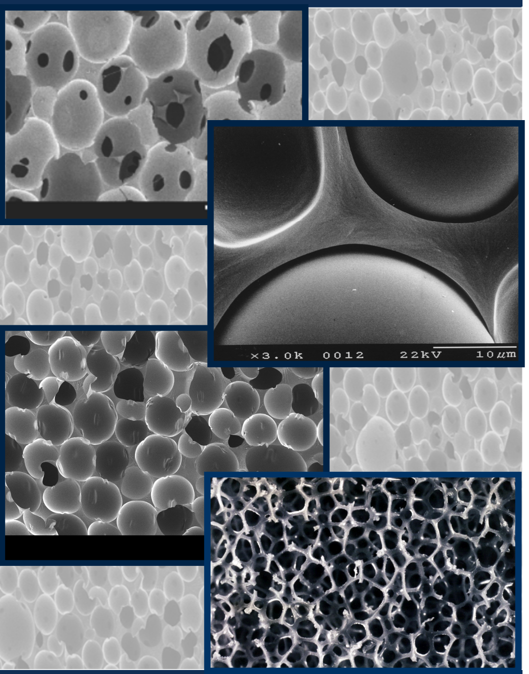
Component Science
and Mechanics

SAND2017-3845C



Flex Foam Model for Rigid and Flexible Foams

Mike Neilsen, Wei-Yang Lu,
Brian Werner, David Lo

Sandia National Laboratories

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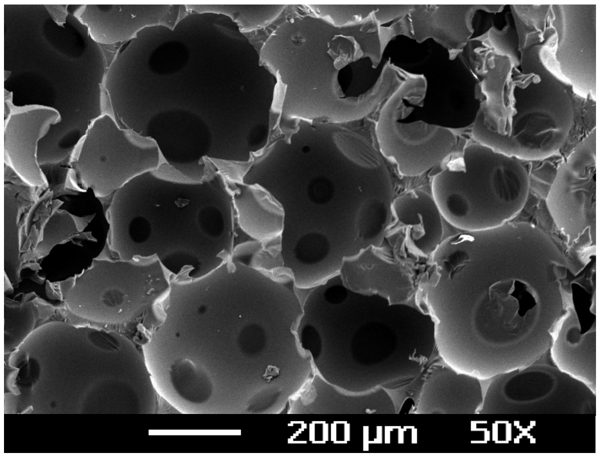
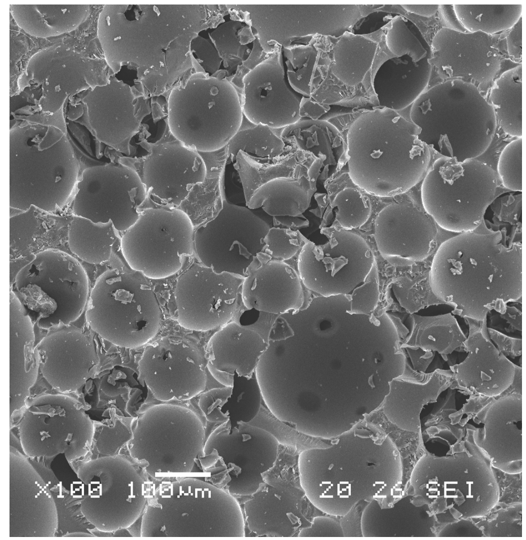
Outline

- Behavior of Foams
- Foam Micromechanics (cell level)
- Unified Creep Plasticity Damage (UCPD) Model for Rigid Foams
- Flex Foam Model for Flexible and Rigid Foams
- Simulations
- Summary and Future Work

