Midwest ANSYS Users Group

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Analyzing Hyperelastic Materials

w/ Some Practical Considerations

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Updated by: Vince Adams; IMPACT

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What Is a Hyperelastic Material ?

- Can experience large strains (up to 500%) and most of it - if not all - is recoverable.
- Rubber is a hyperelastic material; behavior is reminiscent of a viscous fluid during its processing to shape.
- The vulcanization and/or curing of rubber type materials causes their polymer chains to crosslink which allows the material to fully recover from elastic deformations.
- Load-Extension behavior is nonlinear
- Nearly incompressible – Exception is some rubber foam materials where large volume changes can be achieved.
- Low Cost / Flexible / Resilient - Work in many environments (moisture, pressure, heat)

Where are Hyperelastic Materials Used?

- Automotive (Tires, Belts, Hoses, Mounts)
- Aerospace (Remember the failed O-ring on the Space Shuttle ??)
- Biomedical/Dental Industries (artificial organs, wheelchairs, implantable surgical devices)
- Packaging (Styrofoam)
- Sports (Equipment safety, Shoes, Helmets)

Available Hyperelastic Material Models in ANSYS 9.0

- Mooney-Rivlin, Polynomial Form, Neo-Hookean, Ogden Potential, Arruda-Boyce, Gent, Yeoh
- For special apps like foam:
  Use Blatz-Ko and Ogden Compressible Foam

Beyond the available models in ANSYS 9.0

- User-Programmable Features (UPFs) are available to code your own material model.

- Currently available UPFs for hyperelasticity use **HYPERxx** types of elements.

Material Modeling Basics…

- A poor material model will
  - Prevent your FE model from running
  - MOST likely will give you erroneous results and you will not even know it….
- Minimum Data: Uniaxial tension
  - Try a NeoHookean Material
- Best Scenario: Uniaxial AND Biaxial Tension + Pure Shear.
- Do a Curve Fit and plot both test and fitted data on same plot.
- Chapter 4 *Structures with Material Nonlinearities in ANSYS*
  - Figures 4.16 and 4.17 give you all the available AND equivalent testing modes

Material Modeling Basics…

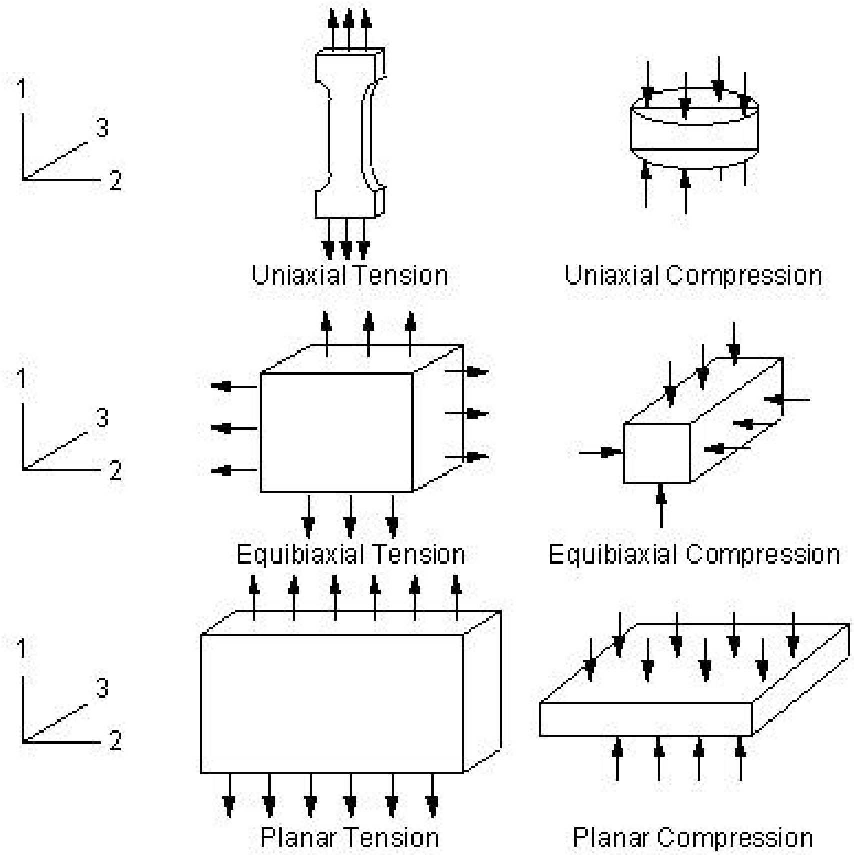


Figure 4.16 – Deformation Modes

Source: ANSYS 9.0 Theory – Chapter 4.6

Material Modeling Basics…

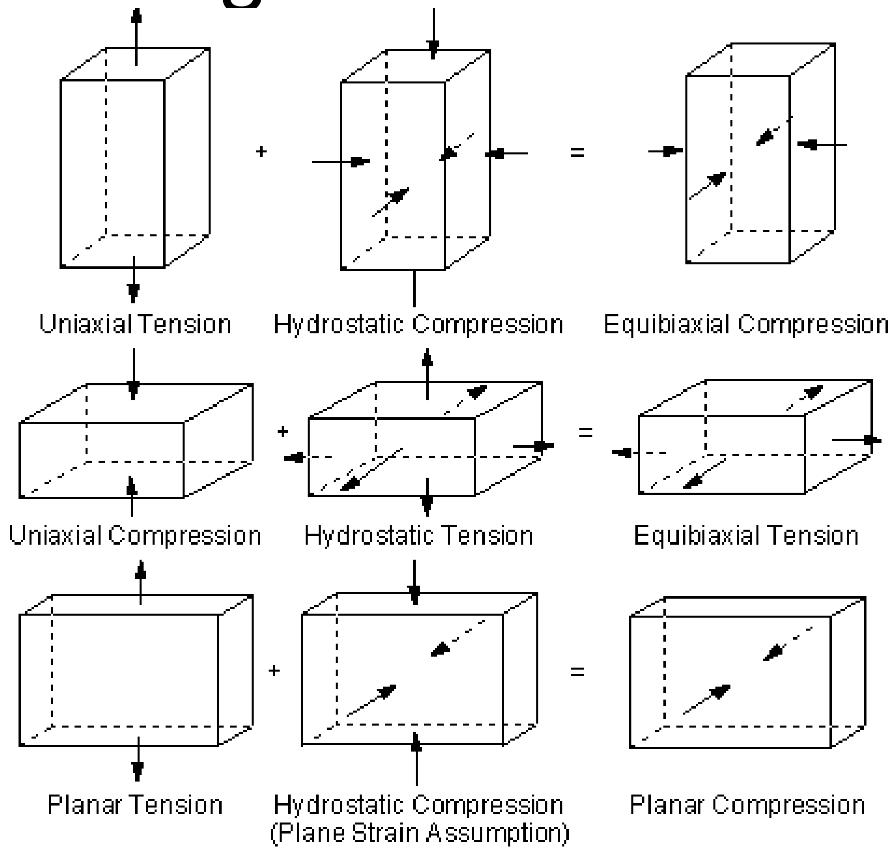
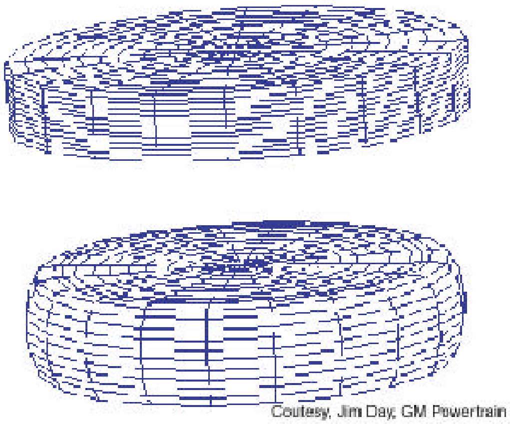


