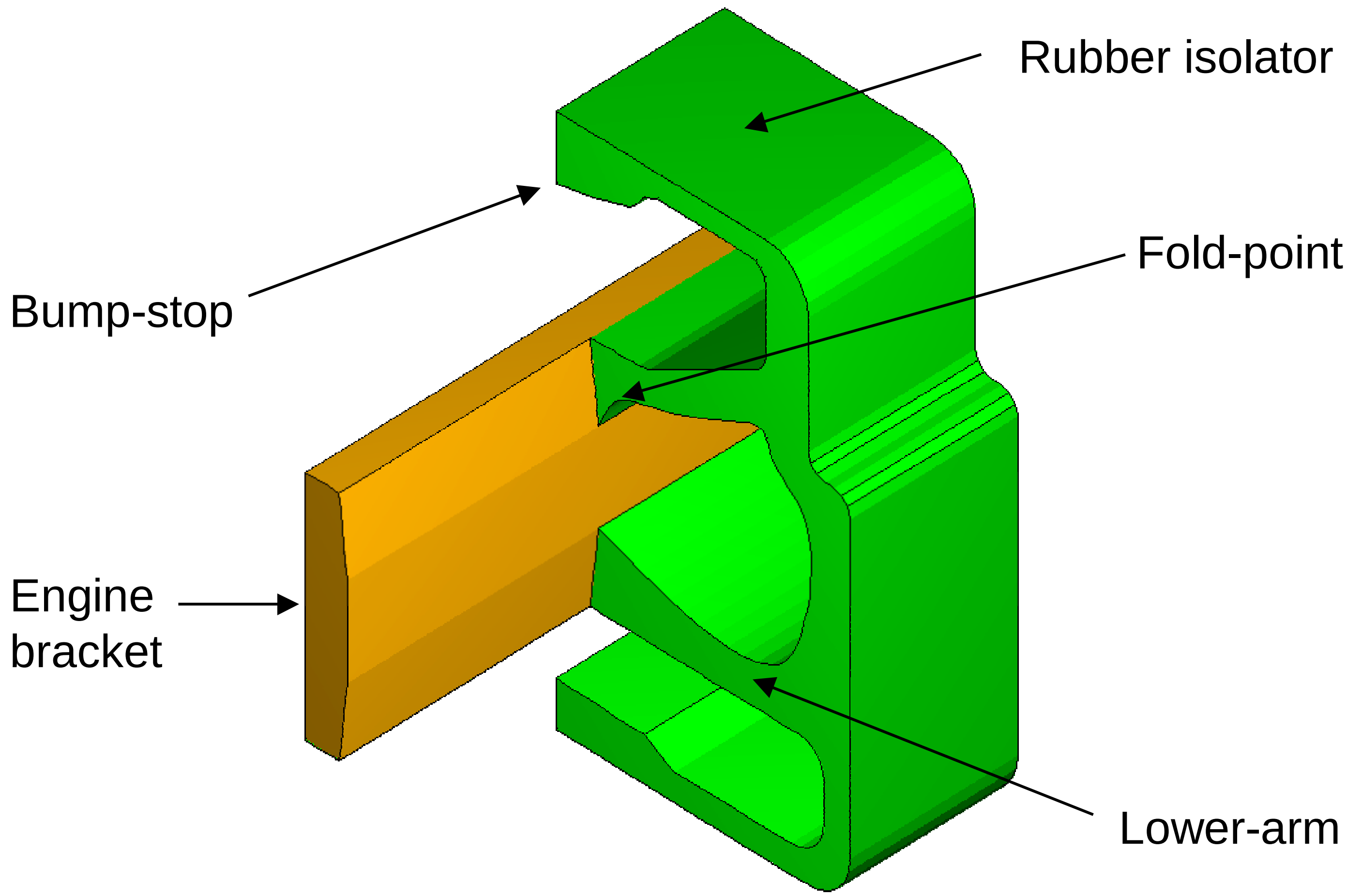
Suitable for history-dependent problems

Must perform DSA every increment

All elements in structure must be DSA enabled

More expensive than total formulation

Example Problem: Engine Mount (half model)