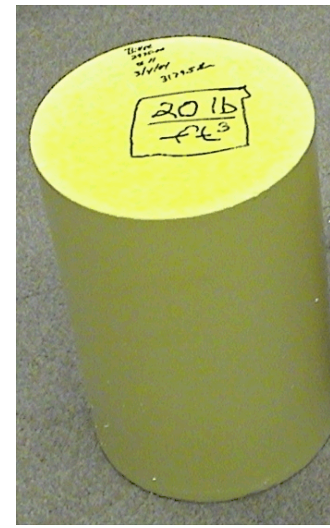
Polyurethane Foam



176 kg/m^3 (11 pcf) polyurethane foam

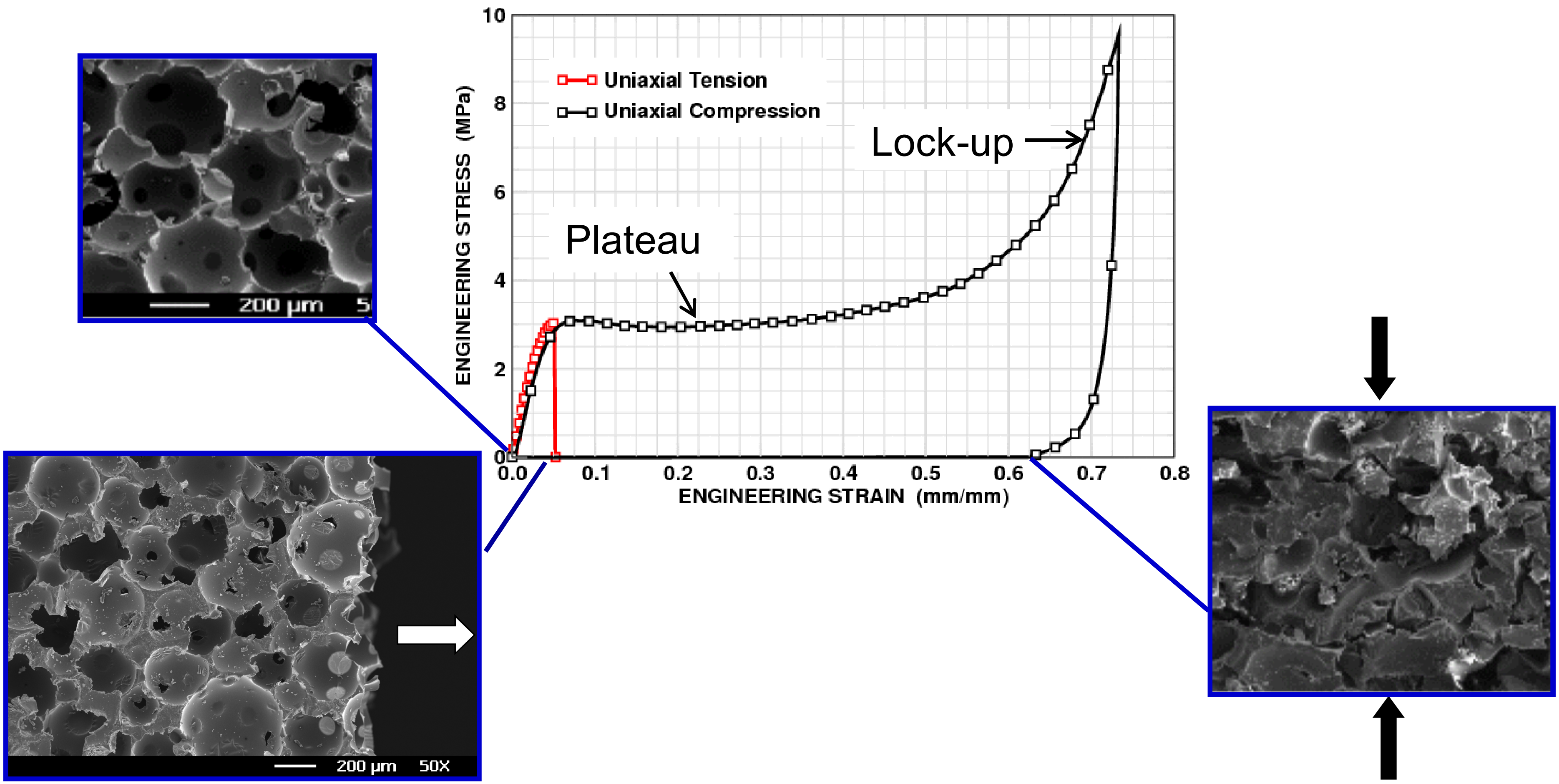


320 kg/m^3 (20 pcf) rigid polyurethane foam



30.5 cm (12 in.) tall billet

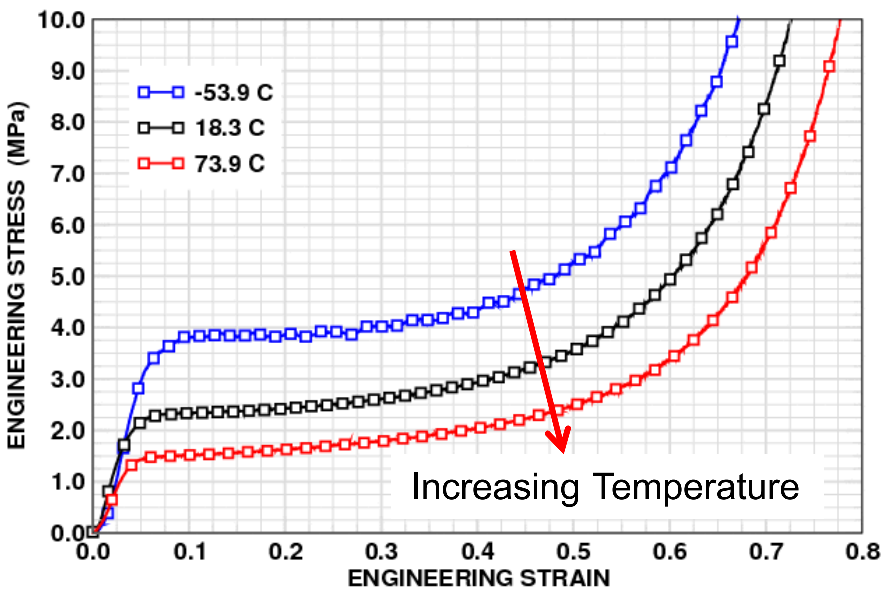
Experiments on 176 kg/m^3 (11 pcf) Foam



Uniaxial Tension

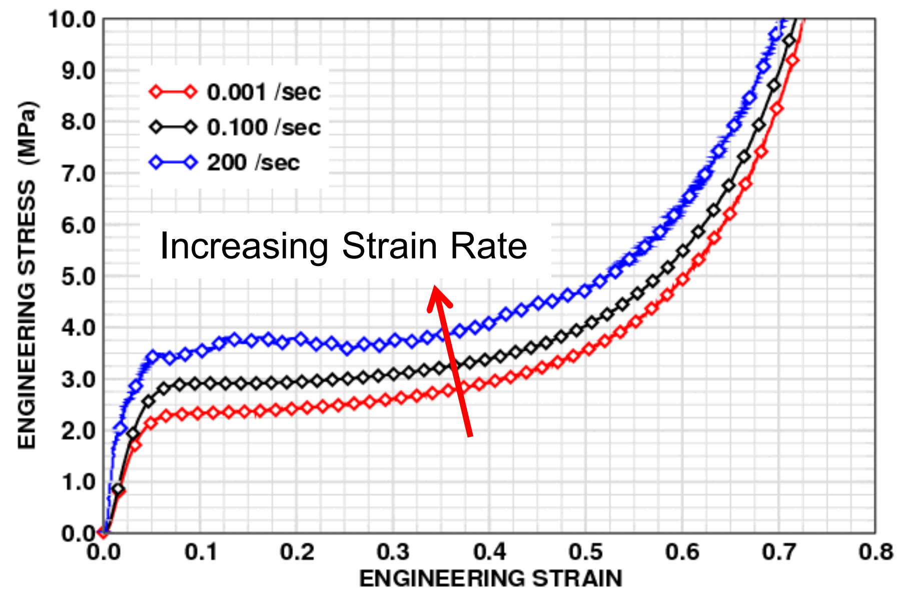
Uniaxial Compression

Experiments on 192 kg/m^3 (12 pcf) Foam



Temperature Effects

Constant Strain Rate = 0.001 / second



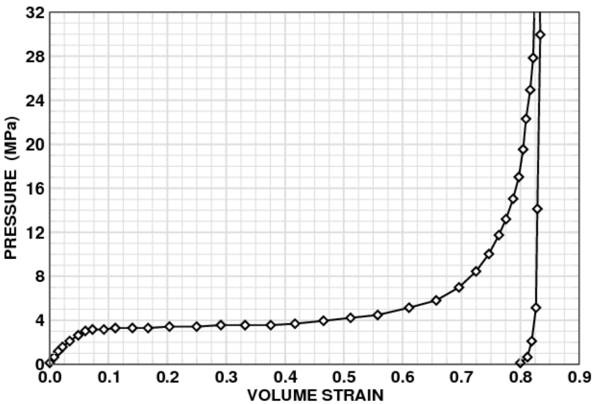
Strain-Rate Effects

Constant Temperature = 18.3 ^{o}C

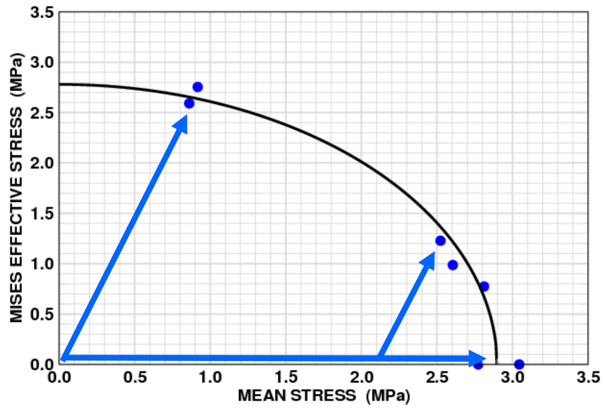
