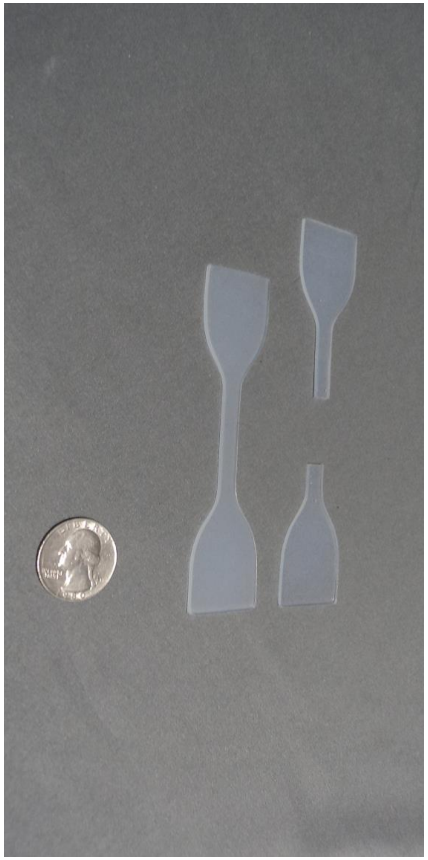
Testing, Modeling and Validation for Rubber Simulation in ANSYS

Hubert Lobo & Brian Croop

What Defines a Hyperelastic Material?

- Required behavior
  - Recovery of strain
  - Not just high elongation
  - No yielding
  - Poisson’s ratio ~ 0.5

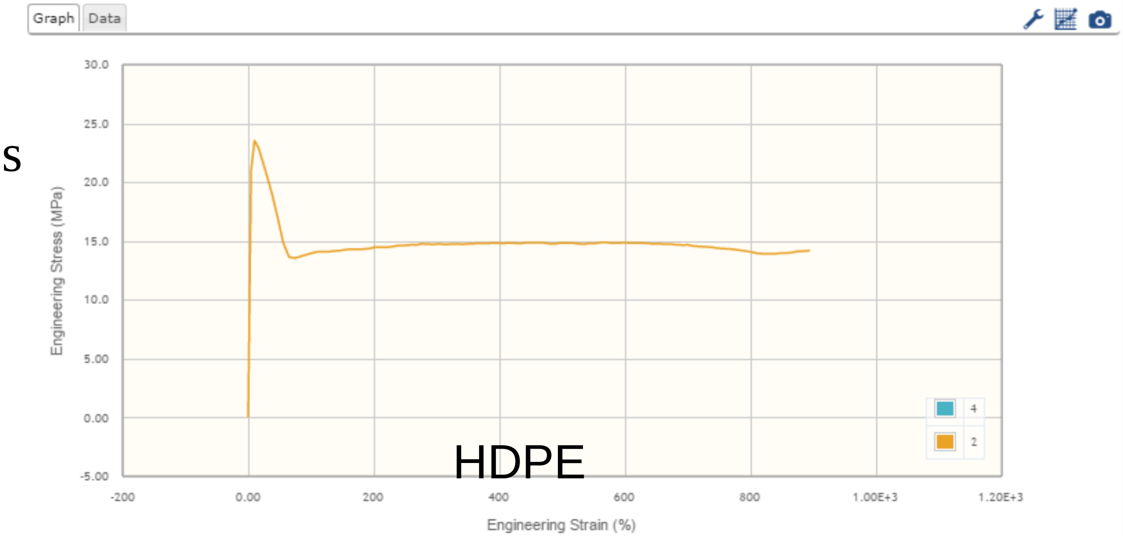


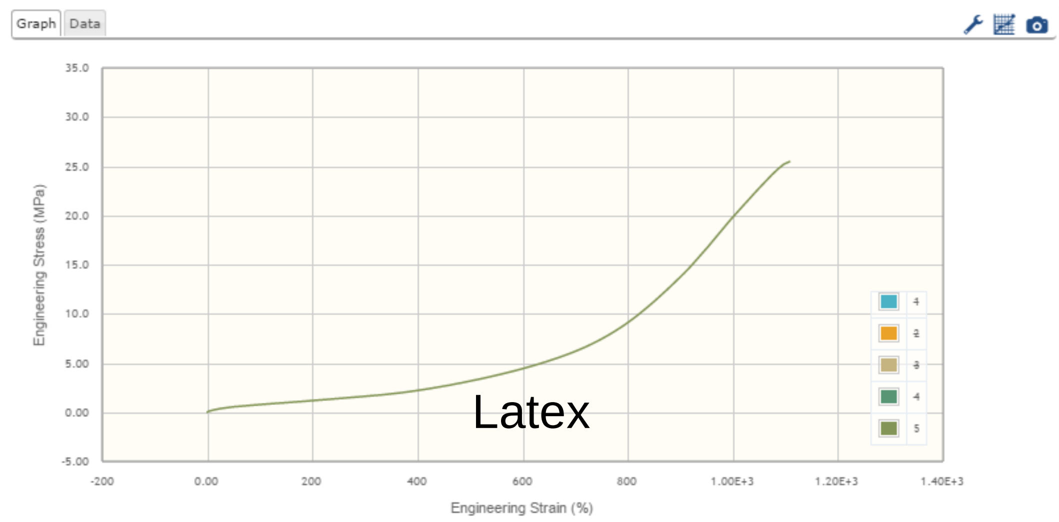
“Hyperelastic”

“Ductile Plastic”

Curve Shape

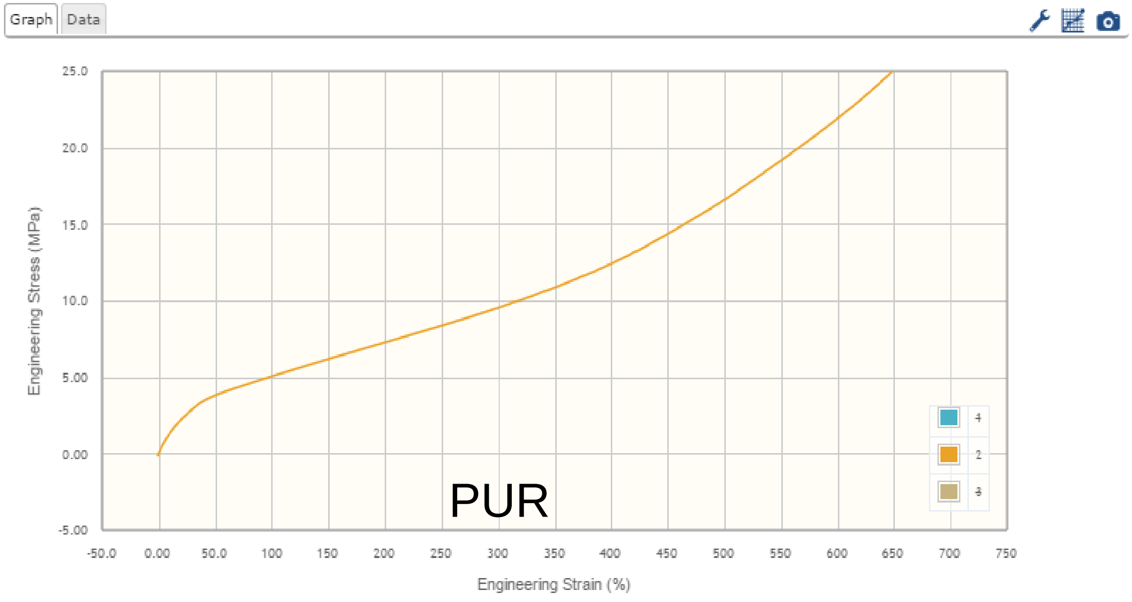
- Curve Shape
  - Increasing stress with s
  - No multiple inflection
  - No zero slope point





In Between Materials

- Elastomers
  - Blend of polymer and rubber
  - Hyperelastic to some point
  - Yielding
  - Urethanes
  - Polyester elastomers
  - Some TPEs



Rubber vs Elastomer

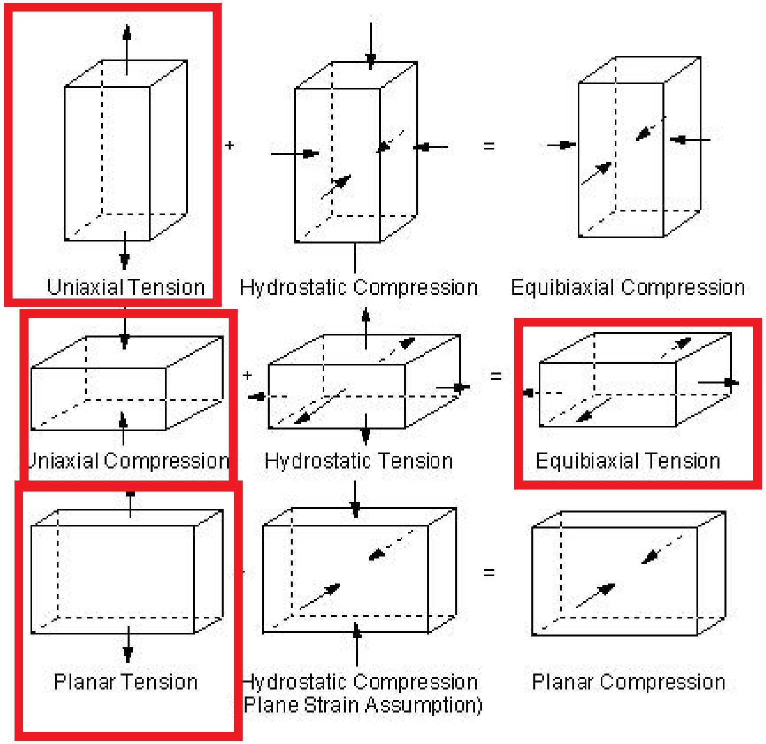
- Difference in damage mechanism
  - Rubber damage by cross-link breakage
    - Stress decrease after damage
    - Softer upon reloading
    - Returns to initial shape
  - Elastomer damage by plasticity
    - Irrecoverable strains (becomes larger)
    - Stiffer upon reloading