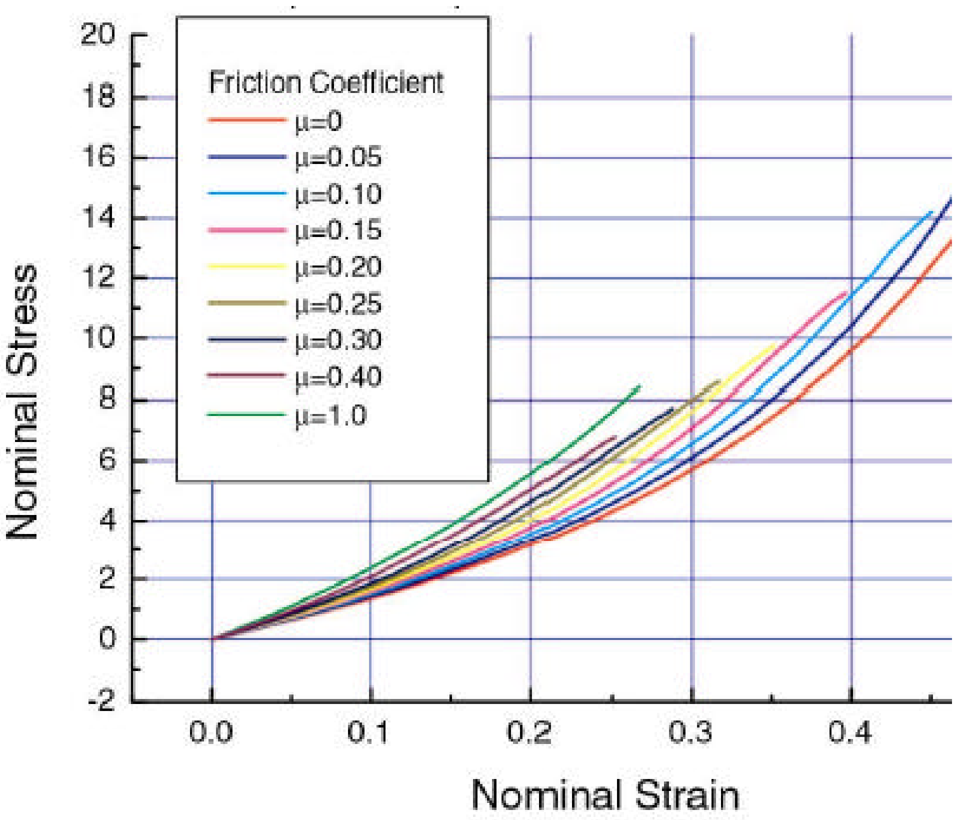
Figure 4.17 – Equivalent testing modes

Source: ANSYS 9.0 Theory – Chapter 4.6

Equibiaxial vs. Compression Testing

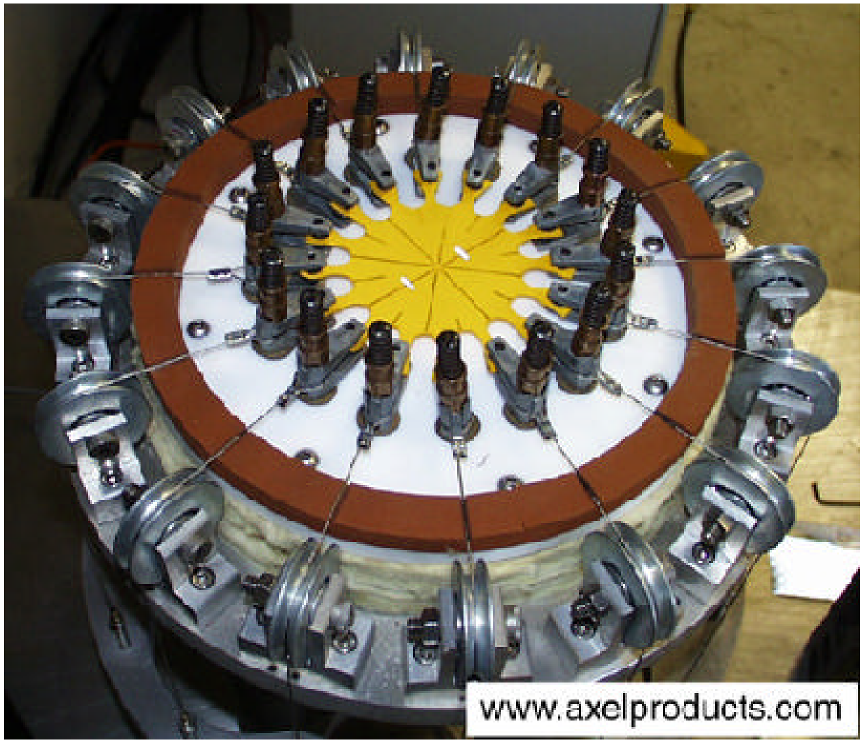
- Pure Compression Requires:
- Uniaxial Loading
- No Lateral Constraints
  - i.e. No Friction

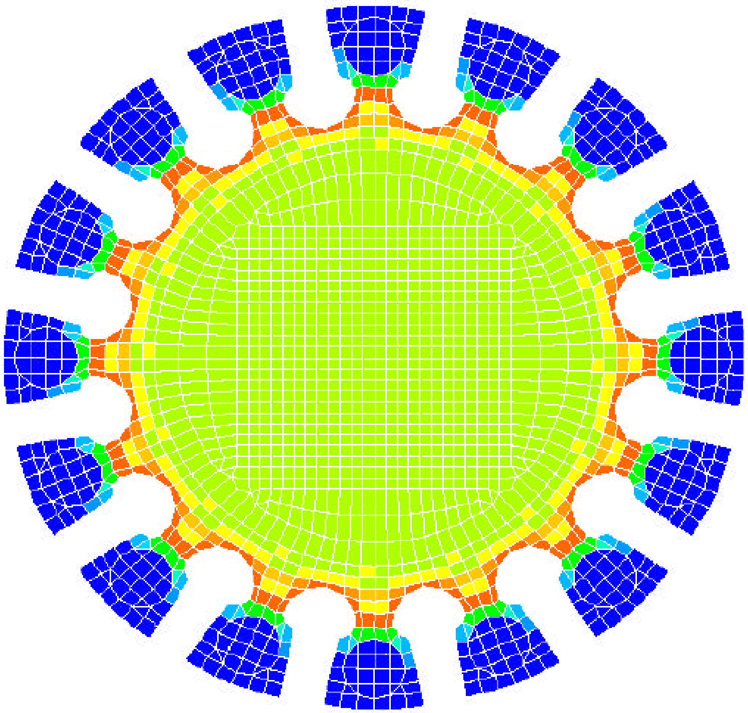




Friction Affects Compression Test Data

Equibiaxial vs. Compression Testing





While not intuitive, Equibiaxial testing gives same response as pure compression

Observations on Material Testing

1. The stress strain function for the 1st time an elastomer is strained is never again repeated. It is a unique event.

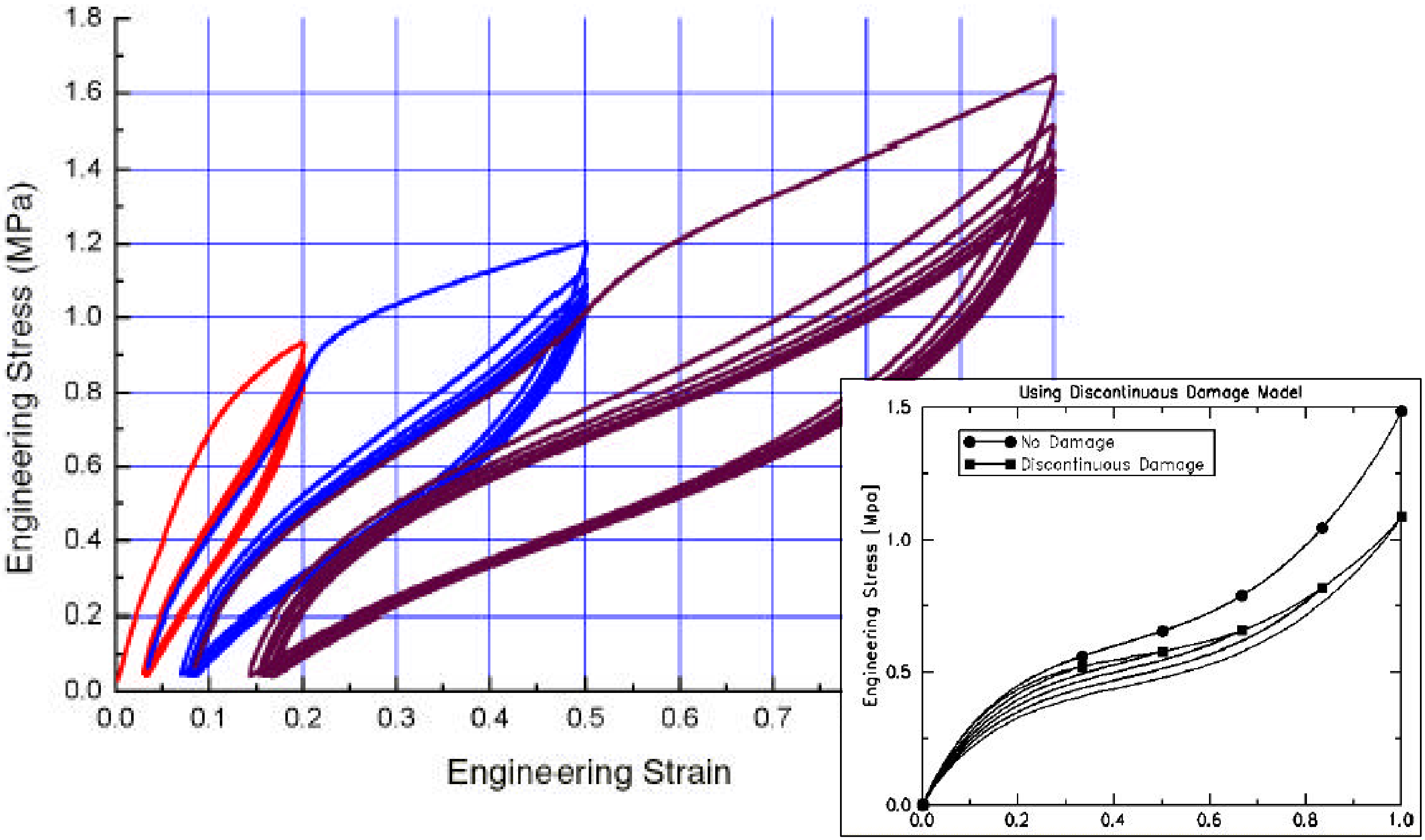
2. The stress strain function does stabilize after between 3 and 20 repetitions for most elastomers.