Uniaxial Compression of FR3712

Experiments on 192 kg/m^3 (12 pcf) Foam

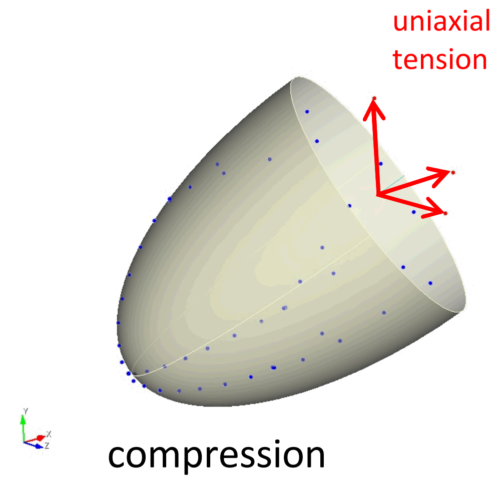
Unlike metals, foams exhibit large permanent volume changes – volumetric plasticity



Hydrostatic Compression
Pressurization Rate 0.1 MPa/sec



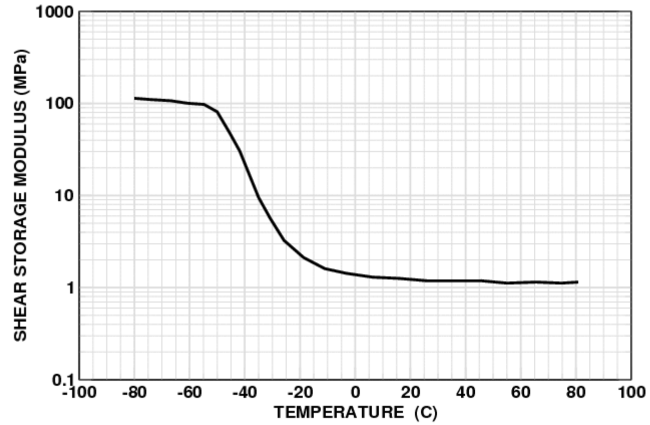
Triaxial Compression
W.A. Olsson, 2006



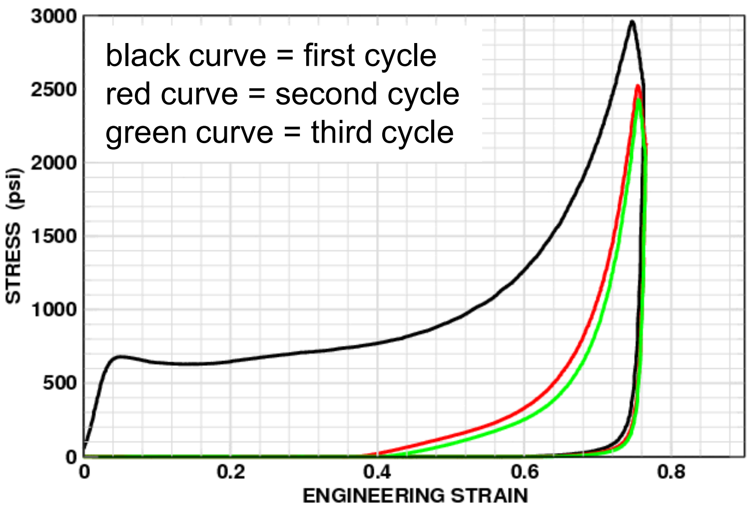
Yield Surface in
Principal Stress Space

Reference: M.K. Neilsen, W-Y. Lu, W.A. Olsson, A.M. Kraynik, W.M. Scherzinger, 'Foam Constitutive Models from Complementary Experiments and Cell-Level Simulations,' 15th UCTAM, Univ. of Colorado at Boulder, 2006.