Considerations Prior to Testing and Modeling

- What Strains do You Expect?
  - Material models will be determined by strain range.
  - Small strains may lead to simple models
- Environment
  - Large temperature effect on behavior
    - Cold temperatures lead to plastic behavior
    - High temperatures may cause degradation
  - Chemicals, oils can change behavior
- Is the Material Damaged Prior to Your Simulation?
  - Hyperelastic materials soften after being deformed
  - Cross-link chains are broken
  - Material should be pre-cycled if interested only in long term behavior
  - Initial installation can be simulated using non-cycled data
  - Capturing Mullins effect can be incorporated into the material model

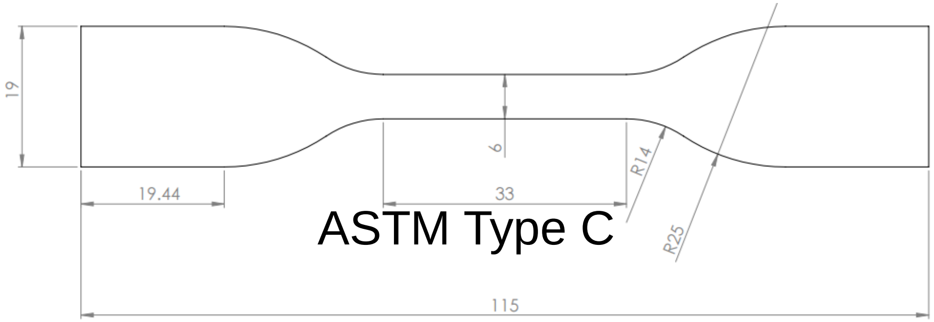
Characterizing Hyperelastic Materials

- Multiple modes of deformation to define material models
  - Uniaxial Tension
  - Uniaxial Compression
  - Planar Shear
  - Biaxial Tension
  - Volumetric Compression

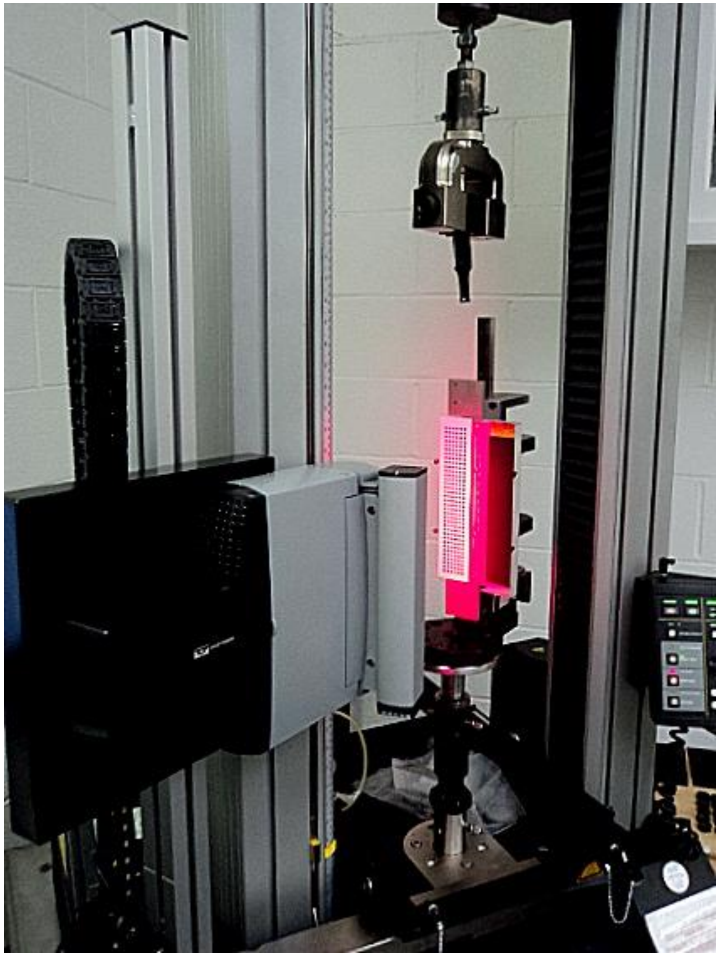


Tensile Test

- Uniaxial deformation
- Wide tabs minimize grip deformation error
- Non-contact extensometry for precise strain



ASTM Type C

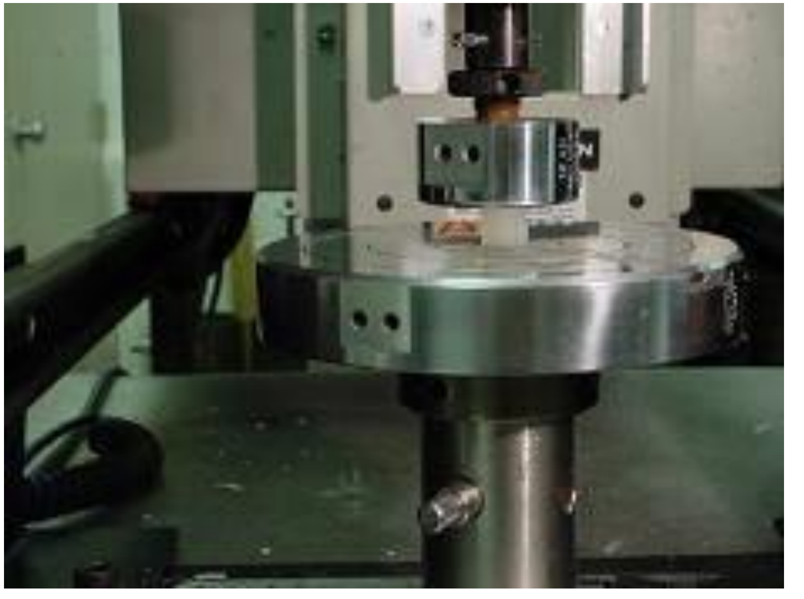


Planar Tension

- Shear deformation
- Large width to length ratio minimizes contraction in width direction
- Non-contact extensometry to eliminate edge effects
- Pneumatic grips used to prevent slippage

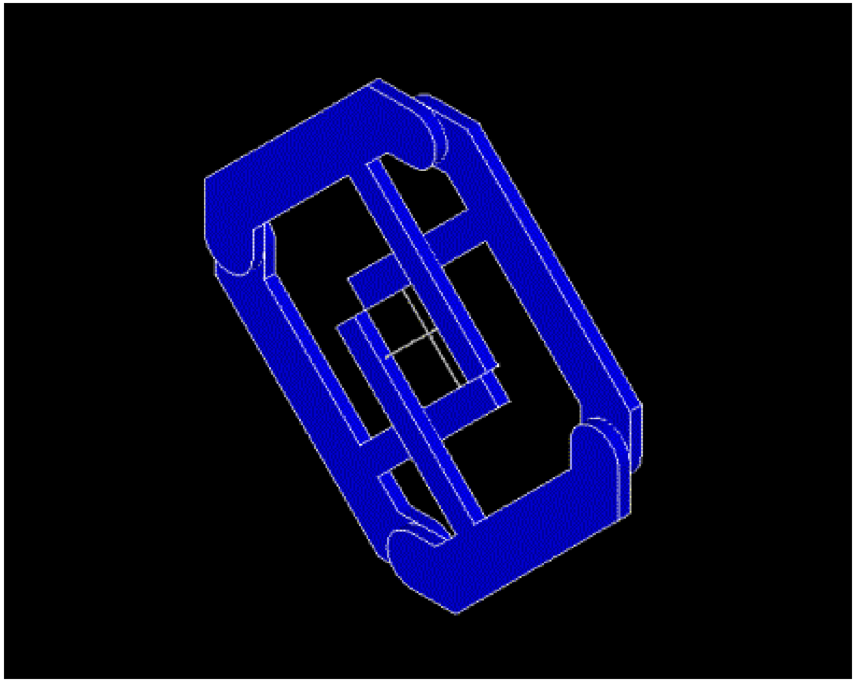
Compressive Test

- Equivalent to biaxial deformation
- Lubricated platens minimize “barrelling”
- May contain volumetric effects
- Not good at high strains