3. The stress strain function will again change significantly if the material experiences strains greater than the previous stabilized level. In general, the stress strain function is sensitive to the maximum strain ever experienced.

4. The stress strain function of the material while increasing strain is different than the stress strain function of the material while decreasing strain.

5. After the initial straining, the material does not return to zero strain at zero stress. There is some degree of permanent deformation.

Cyclic Damage and Mullins Effect



Limitations of Hyperelastic Mat'l Models

Most material models only allow the analyst to describe only a subset of the structural properties of elastomers. In the Mooney-Rivlin and Ogden formulations:

1. The stress strain functions in the model are stable. They do not change with repetitive loading. The material model does not differentiate between a 1st time strain and a 100th time straining of the part under analysis.

2. There is no provision to alter the stress strain description in the material model based on the maximum strains experienced.

3. The stress strain function is fully reversible so that increasing strains and decreasing strains use the same stress strain function. Loading and unloading the part under analysis is the same.

4. The models treat the material as perfectly elastic meaning that there is no provision for permanent strain deformation. Zero stress is always zero strain.

Where is Material Tested ??

- Always test your material with loading that is similar to the actual application
- Contact Axel Products or **Datapoint**Labs for guidelines on what is required.
- Visit their websites and **RTFM** (**R**ead **T**heir **F**antastic **M**ethods). Many papers can be downloaded for reference.

www.axelproducts.com **www.datapointlabs.com**

axel physical testing services DatapointLabs

Curve Fitting of Hyperelastic Parameters

- The recommended method is the ANSYS Curve Fitting Wizard.
- Hardcore users: Use APDL to create your own scripts for the curve fitting portion and post-processing.
- For a decent curve fit using the M-R models, you need 2X the number of M-R Parameters.
- Papers on www.ansys.net provide in-depth info on these techniques… Most will be posted to the MAG site

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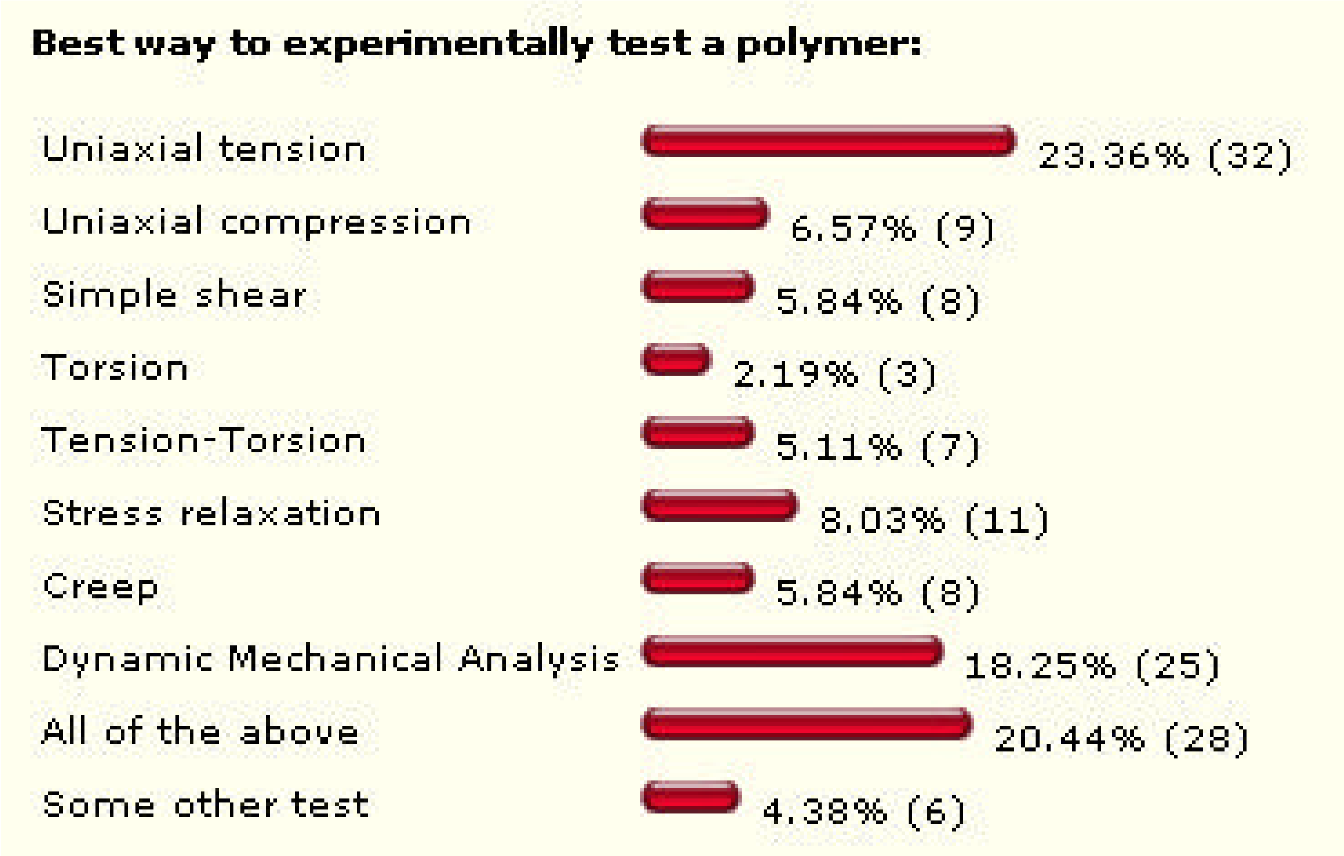
Testing Procedures…



Source http://www.polymerfem.com > Surveys

TIP: DEPENDING ON YOUR DESIGN/APPLICATION NEEDS <u>ANY OR ALL</u> MAY BE REQUIRED FOR THE MATERIAL AT HAND

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2-P Mooney-Rivlin vs. Shore Hardness

Mooney Rivlin Parameters - METRIC

Shore-A [°]	Young's Modulus [N/mm2]	Shear Mod (G [N/mm2]	C10 [N/mm2]	C01 [N/mm2]
35	1.102	0.406	0.162	0.041
36	1.148	0.407	0.163	0.041
37	1.199	0.412	0.165	0.041
38	1.255	0.421	0.168	0.042
39	1.315	0.435	0.174	0.044
40	1.381	0.452	0.181	0.045
41	1.452	0.473	0.189	0.047
42	1.530	0.496	0.198	0.050
43	1.613	0.523	0.209	0.052
44	1.703	0.551	0.220	0.055
45	1.800	0.581	0.232	0.058
46	1.904	0.613	0.245	0.061
47	2.015	0.647	0.259	0.065
48	2.134	0.682	0.273	0.068
49	2.261	0.718	0.287	0.072
50	2.397	0.755	0.302	0.076
51	2.540	0.793	0.317	0.079
52	2.693	0.832	0.333	0.083
53	2.855	0.872	0.349	0.087
54	3.026	0.914	0.366	0.091
55	3.207	0.956	0.382	0.096
56	3.398	0.999	0.400	0.100
57	3.599	1.043	0.417	0.104
58	3.811	1.089	0.436	0.109
59	4.034	1.136	0.454	0.114
60	4.268	1.185	0.474	0.118
61	4.513	1.236	0.494	0.124
62	4.771	1.289	0.516	0.129
63	5.040	1.345	0.538	0.135
64	5.322	1.403	0.561	0.140
65	5.616	1.465	0.586	0.147
66	5.924	1.531	0.612	0.153
67	6.244	1.600	0.640	0.160
68	6.579	1.675	0.670	0.168
69	6.927	1.754	0.702	0.175
70	7.289	1.839	0.736	0.184

E (psi) = $11.427 * A - 0.4445 * A^2 + 0.0071 * A^3$

How good is it ?