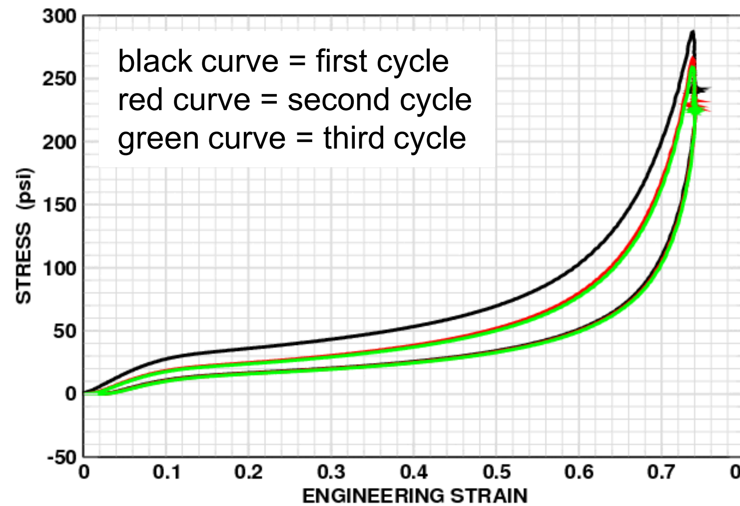
Experiments on Flexible Foam



DMA shows Tg ~ -35 ^{o}C



Rigid at -53.9 ^{o}C

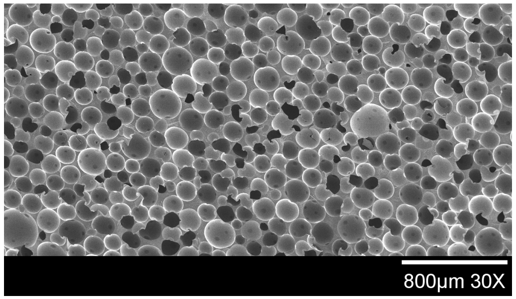


Flexible at 21.1^{o}C

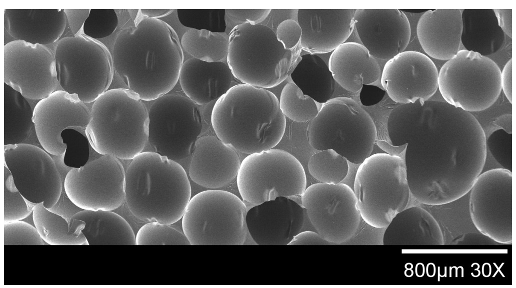
Cyclic stress-strain curves for 15pcf shipping container foam (Brian Werner, 8343 and April Nissen, 8344)

Foam Micromechanics, Cell Geometry – Andy Kraynik

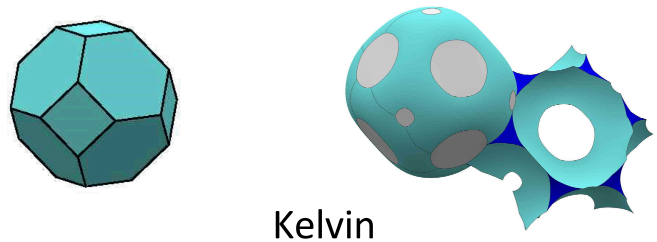
Need spatially-periodic representative volume



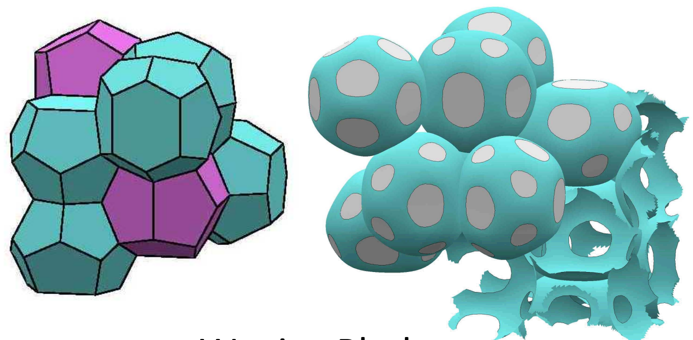
PMDI-20 (Wei-Yang Lu, SNL)



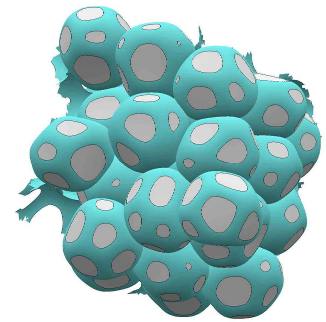
TufFoam (L. Whinnery, SNL)