Biaxial Tension Test

- Stretch in x & y plane
- Thinning in z-plane
- Suitable for thin specimens

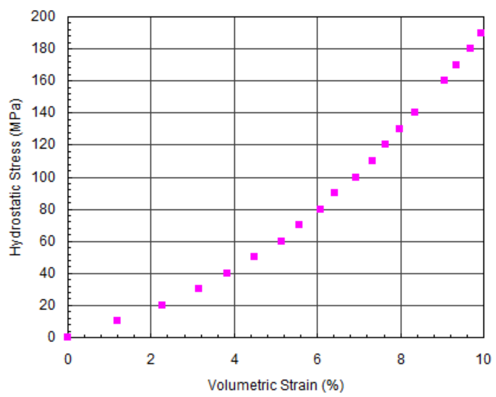


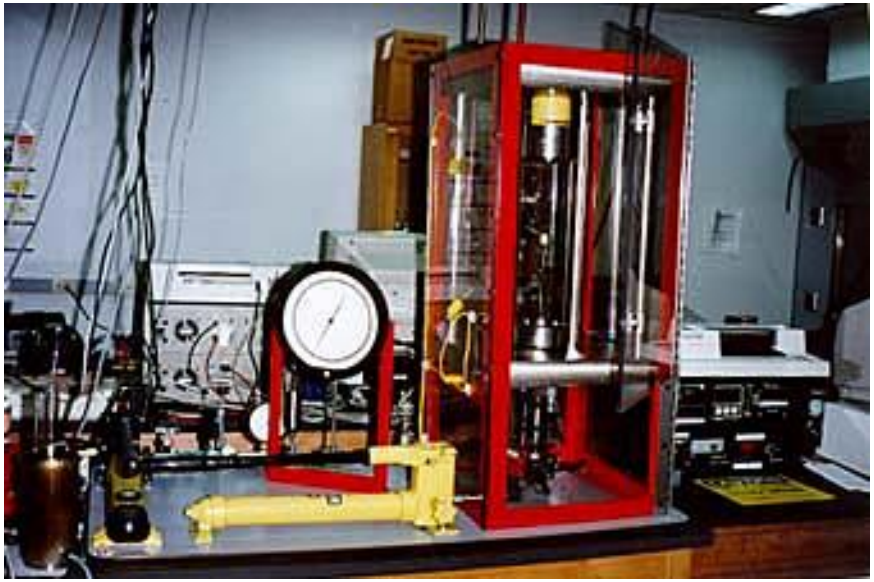
Volumetric Test

- Hydrostatic compression
- Confining fluid provides uniform hydrostatic pressure
- Needed when hydrostatic stress is high, eg. Gaskets and seals.

Pressure-Volume-Temperature Data

Strain %	Pressure MPa
0.00	0
1.21	10
2.28	20
3.14	30
3.85	40
4.48	50
5.13	60
5.56	70
6.07	80
6.43	90
6.93	100
7.32	110
7.64	120
7.97	130
8.34	140
8.69	
9.05	160
9.34	170
9.69	180
9.94	190
10.28	200

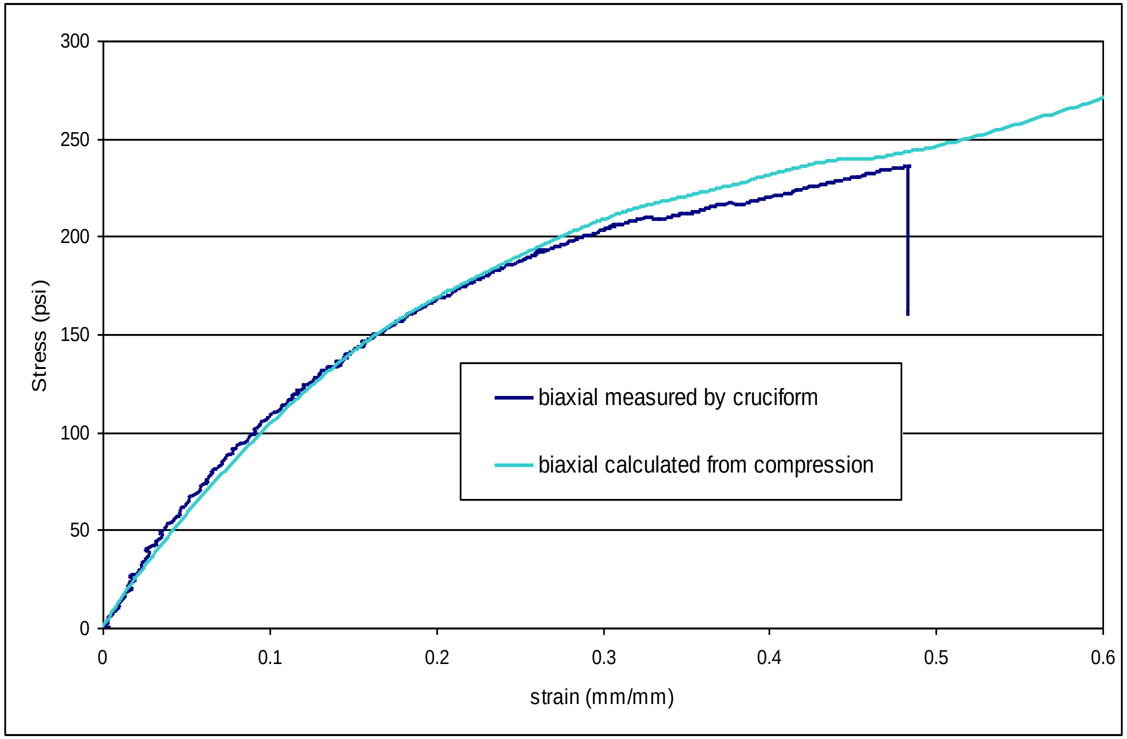




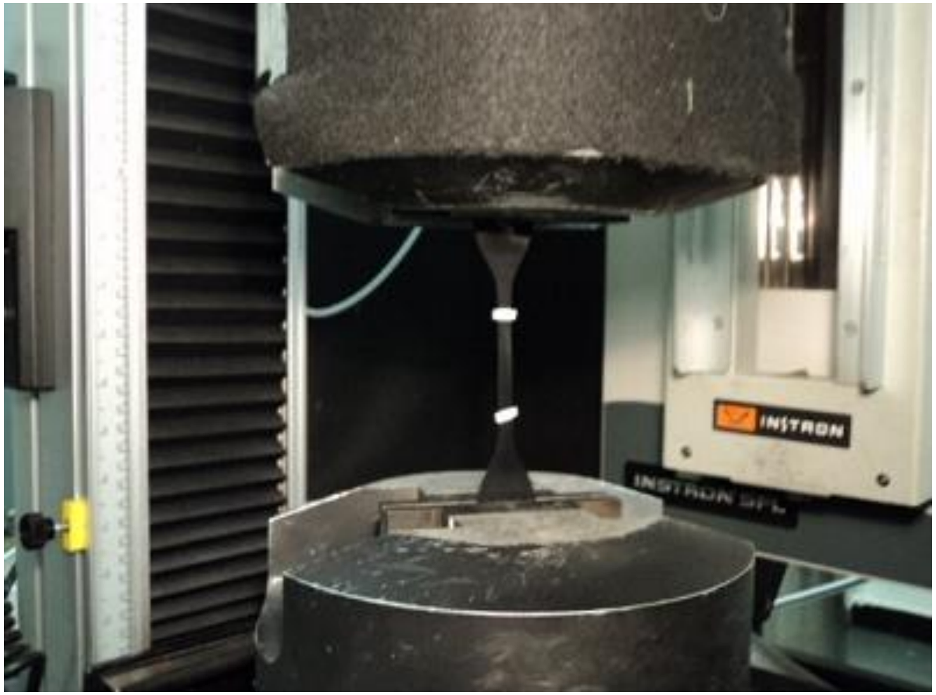
Biaxial v. Compression Testing

- Equibiaxial and compression data are equivalent
  - At least up to moderate strains

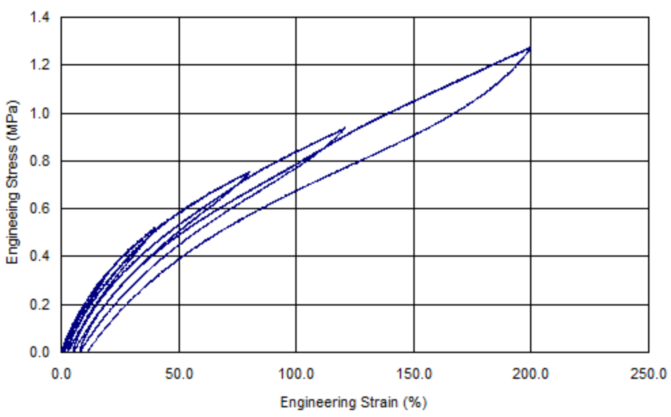
$$\varepsilon_b = (1/(\varepsilon_c+1))^{1/2}-1$$
$$\sigma_b = \sigma_c/((1+\varepsilon_b)^3)$$