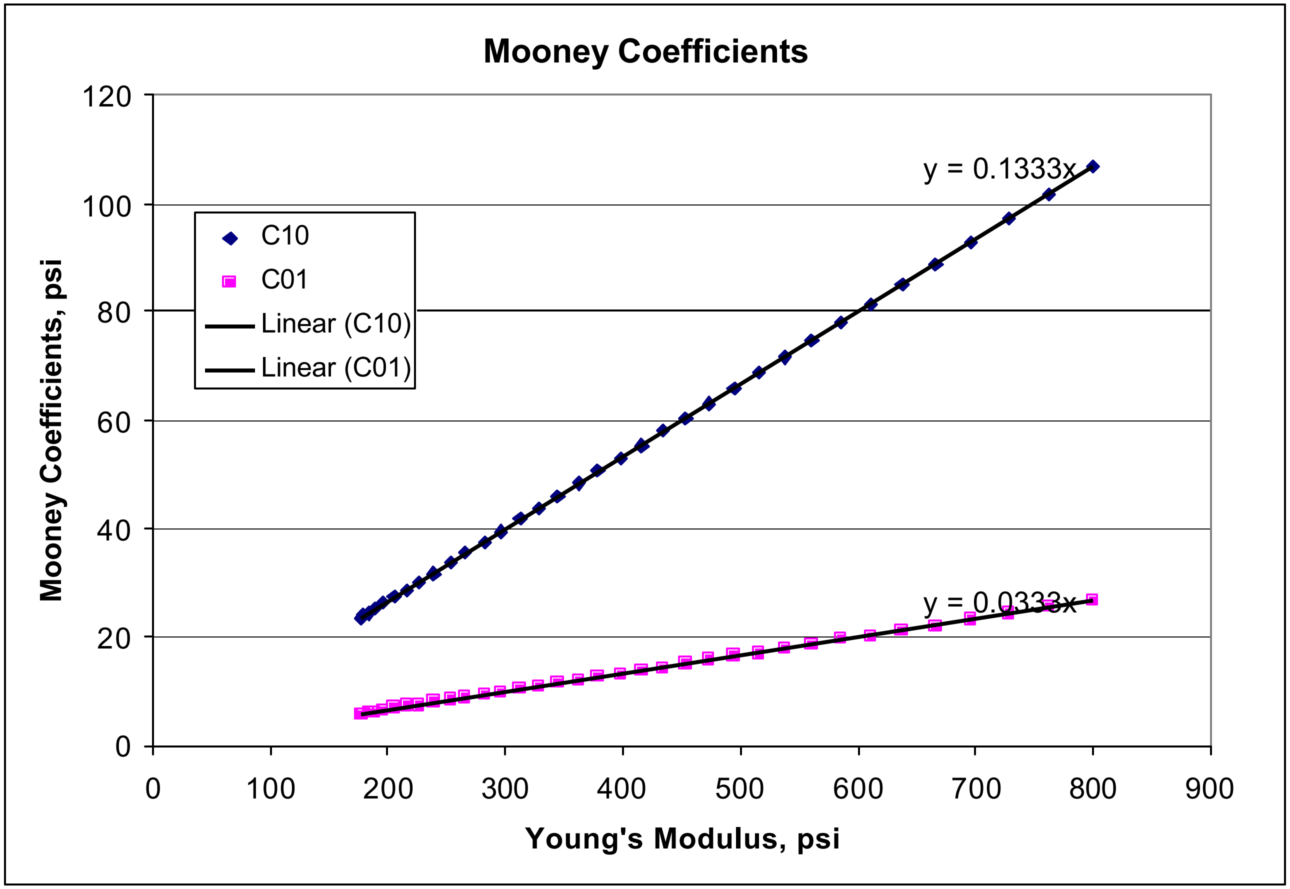
- **Has been seen in ANSYS and other user groups**
- **ONLY For Reference**
- **Experience has shown that it is not consistent for ALL GRADES and TYPES of hyperelastic materials.**

Worth using it in ANSYS as a first-pass analysis ??

- **I'd rather test the material at hand in tension at least.**

2-P Mooney-Rivlin vs. Shore Hardness

Shore-A	E	C10	C01
[°]	psi	psi	psi
35	176.61	23.49	5.945
36	177.045	23.635	5.945
37	179.22	23.925	5.945
38	183.135	24.36	6.09
39	189.225	25.23	6.38
40	196.62	26.245	6.525
41	205.755	27.405	6.815
42	215.76	28.71	7.25
43	227.505	30.305	7.54
44	239.685	31.9	7.975
45	252.735	33.64	8.41
46	266.655	35.525	8.845
47	281.445	37.555	9.425
48	296.67	39.585	9.86
49	312.33	41.615	10.44
50	328.425	43.79	11.02
51	344.955	45.965	11.455
52	361.92	48.285	12.035
53	379.32	50.605	12.615
54	397.59	53.07	13.195
55	415.86	55.39	13.92
56	434.565	58	14.5
57	453.705	60.465	15.08
58	473.715	63.22	15.805
59	494.16	65.83	16.53
60	515.475	68.73	17.11
61	537.66	71.63	17.98
62	560.715	74.82	18.705
63	585.075	78.01	19.575
64	610.305	81.345	20.3
65	637.275	84.97	21.315
66	665.985	88.74	22.185
67	696	92.8	23.2
68	728.625	97.15	24.36
69	762.99	101.79	25.375
70	799.965	106.72	26.68



From Waltz (XANSYS)

2-P Mooney-Rivlin vs. Shore Hardness

E (psi) = 11.427*A -0.4445*A^2 + 0.0071*A^3 Lindemann (XANSYS)

From E. F. Gobel, Rubber Springs Design, John Wiley, New York, 1978.

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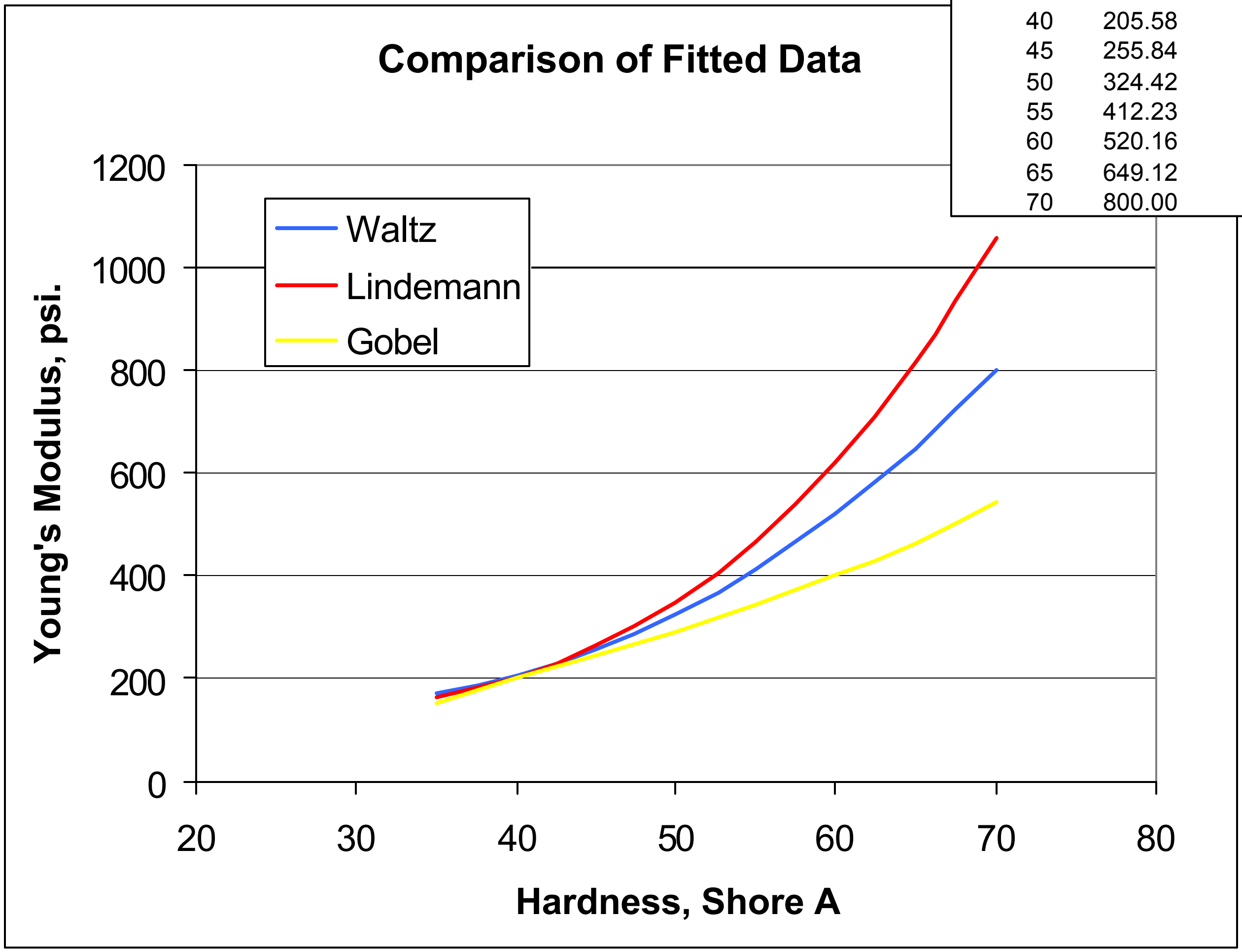
2-P Mooney-Rivlin vs. Shore Hardness

Shore A	Waltz	Lindemann	Gobel
35	172.75	159.85	154.42
40	205.58	200.28	198.56
45	255.84	261.09	244.15
50	324.42	347.60	291.63
55	412.23	465.14	342.36
60	520.16	619.02	398.58
65	649.12	814.58	463.45
70	800.00	1057.14	541.01