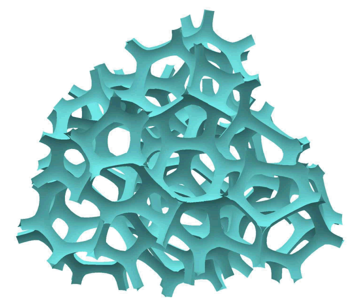
Kelvin



Weaire-Phelan



Random 27 bubbles



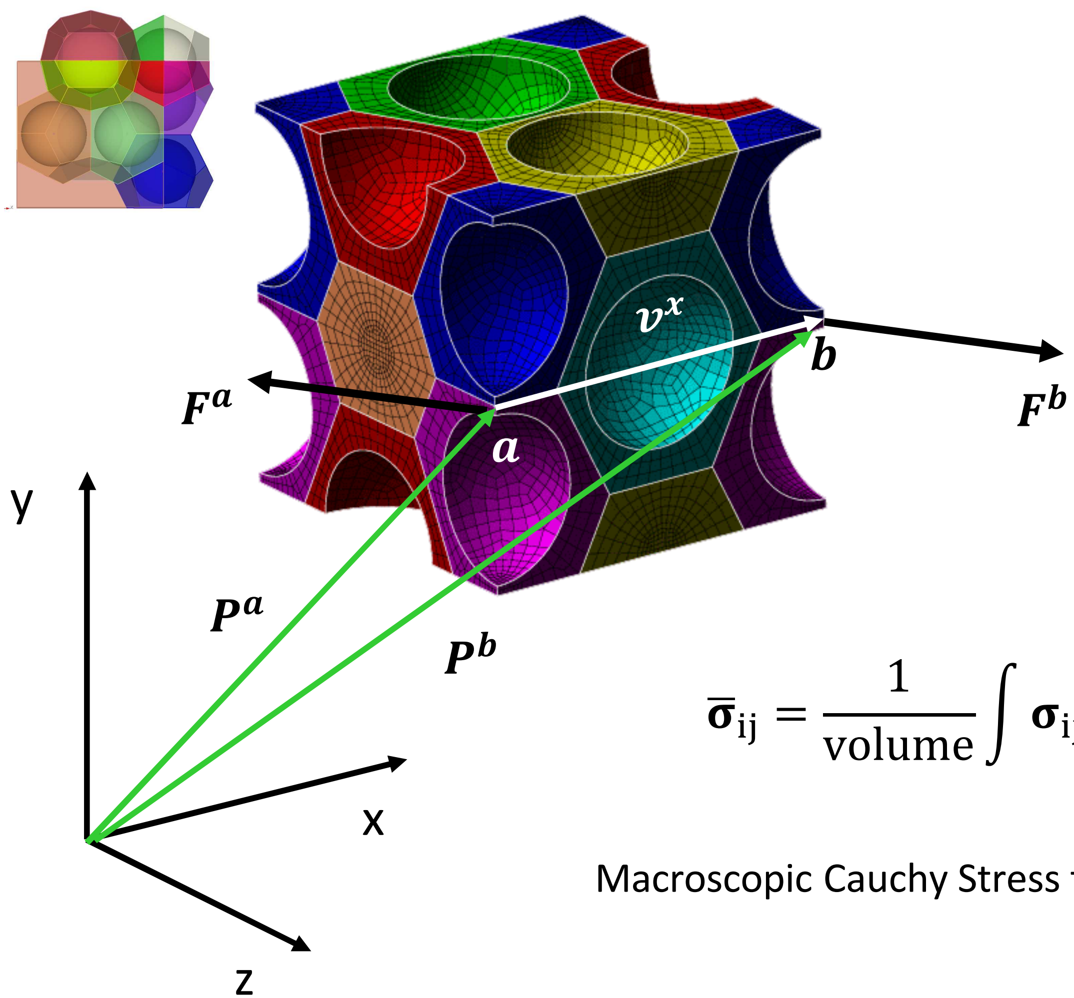
Plateau borders

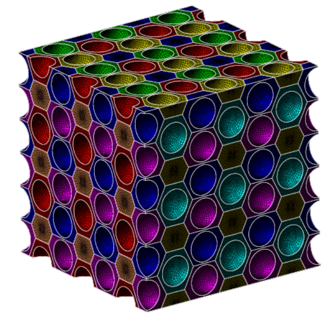
A.M. Kraynik, "Foam structure: From soap froth to solid foams." *MRS Bulletin* 28.04 (2003): 275-278.
W. Thomson, Lord Kelvin, "On the division of space with minimum partitional area", *Phil. Mag.* vol. 24 (1887), 503.
D. Weaire and R. Phelan, "A counterexample to Kelvin's conjecture on minimal surfaces", *Phil. Mag. Lett.* **69** (1994), 107.
Prof. K. Brakke, Susquehanna University, **Surface Evolver**, www.susqu.edu/brakke/evolver

Cell-Level to Macro Connection

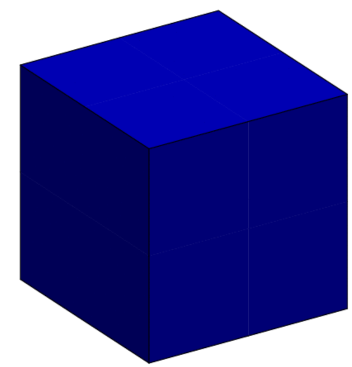
Weaire-Phelan Unit Cell

Periodic b.c. : $\boldsymbol{P^b} = \boldsymbol{P^a} + \boldsymbol{v^x}$





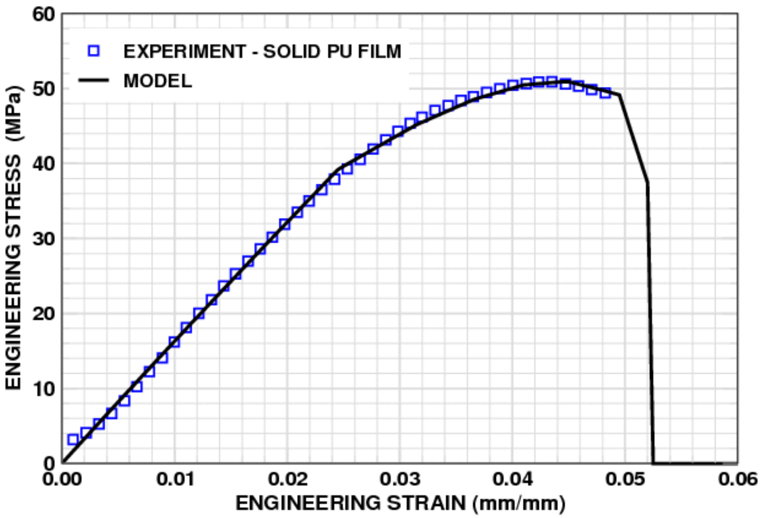
“Equivalent” Continuum



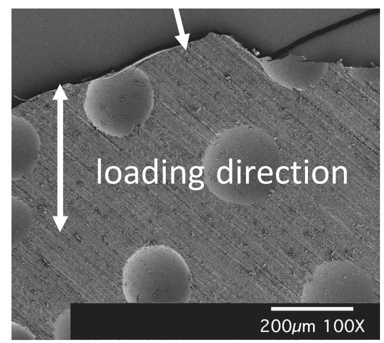
$$\bar{\boldsymbol{\sigma}}_{ij} = \frac{1}{\text{volume}} \int \boldsymbol{\sigma}_{ij}\, dv = \frac{1}{\text{volume}} \sum_{\substack{n=periodic\\ nodes}} \boldsymbol{P}_i^n \, \boldsymbol{F}_j^n$$