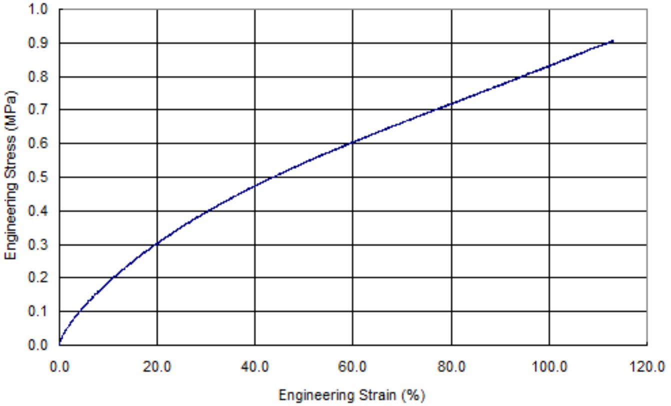
Mullins Effect Testing



Cyclic Stress-Strain Data



Post-Cycling Stress-Strain Curve



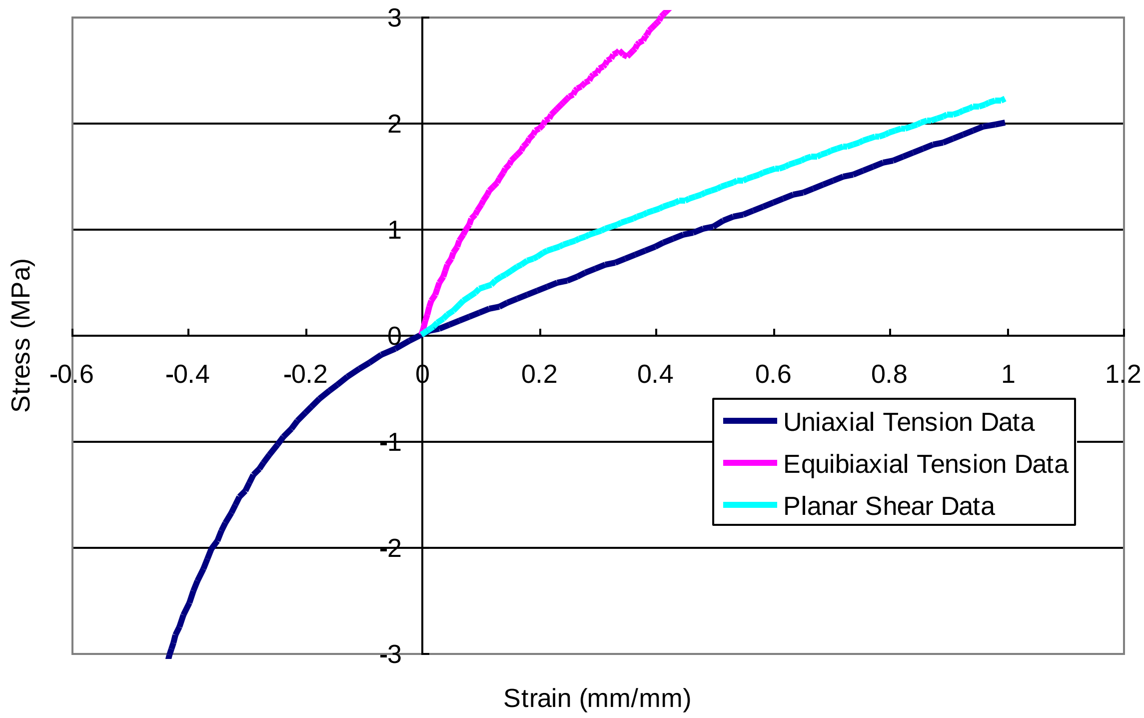
Model Selection

- Depends on magnitude of deformation
  - Small deformation
    - Use Neo-Hookean model
  - Large deformation
    - 0-100% strain typically Mooney-Rivlin
    - Over 100% Ogden

know your real life strains before you test

Typical rubber data

- Things to Note
  - Order of stiffness
    - Uniaxial
    - Planar
    - Biaxial
  - Continuous slope through origin
  - No inflections
  - Equal number of points per curve



Fitting of Test Data to Material Models

- Most models are strain energy based
  - Stretch ratio conversion
  - Each mode of deformation produces deformations in the other modes

Deformation Gradient

$$F = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$

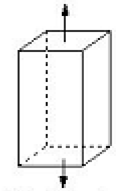
1st and 2nd Invariants

$$\overline{I}_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$

$$\overline{I}_2 = \lambda_1^{-2} + \lambda_2^{-2} + \lambda_3^{-2}$$

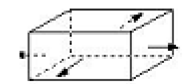
Deformation Mode Conversion

$$\lambda_1 = \lambda_U = \varepsilon_U + 1 \, , \lambda_2 = \lambda_3 = {}^{1}\!/\!\sqrt{\lambda_U}$$



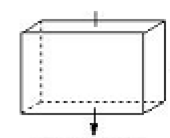
Uniaxial Tension

$$\lambda_1 = \lambda_2 = \varepsilon_B + 1 \, , \quad \lambda_3 = 1/\lambda_B^2$$



Equibiaxial Tension

$$\lambda_1 = \lambda_S = \varepsilon_S + 1 \, , \quad \lambda_2 = 1 \, , \quad \lambda_3 = {}^{1}\!/\!\lambda_S$$



Planar Tension

$$\lambda_1 = \lambda_2 = \lambda_3 = \lambda_V \, , \quad \frac{V}{V_0} = \lambda_V^3$$

Fitting of Test Data to Material Models

- Mooney-Rivlin

$$U=\sum_{i+j=1}^{N}C_{ij}(\bar{I}_1-3)^i(\bar{I}_2-3)^j+\sum_{i=1}^{N}\frac{1}{D_i}((J-1)^{2i}$$

1st and 2nd Invariants

$$\bar{I}_1=\lambda_1^2+\lambda_2^2+\lambda_3^2$$
$$\bar{I}_2=\lambda_1^{-2}+\lambda_2^{-2}+\lambda_3^{-2}$$

- Ogden

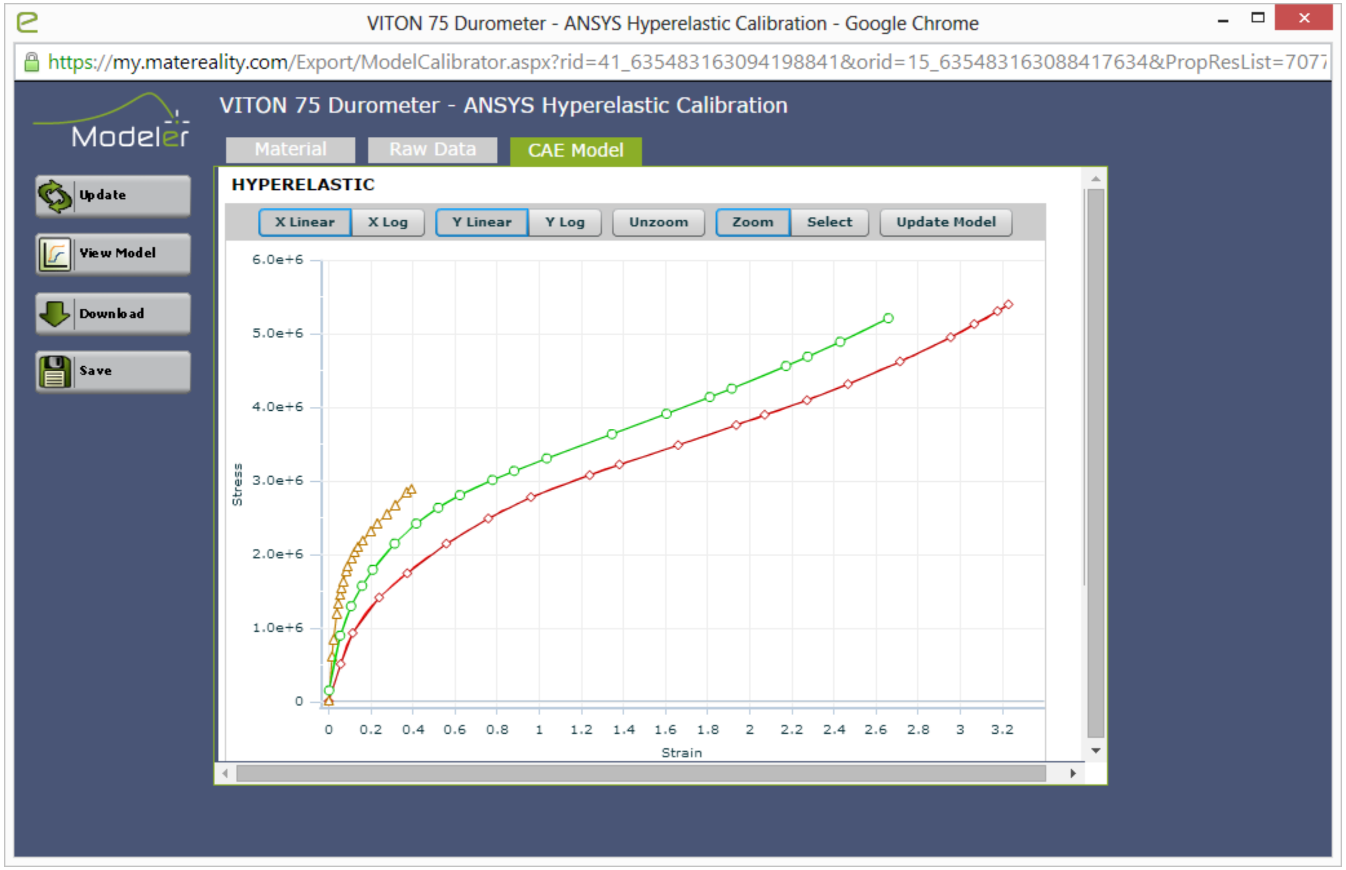
$$U=\sum_{i=1}^{N}\frac{2\mu_i}{\alpha_i^2}\left(\lambda_1^{\alpha_i}+\lambda_2^{\alpha_i}+\lambda_3^{\alpha_i}-3\right)+\sum_{i=1}^{N}\frac{1}{D_i}(J-1)^{2i}$$

- Take derivative to get into stress

$$\sigma_{Uniaxial}=\frac{\delta U}{\delta\lambda}\qquad\sigma_{Biaxial}=\frac{1}{2}\frac{\delta U}{\delta\lambda}\qquad\sigma_{Planar}=\frac{\delta U}{\delta\lambda}$$