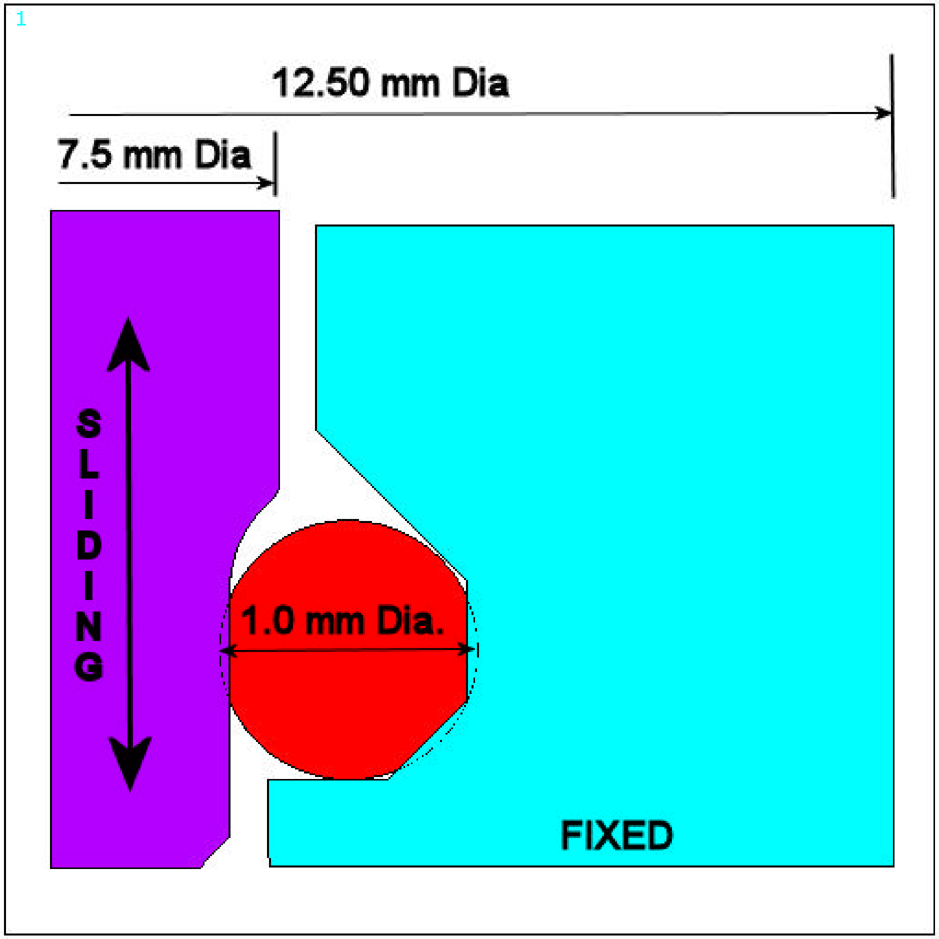
Material Model Recommendations

Material	Hyperelastic Model
Acrylate-butadiene rubber	Neo-Hookean
Chloroprene Rubber	Arruda-Boyce / Yeoh
Natural Rubber (55 pph CB)	Yeoh
Nitrile Rubber	Neo-Hookean
Silicon Rubber	Arruda-Boyce
Viton	Arruda-Boyce

Source http://www.polymerfem.com

Other material models from the same source may be used in ANSYS via UPFs.

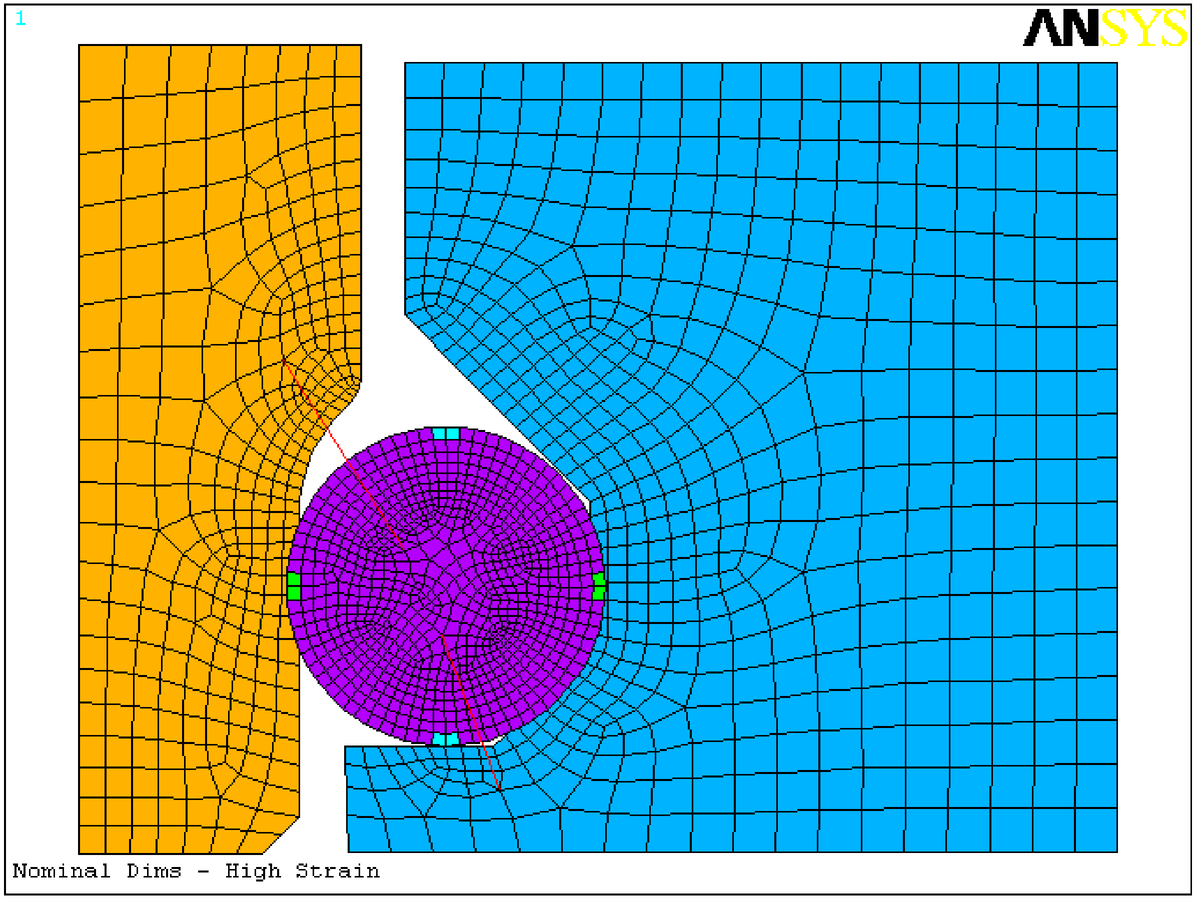
Example of O-Ring Compression



Example of O-Ring Compression

- **Scope:** *The performance of an O-Ring (used in a medical device) during assembly as a seal needs to be analyzed and the contact forces to the mating parts be extracted.*
- **Element Type:** *PLANE182 Axisymmetric (Keyopt(1)=0 Full integration with B-bar method (No Hourglass control)*
- **Materials:** *O-Ring: Hyperelastic Material (Other grade information not available); All other parts: Steel*