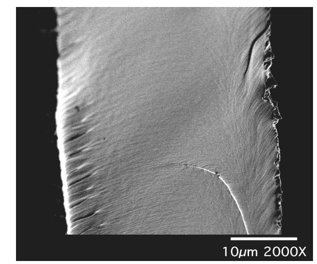
Macroscopic Cauchy Stress for “Equivalent” Continuum

Tension of Solid Polyurethane (PU)



fracture edge

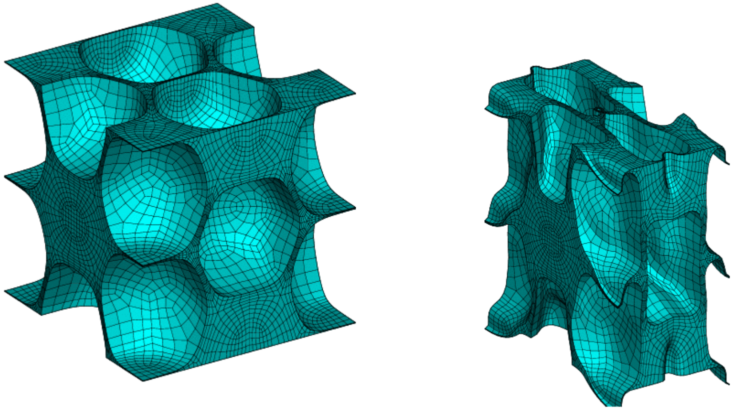




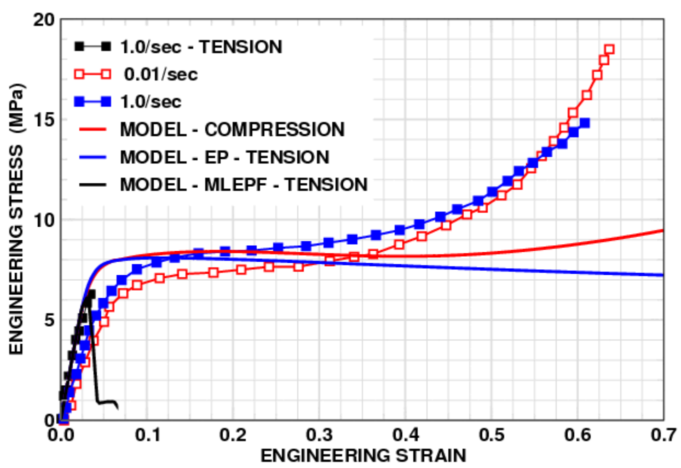
FR3712 Solid Film

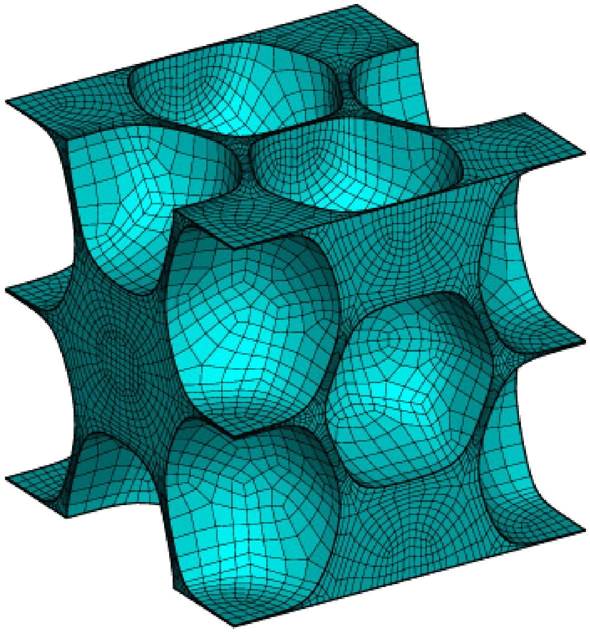
G.W. Wellman, 'A Simple Approach to Modeling Ductile Failure,' SAND2012-1343, Sandia National Labs., June 2012.