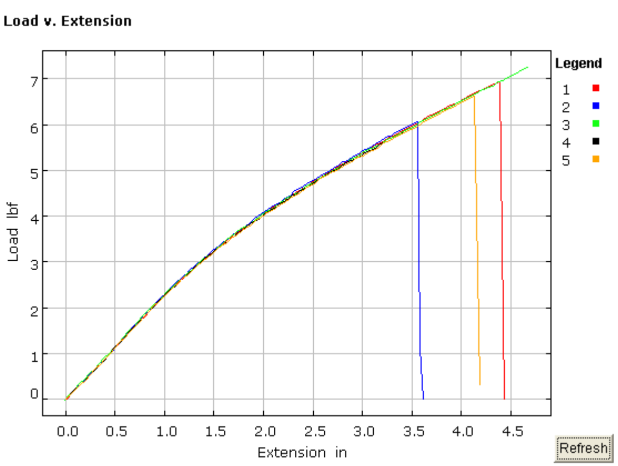
- Fit simultaneous equations

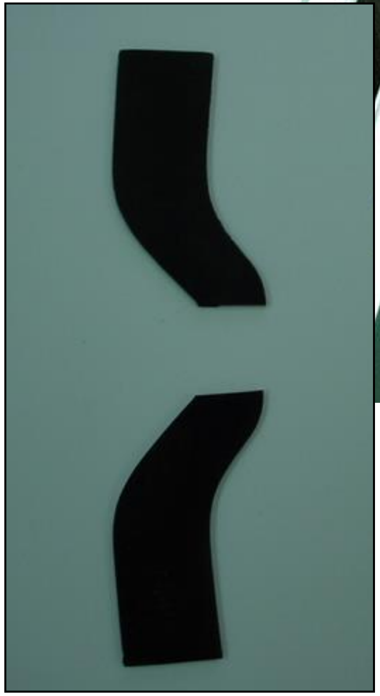
Rubber Modeling



Handling failure

- Perform tear strength test on rubber
  - ASTM D624 Type C ‘bow-tie’
  - Obtain test data

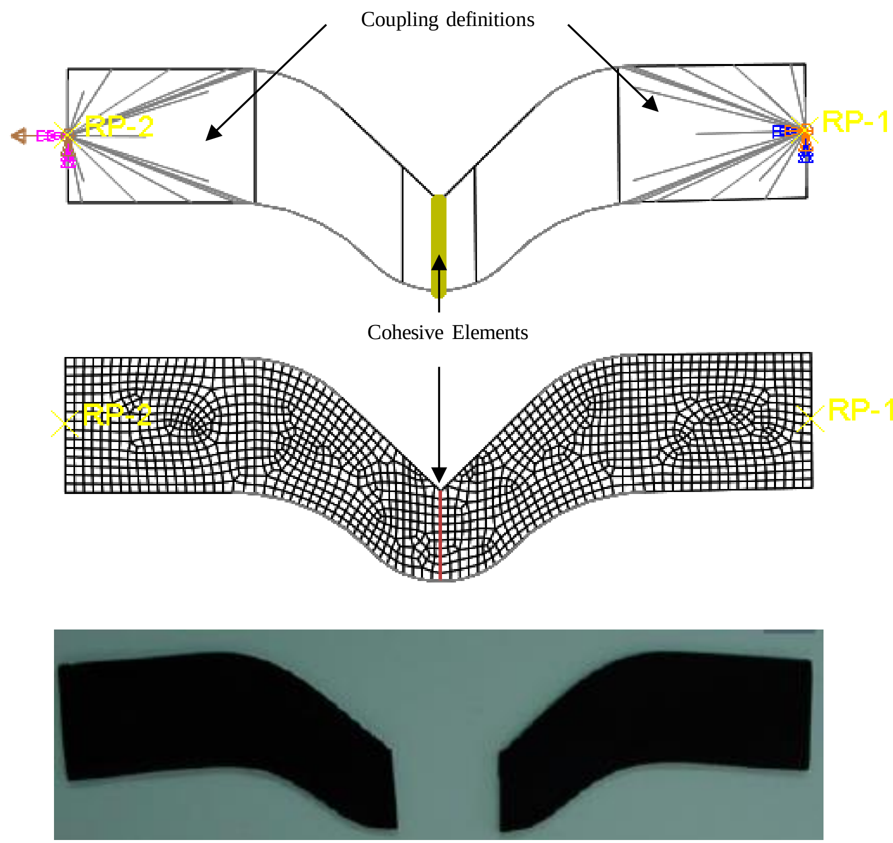




Credits: Nair, Bestelmeyer, Lobo (2009)

Handling failure in elastomers

- Model failure with cohesive elements
  - Obtain fail strength to elements
- Apply to real-life model
  - Damage path must be known or postulated



Failure mode during the tear test (ASTM D624 Type C Specimen)

Credits: Nair, Bestelmeyer, Lobo (2009)

CAETestBench Validation Mechanism

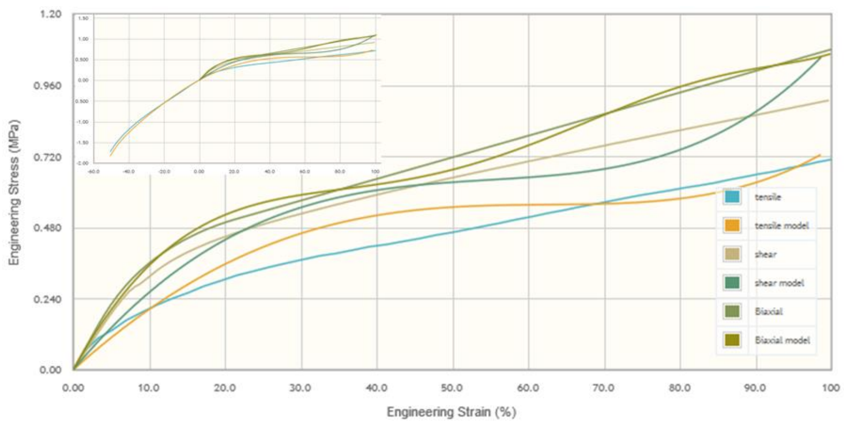
- Use a standardized geometry
  - May not be real-life part
- Test must be ‘perfect’
  - Boundary conditions can be correctly simulated
  - Load case can be correctly simulated
- Comparison
  - Obtain test output that is also available in simulation
  - For example, DIC strain pattern, force v. time…

Overview of this Validation

- Measure hyperelastic properties
- Create material model
- Devise “standardized” compression test
    - Both faces slipping (closed loop case)
    - Top face fixed (open loop)
    - Top and bottom faces fixed (open loop)
- Simulate and compare to experiment
- Quantify simulation accuracy

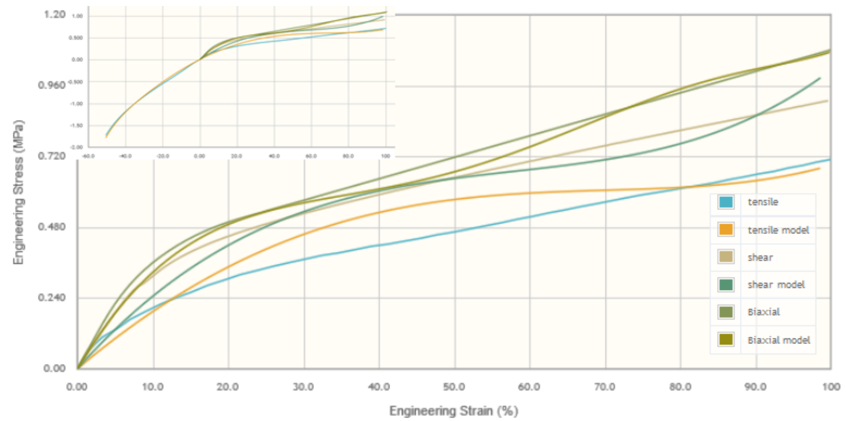
Mooney-Rivlin 9 Parameter

Matereality



C10	3.47E-01	MPa
C01	3.52E-02	MPa
C20	-1.36E-01	MPa
C11	2.88E-02	MPa
C02	-7.90E-03	MPa
C30	2.33E-02	MPa
C21	1.44E-02	MPa
C12	-1.15E-02	MPa
C03	1.91E-03	MPa
D1	1.34E-03	1/MPa

Workbench

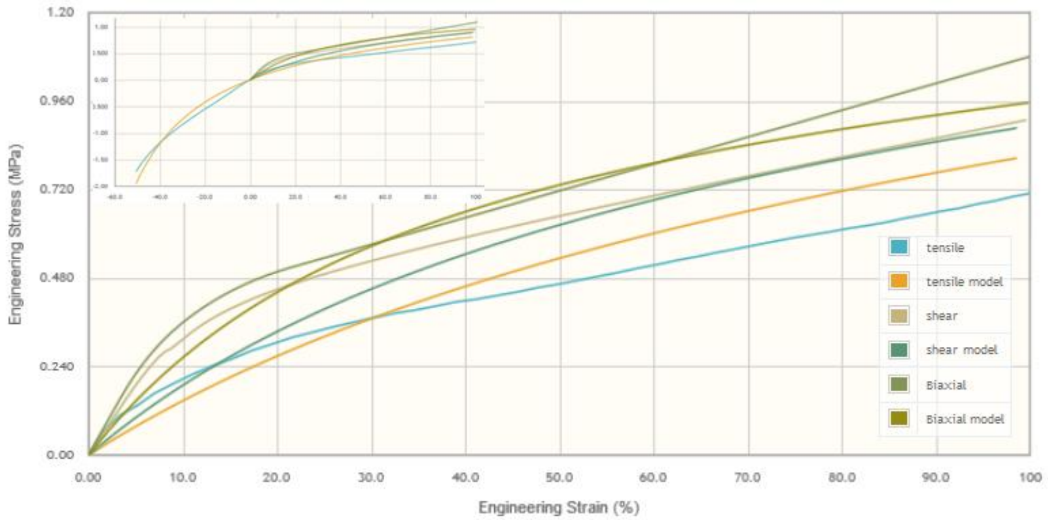


C10	3.64E-01	MPa
C01	-5.81E-03	MPa
C20	-1.19E-01	MPa
C11	4.54E-02	MPa
C02	-1.11E-02	MPa
C30	1.38E-02	MPa
C21	1.35E-02	MPa
C12	-9.47E-03	MPa
C03	1.56E-03	MPa
C10	3.64E-01	MPa