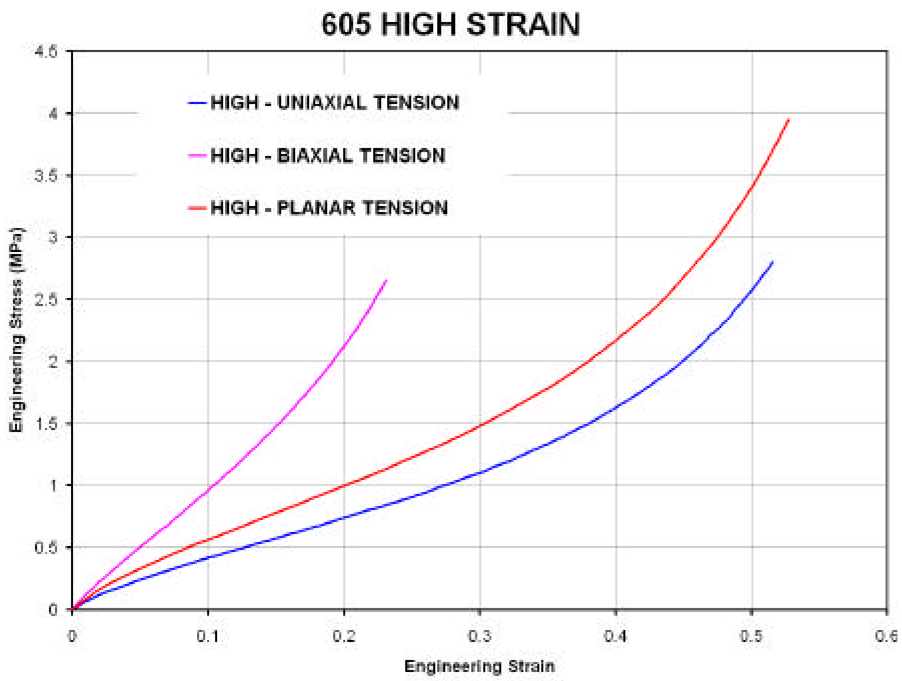
Example of O-Ring Compression

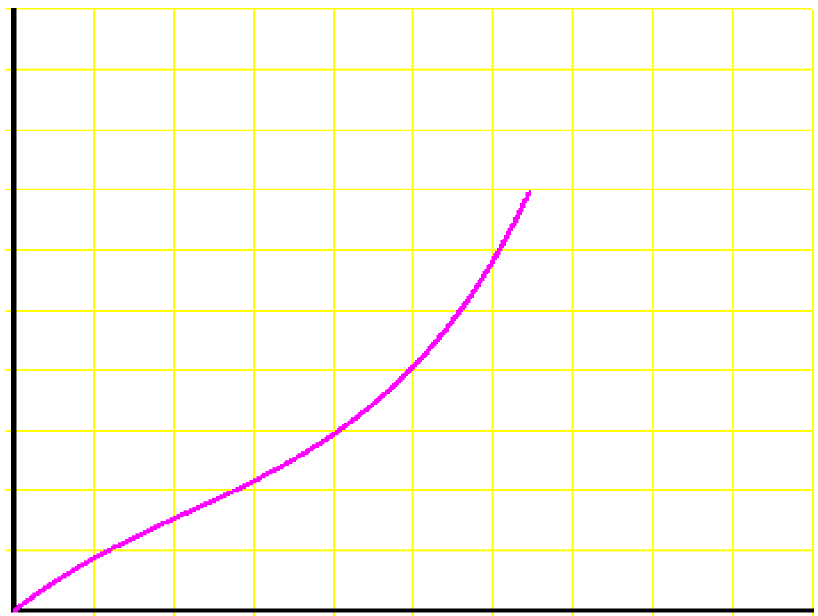


Example of O-Ring Compression

Step 1: The lack of information about the material would not allow any guessing (**BAD MOVE**). So, material tested by Axel products as shown below.

Step 2: Curve fitted to 9P M-R Model (**BETTER**) (method APDL)





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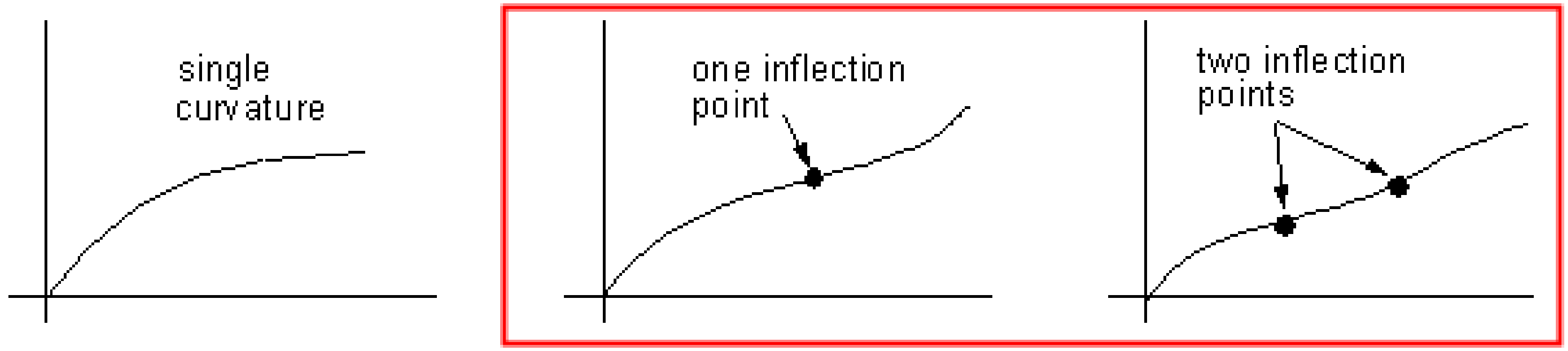
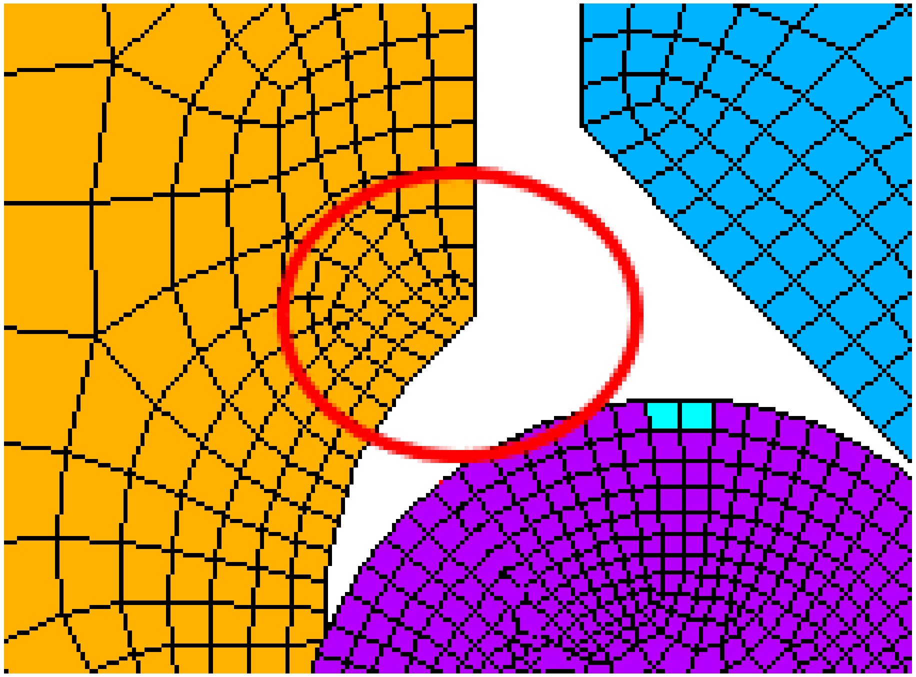
Why a 9P Mooney-Rivlin Model



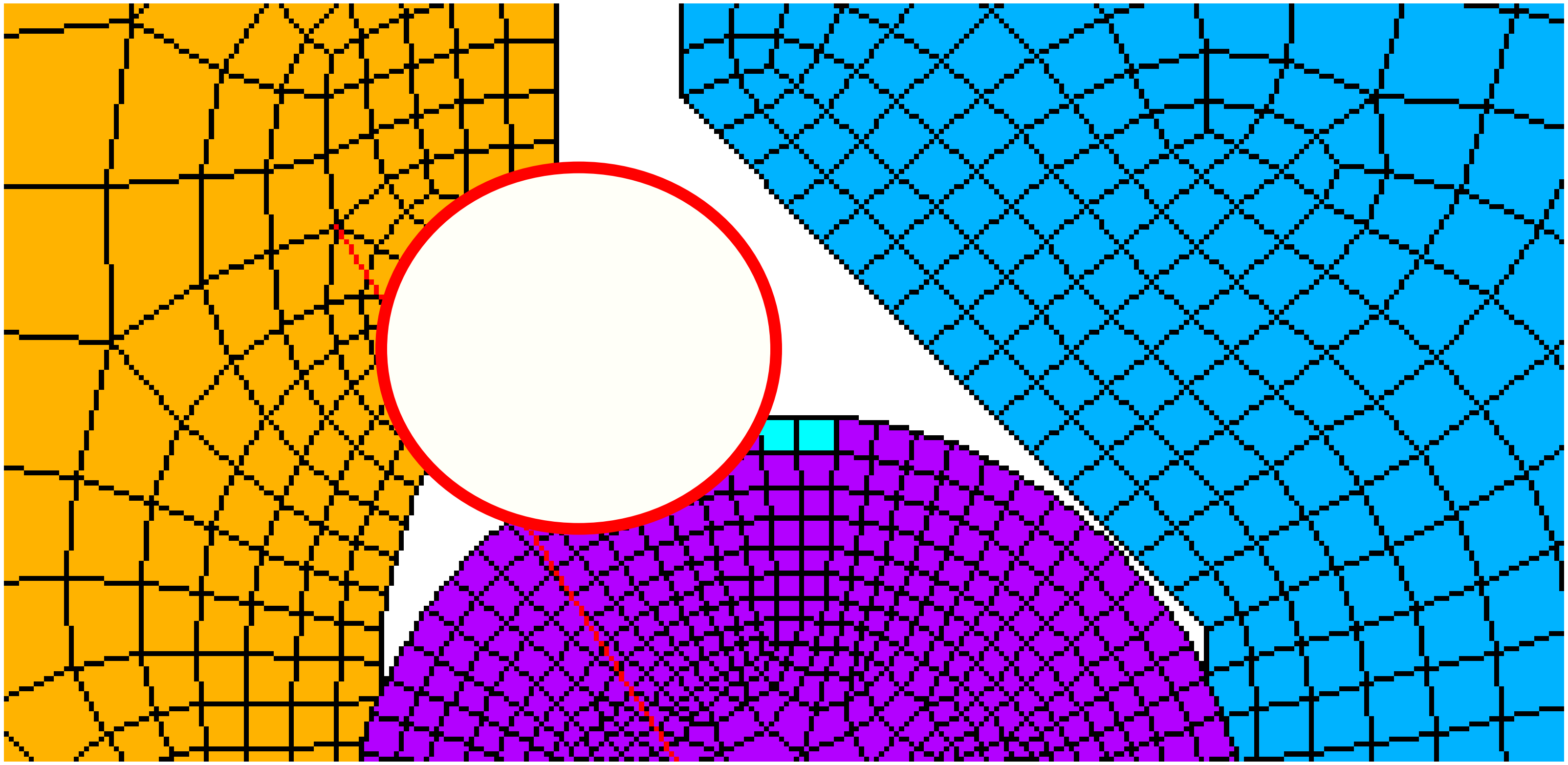
- Better Fit for the strain range
- A 5-P might have worked just as well
- A Curve fit of ALL Available mat. Models and parameters were not feasible/available at the time. (BEST CHOICE)