WP Cell Model Compression – 20 pcf Foam

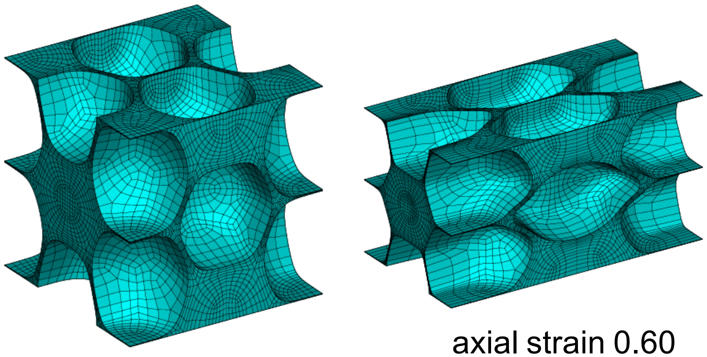


Compression - 100



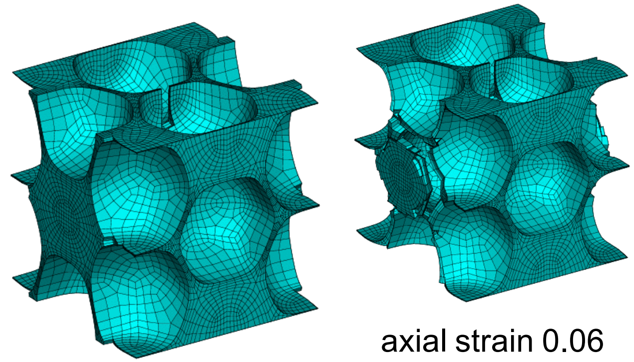


WP Cell Model - Tension



axial strain 0.60

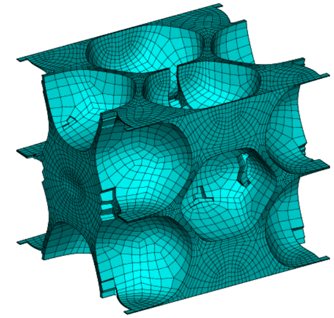
Tension – Elastic Plastic



axial strain 0.03

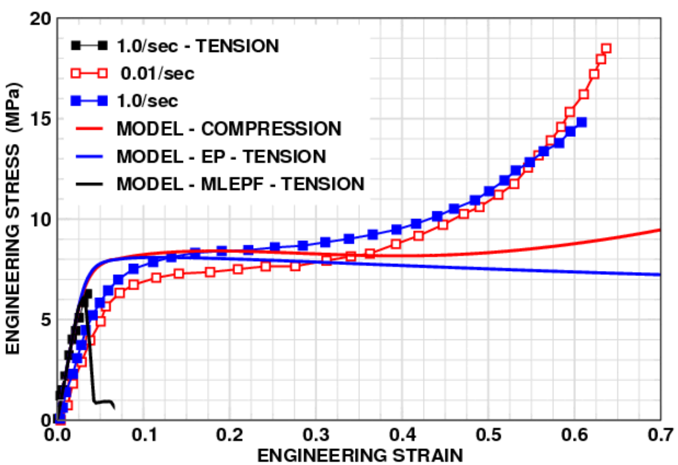
axial strain 0.06

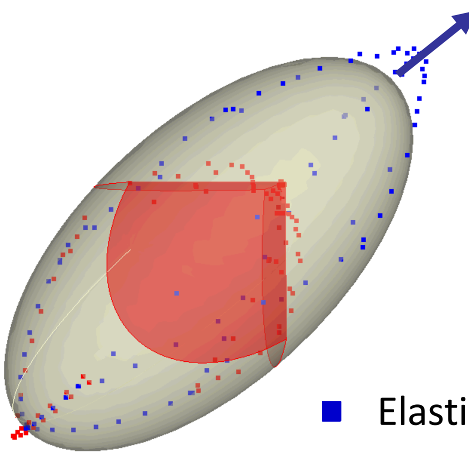
Tension – MLEPF



axial strain 0.10

Tension – MLEPF with lateral compression





Hydrostat

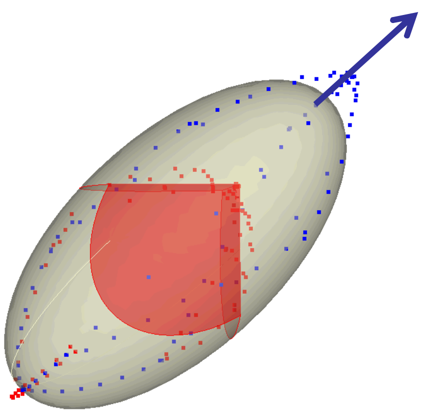
Elastic-Plastic Polymer

MLEPF – Tearing Polymer

Yield and Damage Surfaces for Foams

Yield /Damage Surfaces Proposed for Rigid Foam

Triantafillou et al. (1989) Stretched ellipsoid w/ buckling cap.
Neilsen et al. (1995). Principal stress criterion.
Puso and Govindjee (1995) Stretched ellipsoid w/ ellipsoidal cap.
Zhang et al. (1998). Ellipsoid about hydrostat, pressure offset.
Deshpande and Fleck (2000) Ellipsoid about hydrostat – metal foams
Deshpande and Fleck (2001) Ellipsoid capped by max. compressive principal stress surface



Experiments and Cell Level Models indicate we should use

Ellipsoid capped by maximum tensile stress damage surfaces

Gibson, L.J., and Ashby, M.F., **Cellular Solids – Structural and Properties**, Pergamon Press, New York, 1988
Neilsen, M. K., Krieg, R. D., and Schreyer, H.L., *Polymer Engineering and Science*, **35**, No. 5, pp. 387-94, 1995
Puso, M.A., and Govindjee, S., ASME MD-Vol. 68/AMD-Vol. 215, **Mechanics of Plastics & Composites**, 1995
Zhang, J., Kikuchi, N., Li, V., Yee, A., and Nusholtz,G., *Intl. J. Impact Engr.*, **21**, No. 5, pp. 369-386, 1998.
Deshpande, V.S., and Fleck, N.A., *J. Mech. Phys. Solids,* **48**, pp. 1253-83, 2000.
Deshpande, V.S., and Fleck, N.A., *Acta. Mater.*, **49**, pp. 1859-1866, 2001.

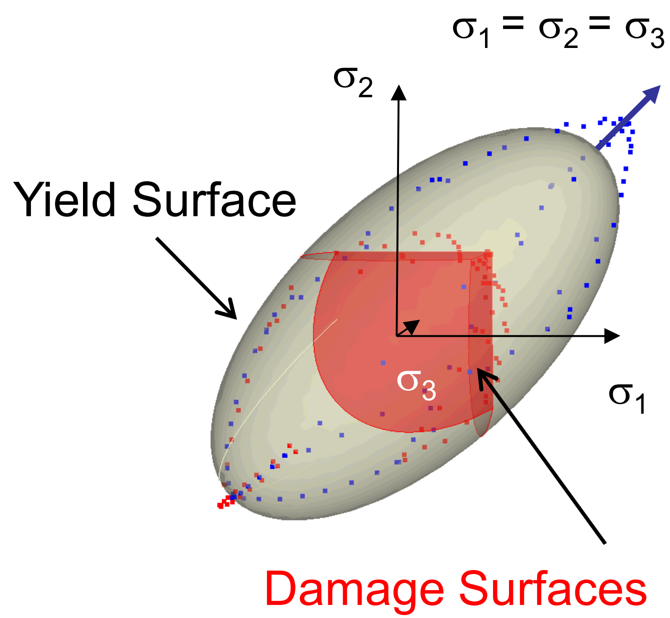
UCPD Model for Rigid Foam

$$\dot{\boldsymbol{\sigma}} = \mathbf{E} : \dot{\boldsymbol{\varepsilon}}^{e} = \mathbf{E} : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{in})$$