Ogden 3 Term

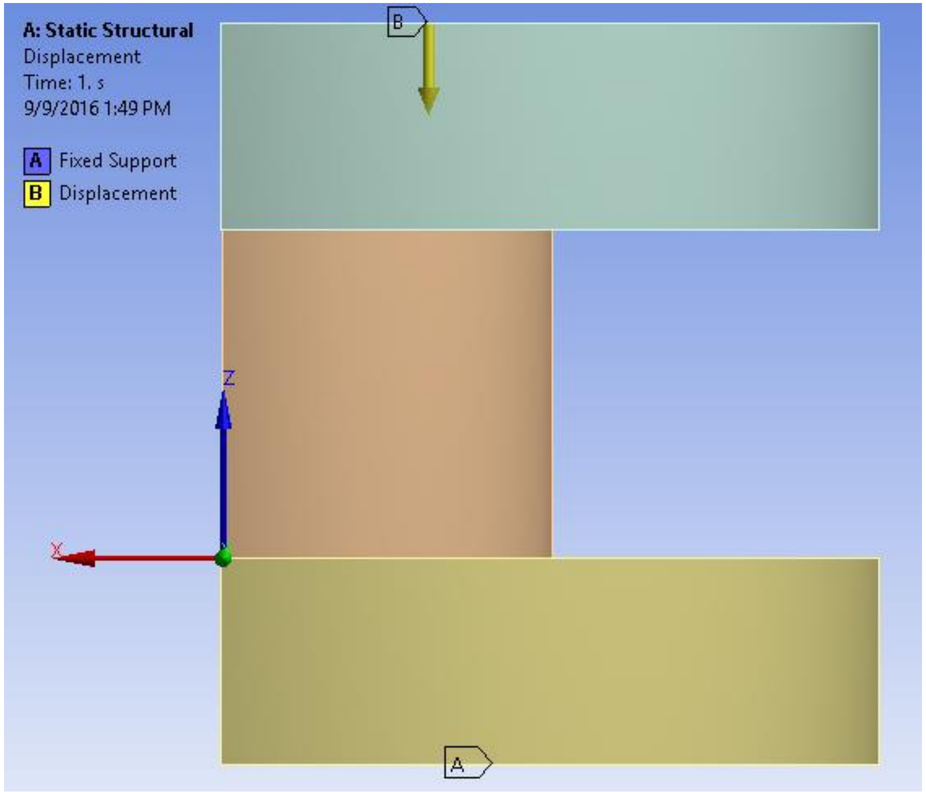
Matereality

MU1	3.715023	MPa
MU2	-1.58648	MPa
MU3	-1.58647	MPa
A1	1.141617	
A2	0.994652	
A3	0.99404	
D1	0.001763	1/MPa
D2	3.1128e-5	1/MPa
D3	-1.5446e-6	1/MPa



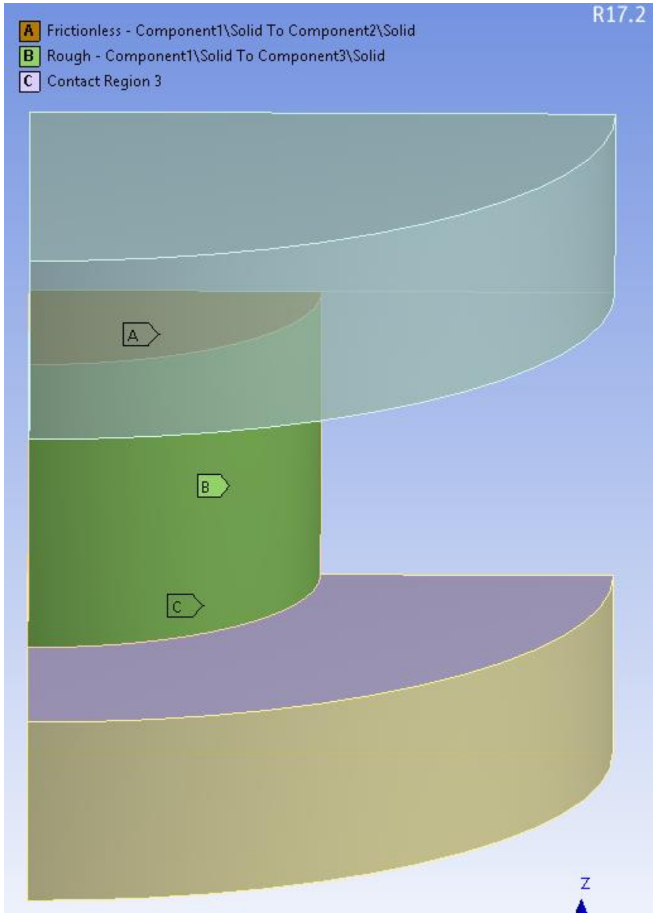
Simulation B.C.s

- Top is displaced
- Bottom platen fixed
- Contact varies between sliding and fixed
- Quarter model



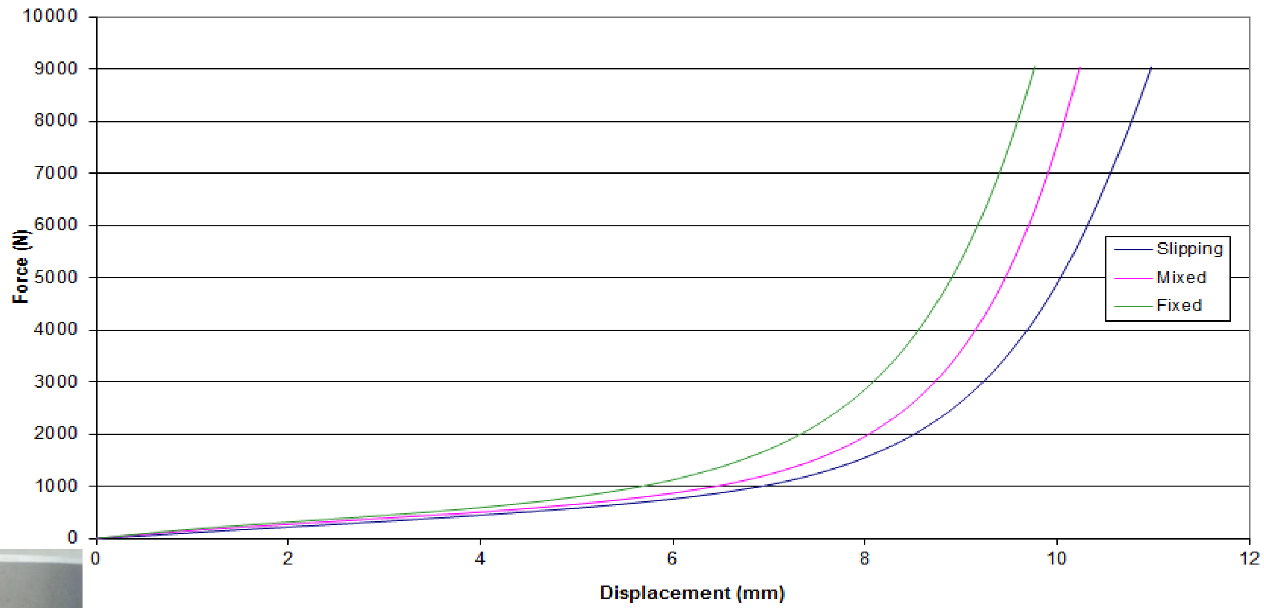
Contact Conditions

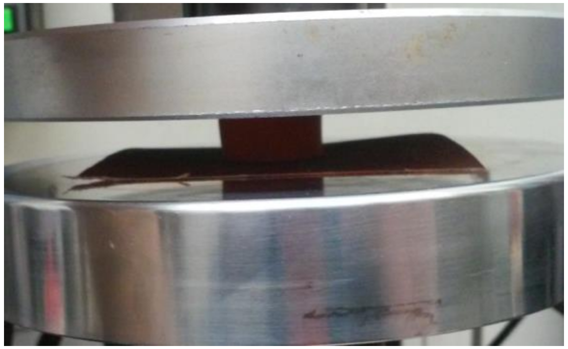
Quarter model, symmetry on the x and y faces		
Fixed bottom platen		
Displacement to 6.35mm on the top platen		
Bonded contacts accompany a rough contact for the circumferential side		
Contact	Location	Type
Slipping	Top	Frictionless
	Bottom	Frictionless
Mixed	Top	Frictionless
	Bottom	Bonded
Fixed	Top	Bonded
	Bottom	Bonded