The Assembly as Designed

Guess where the Solution bombed out due to highly distorted Elements. (~ 25% into final loadstep – after preliminary contact resolution).



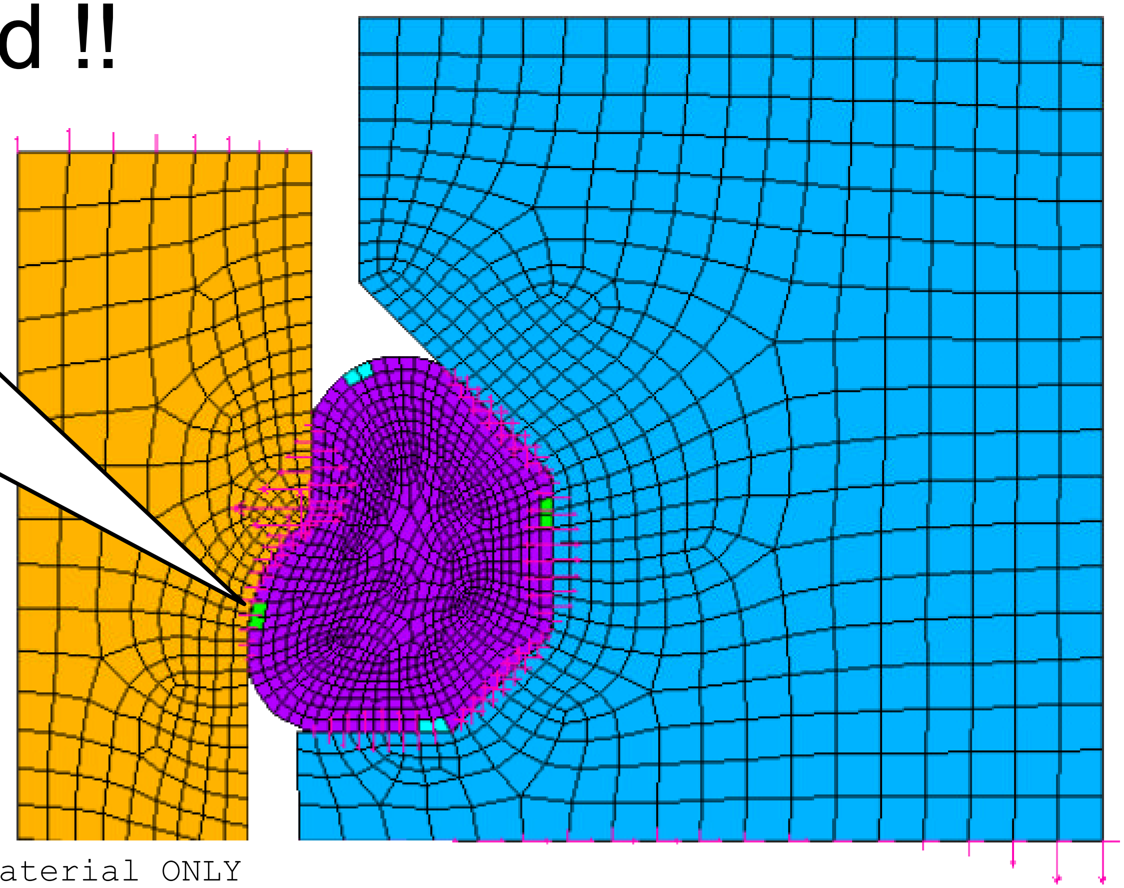
The assembly as Modified to help in the Convergence



TIP : Use rounded corners in areas where the soft material gets (or is expected to become) highly distorted and causes shear locking and hourglassing. (Rick?)

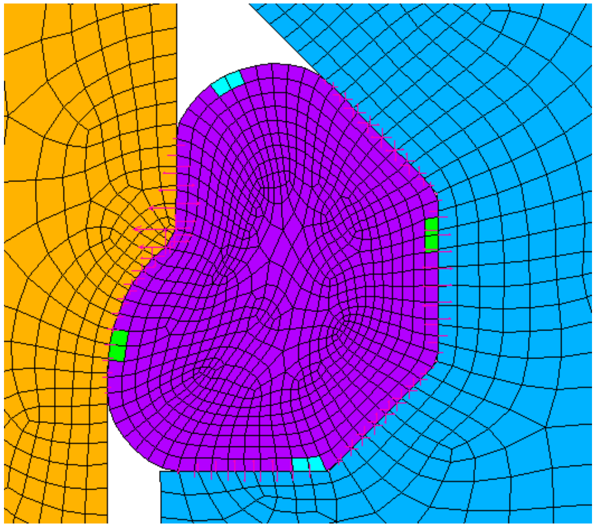
Problem Solved !!

Used a Different color to monitor the change in orientation of all points of interest during the animation process



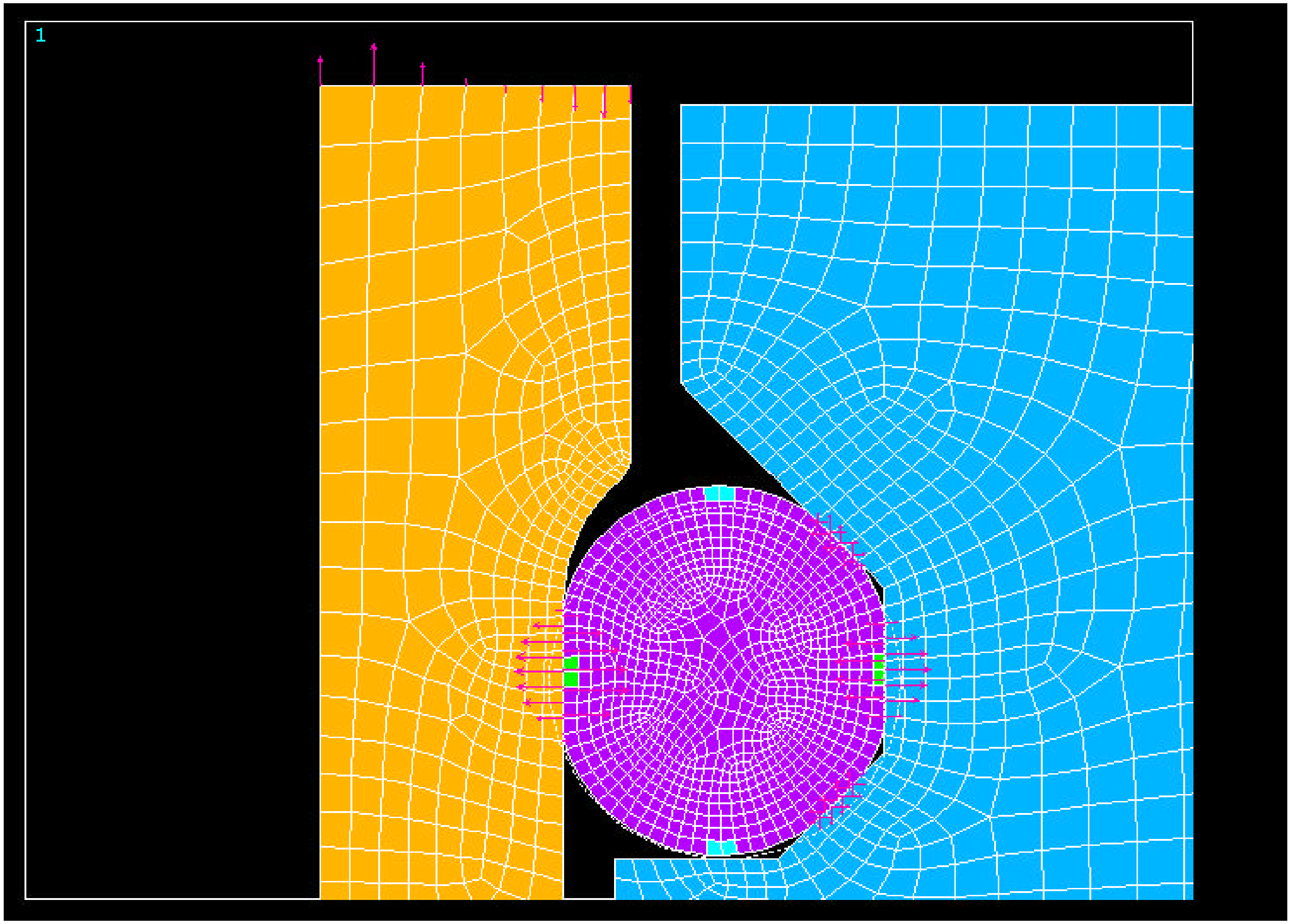
```
/pnum,mat ! Plot Element by material ONLY
/num,2     ! Colors only
esel,,type,,1,2 ! Select Solid Elements
/nfor,on   ! Turn on nodal Forces
Pldisp     ! Show Displacement plot
```