Engine Mount: Design Parameters

Material property

Mooney-Rivlin $\mathbf{C_{10}}$ modulus

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

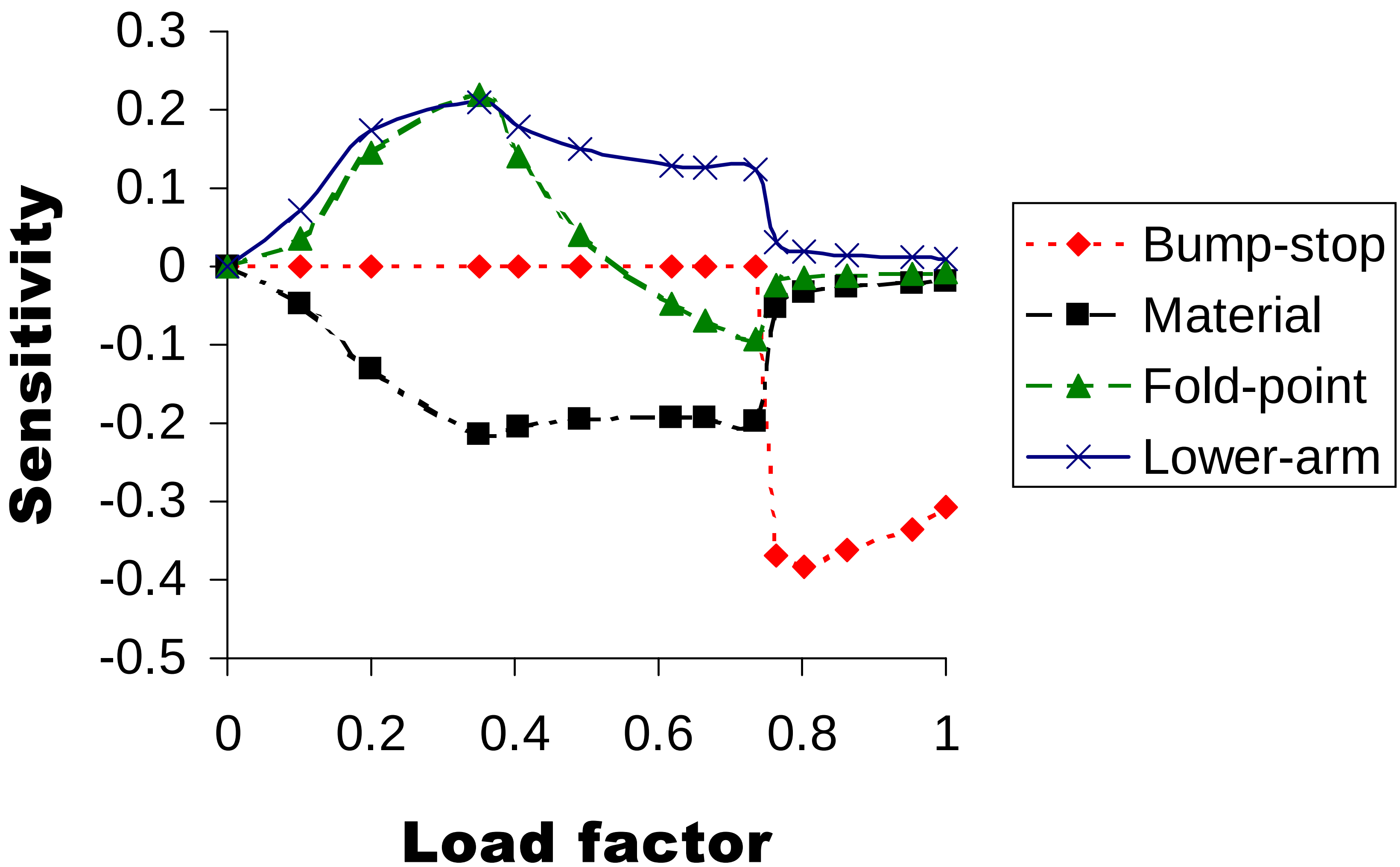
Shape variations controlled by:

Bump-stop dimension

Lower-arm dimension

Fold-point dimension

Results: History of Sensitivities of Vertical Displacement



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