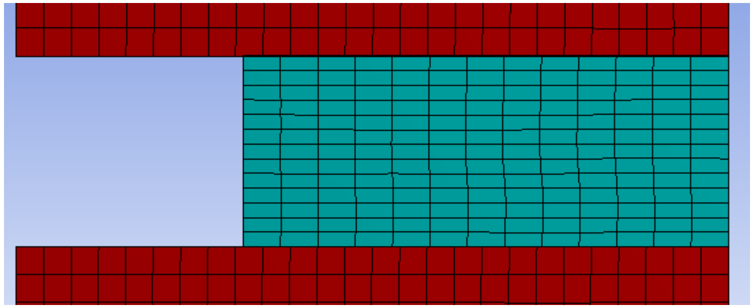
Validation Experiments

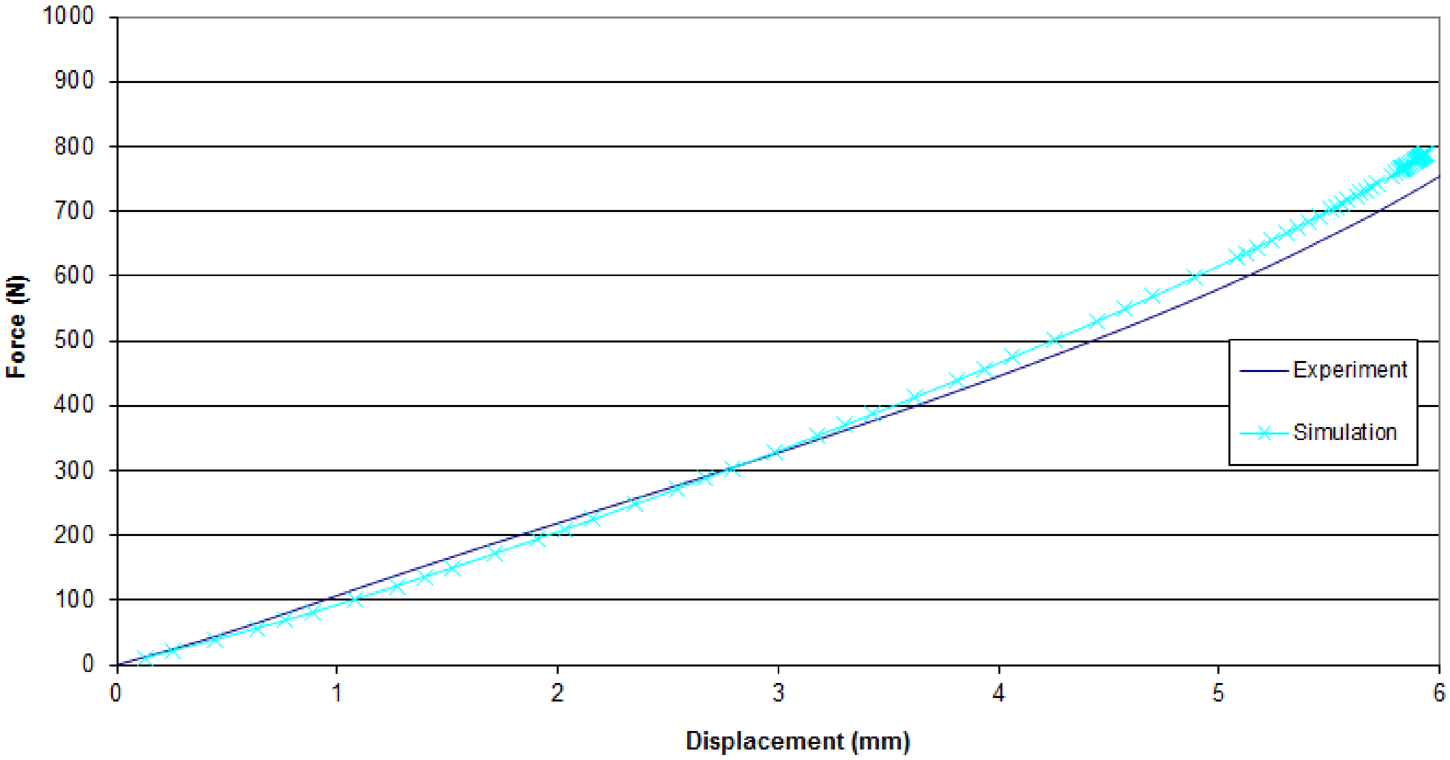
- Slip
- Mixed
- Fixed





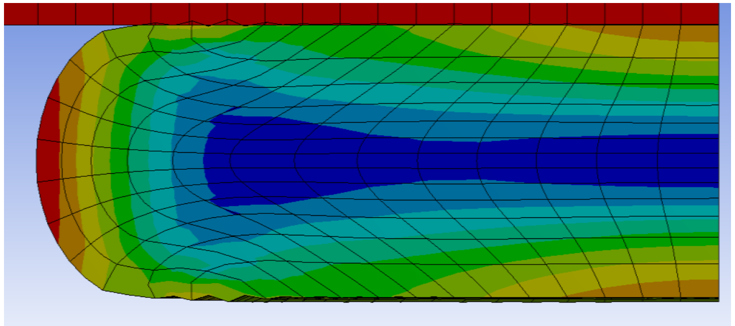
Slip

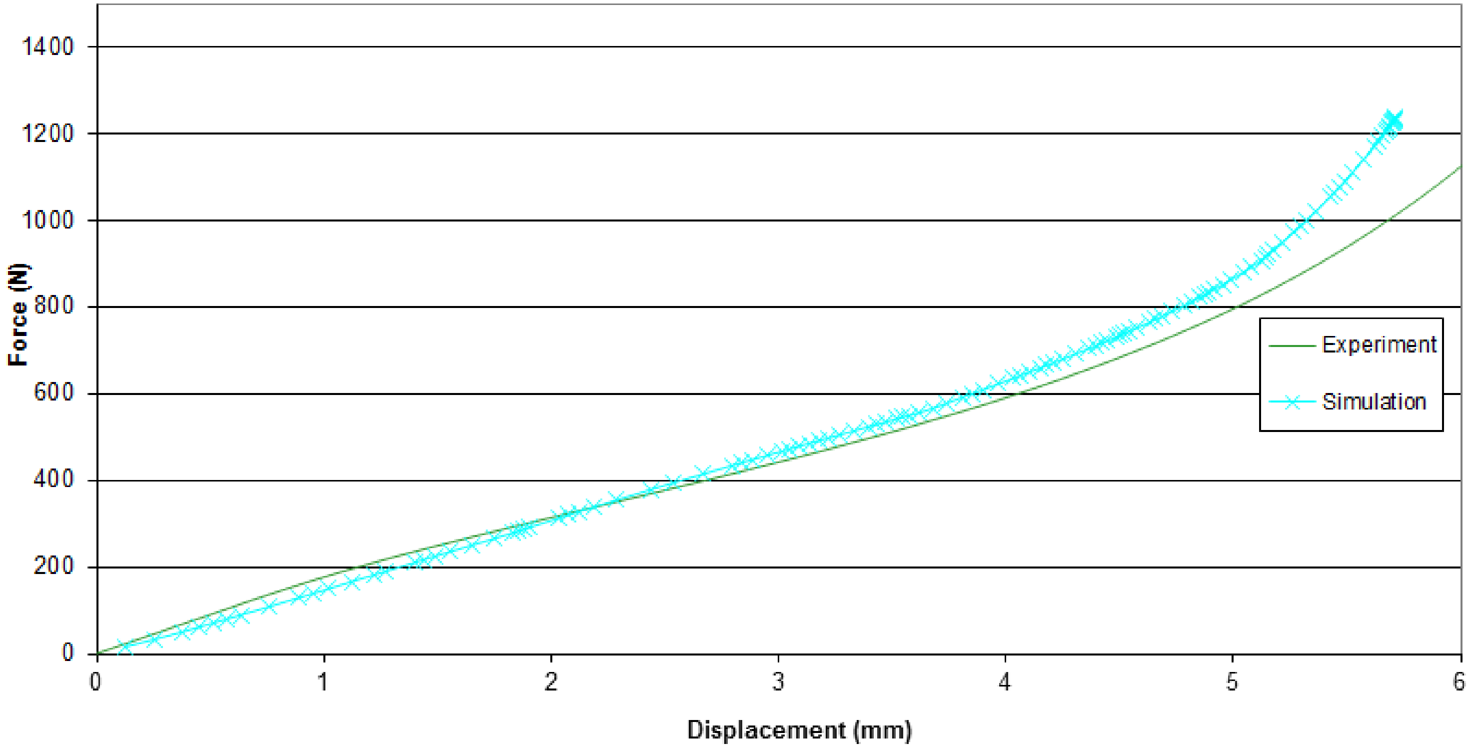




Force (N)
1000
900
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
Displacement (mm)
Experiment
Simulation

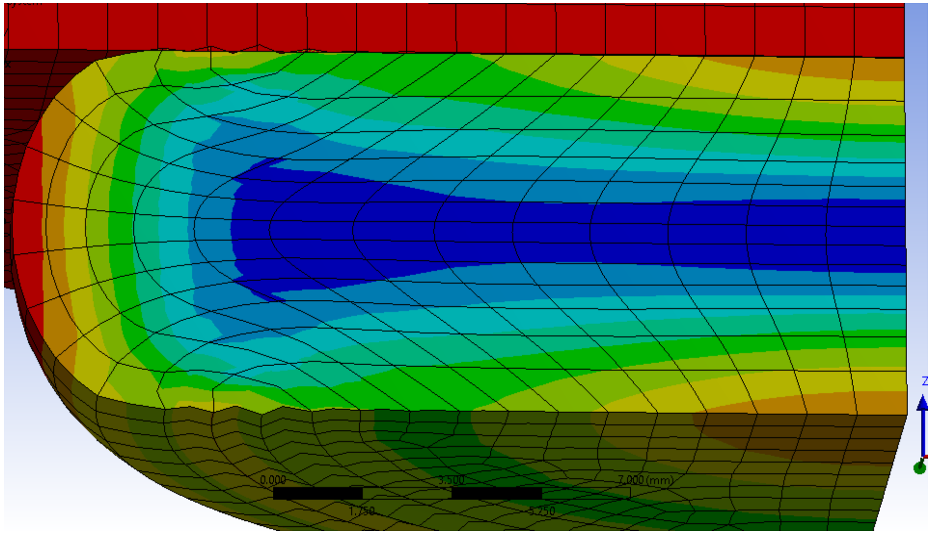
Fixed



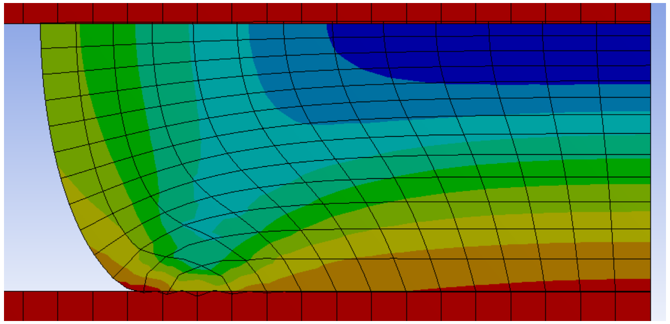

Force (N)
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
Displacement (mm)
Experiment
Simulation