Lessons Learned…

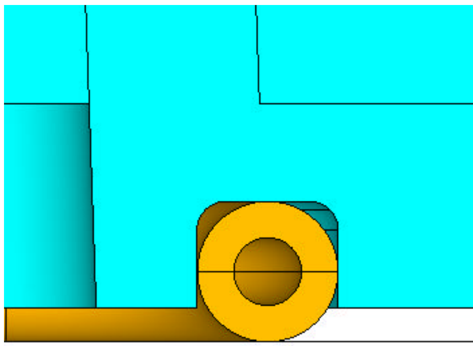


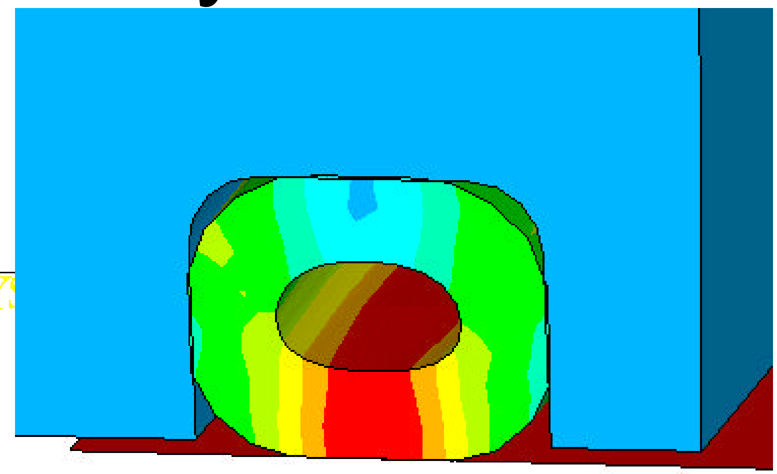
- The use of the rounded Fillet helped (*read: saved me*) in completing the O-Ring assembly.
- Mesh deformation is acceptable.
- Contact resolution w/ mating parts as expected.
- Orientation of “monitor” elements indicate lack of friction at the contact.
- Next iteration should incorporate friction
  - Did Rich tell you about friction in contact pairs ??

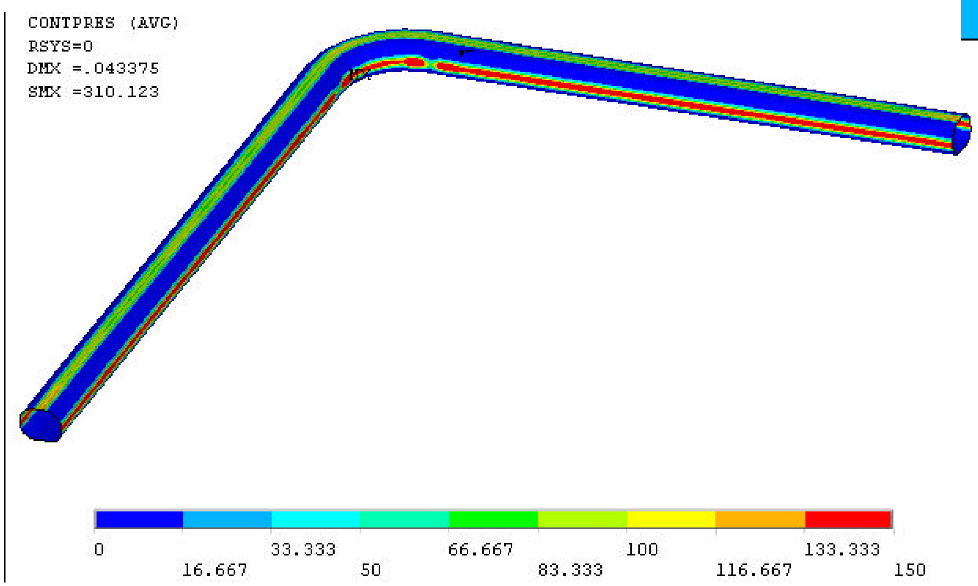
Solution with Friction Added…



Another O-Ring Case Study…







2 Parameter Mooney-Rivlin Model Used

C_{10}=107.18, C_{01}=26.8

Hourglassing

- Hourglassing occurs when there is compression in the material.
- Hourglass-shaped elements can propagate through the mesh IF THERE ARE LESS THAN 2 ROWS OF ELEMENTS IN EACH DIRECTION.
- Hourglassing IS NOT LIMITED to full integration elements. Use the wrong Stiffness factor w/ the **Uniform Reduced Integration** method and you'll see it….
- Think of it as "Rubber Turbulence" as the deformation change is rapid and violent.
- In reality, Hourglassing DOES NOT EXIST. Combination of material model, geometry, mesh density and element selection can induce Hourglassing in hyperelastic materials.
- Use full scale plot to see Hourglassing effects.

Hourglassing

- Elements Supporting Hourglass control : Plane182/183, Solid 164 / 185 / 186 / 45
- Use HGSTF Real Constant to Specify the Hourglass stiffness scaling factor
- However, the artificial energy introduced to control the hourglass effect may affect solution accuracy adversely.
  - Don't just increase the Stiffness 10% for every successive iteration
  - Bump it up to some high number and then back off
  - Chances are ANSYS will solve FASTER using a HIGH HGSTF rather than a LOW and Gradually increasing value.

Hourglassing

CAUTION:

Introducing the HGSTF changes the the problem.
(Especially if the deformation is Bending Dominated)

- Compare the total energy (SENE) to the artificial energy (AENE) that is being introduced by the hourglass stiffness.
  - If the Ratio SENE / AENE is < 5 % the solution is acceptable.
  - More than 5 % ?? Refine the mesh OR reduce the HGSTF.

Wisdom on Hyperelastic Materials from XANSYS - **THE** School of Hard Knocks

- NEVER ask a forum member to give you their material data. Yes, it cost $ to test but this is not the area to cut corners. How do you know the material is made from the same stuff ?? (grade, processing etc.)
- The term “Strain” in hyperelastic materials is replaced by “Stretch”. The first and second invariants of M-R and other models are based on Stretch Ratios. The principal stretch ratio = 1 + eng. Strain. Therefore, the test data you obtain are Engineering and NOT True Stress and Strain.
- Use the more comprehensive `TB,Hyper,,option` instead of `TB,Mooney` which is for HYPER56/58 elements.

Wisdom on Hyperelastic Materials from XANSYS - **THE** School of Hard Knocks

- For perfectly incompressible material, Poisson's ratio of 0.5 is unacceptable as it makes the bulk modulus infinite. To keep ANSYS happy, use 0.49995
- Polyurethane foams ?? Use Hyper56 with Blatz-Ko function (Keyopt(2)=1) IF you have the parameters for it. The literature is leaning towards M-R or hyperelastic w/ Ogden function.
- Polyurethane foams and access to LS-DYNA ??

  See this reference:

  http://web.bham.ac.uk/millsnj/pdf/matpaperkyoto.pdf

References on the Internet

- All about Testing Hyperelastic Materials and more…
  http://www.axelproducts.com/pages/Downloads.html

- *www.PolymerFEM.com*
  As the name suggests it is THE place to start w/ questions pertaining to elastomer modeling.
  (mostly ABAQUS but some ANSYS and LS-DYNA models are readily available).

- SILICONE RUBBER TESTING
  http://www.pp.bme.hu/me/2001_1/pdf/me2001_1_11.pdf

Conclusions

- Test the material at hand
- Take the Advanced Nonlinearities Class offered by your ASD.
- Use these RESOURCES
  - **IMPACT Engineering Solutions, Inc.**
  - **ANSYS Customer Portal – Sample Models**
  - **Ansys.net**
  - **Axel Products**
  - **Datapoint Labs**
  - **PolymerFEM.com**
  - **XANSYS – Ask (wisely) and thou shall receive…**

- **Wish List** : Currently ANSYS does not have the option for Mullins Effect to account for hysteretic damage. Is this option something we can expect to see in the near future ???