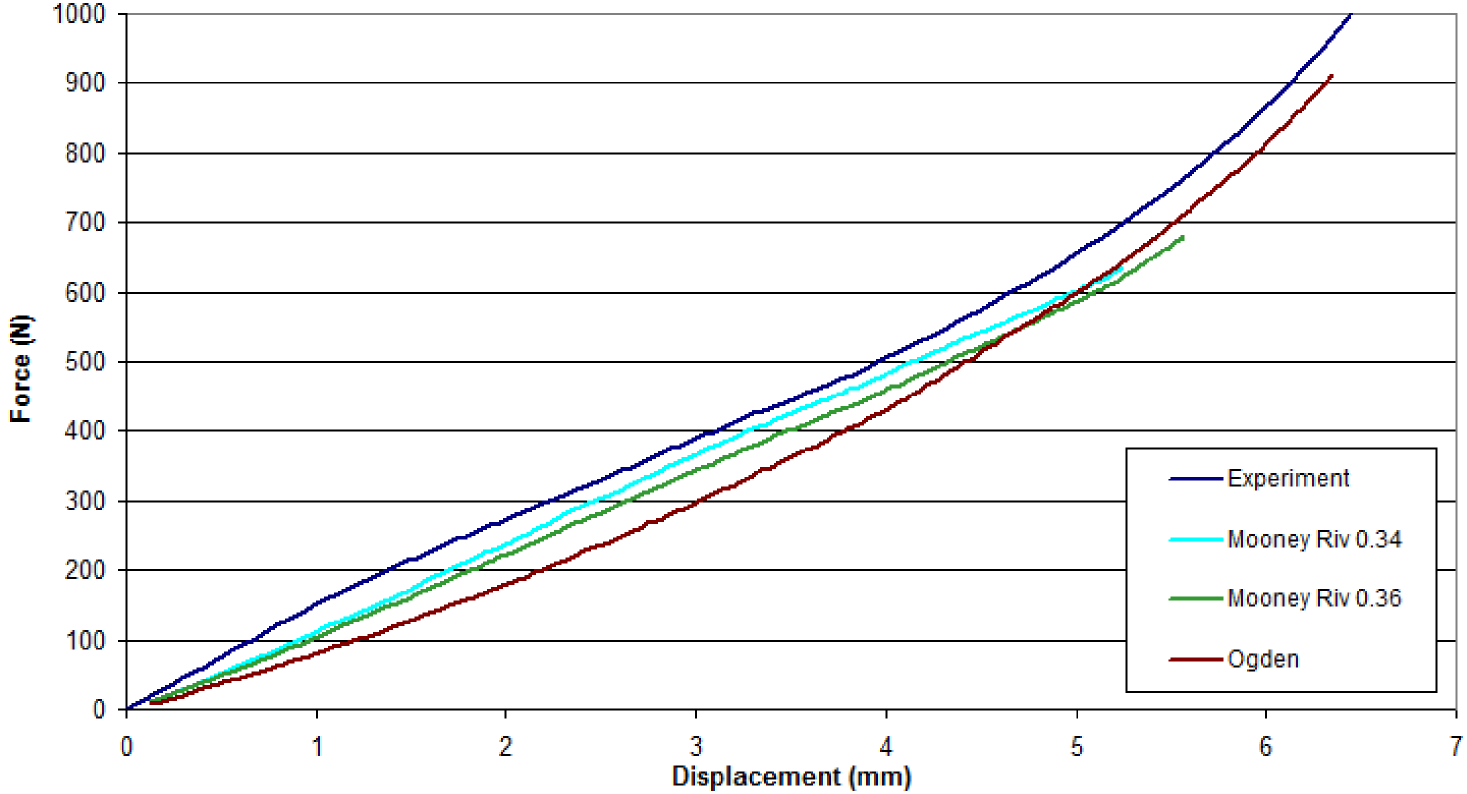
Contact Issues

- Fixed boundary has roll over which is addressed with the rough contact
- The corner element and nearby mesh are distorted

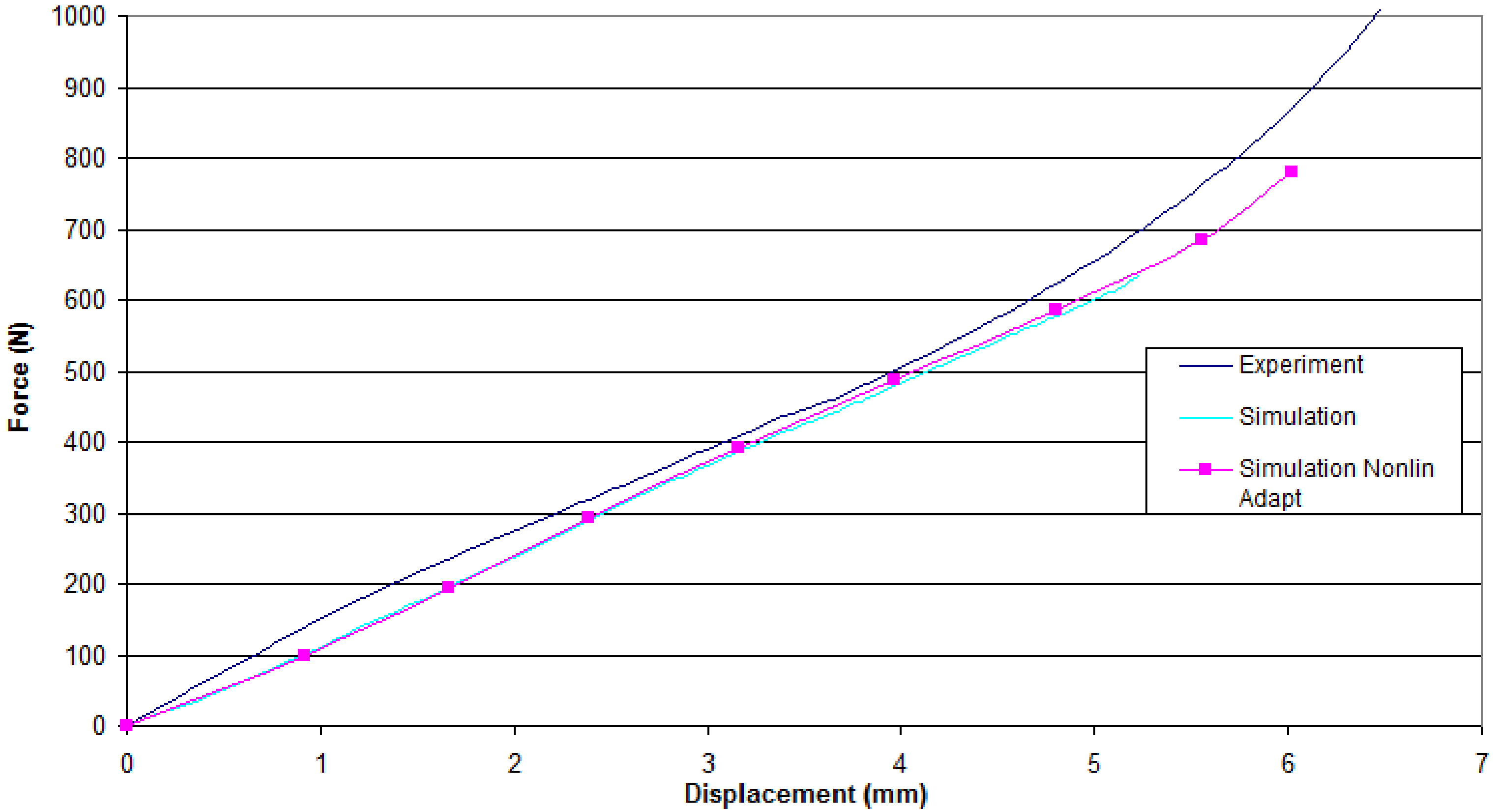


Mixed




1000
900
800
700
600
500
400
300
200
100
0
Force (N)
0
1
2
3
4
5
6
7
Displacement (mm)
Experiment
Mooney Riv 0.34
Mooney Riv 0.36
Ogden

Mix - Nonlinear Adaptive Mesh



Results

- Accurate for moderate strains (40%)
- Closed-loop validation unsurprisingly shows least deviation
- The most complex set of boundary conditions (mixed) has the least accuracy
- Different data fitting programs yields variability on parameters, with only slight impact on the simulation

Conclusions

- Validation of simulation quantifies the difference between virtual world and reality
- Should be performed each time a material is being tested for use in simulation
- Data, model, and simulation can be checked using test cases that contain real-life behaviors, giving confidence to the analyst