$$\varphi = \frac{\overline{\sigma}^2}{a^2} + \frac{p^2}{b^2} - 1.0 \qquad p = \frac{1}{3}\boldsymbol{\sigma} : \mathbf{i} \qquad \overline{\sigma} = \sqrt{\frac{3}{2}\mathbf{s} : \mathbf{s}} \qquad \mathbf{s} = \boldsymbol{\sigma} - p\,\mathbf{i}$$

$$\varphi = \sigma^* - a \qquad \sigma^* = \sqrt{\overline{\sigma}^2 + \frac{a^2}{b^2} p^2}$$

$$\dot{\boldsymbol{\varepsilon}}^{in} = \begin{cases} \dot{\lambda}\,\mathbf{g} = e^h \left\langle \dfrac{\sigma^*}{a} - 1 \right\rangle^n \mathbf{g} & when \quad \dfrac{\sigma^*}{a} - 1 > 0 \\ \mathbf{0} & when \quad \dfrac{\sigma^*}{a} - 1 \le 0 \end{cases}$$



UCPD Model for Rigid Foam

$$\mathbf{g}_{associated} = \frac{\dfrac{\partial \varphi}{\partial \boldsymbol{\sigma}}}{\left|\dfrac{\partial \varphi}{\partial \boldsymbol{\sigma}}\right|} = \frac{\dfrac{3}{a^2}\mathbf{s} + \dfrac{2}{3b^2}p\,\mathbf{i}}{\left|\dfrac{3}{a^2}\mathbf{s} + \dfrac{2}{3b^2}p\,\mathbf{i}\right|}$$

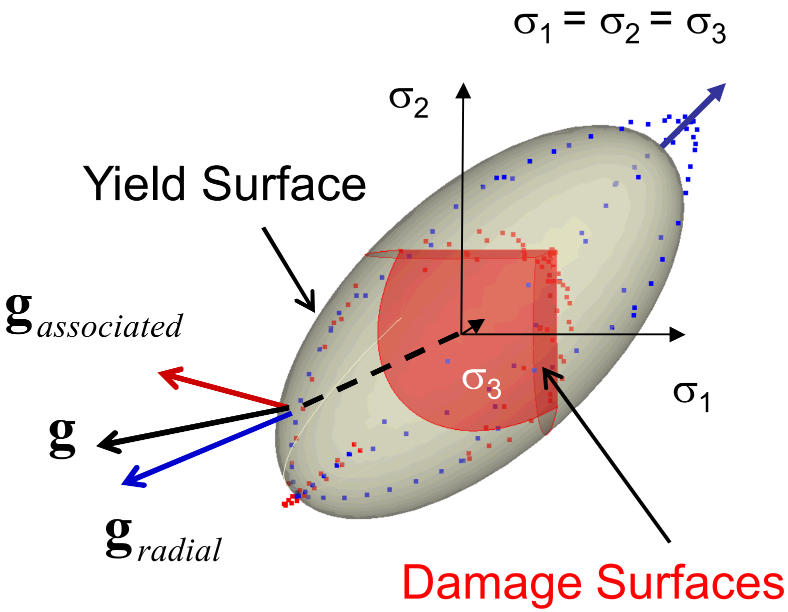
$$\mathbf{g}_{radial} = \frac{\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|} = \frac{\boldsymbol{\sigma}}{\sqrt{\boldsymbol{\sigma}:\boldsymbol{\sigma}}}$$

$$\mathbf{g} = \frac{(1-\beta)\,\mathbf{g}_{associated} + \beta\,\mathbf{g}_{radial}}{\left|(1-\beta)\,\mathbf{g}_{associated} + \beta\,\mathbf{g}_{radial}\right|}$$

$$\phi = \frac{\phi_0 V_0}{V}$$

$$\varphi^i_{Damage} = \sigma^{**i} - c(1-w) = 0,\ i = 1,3$$

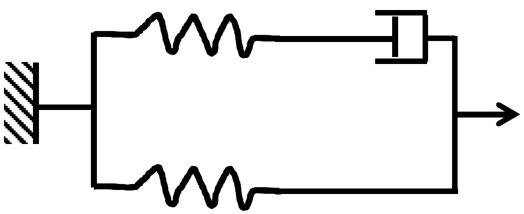
$$w = w(\varepsilon_{dam}) = w\left(a_{dam}\varepsilon_{\max} + b_{dam}\,\varepsilon^p_{vol}\right)$$



Flex Foam Model for Flexible and Rigid Foam

RIGID ~ UCPD MODEL

$$\mathbf{E}_r(\theta,\phi)$$



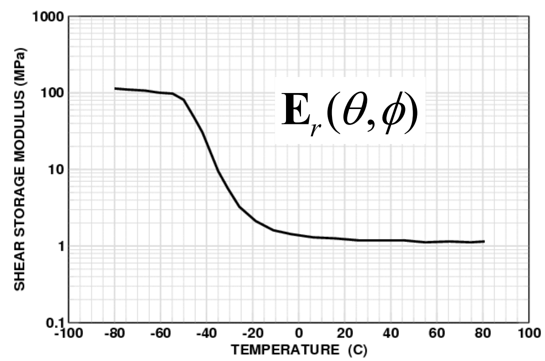
$$\mathbf{E}_f(\theta,\phi)$$

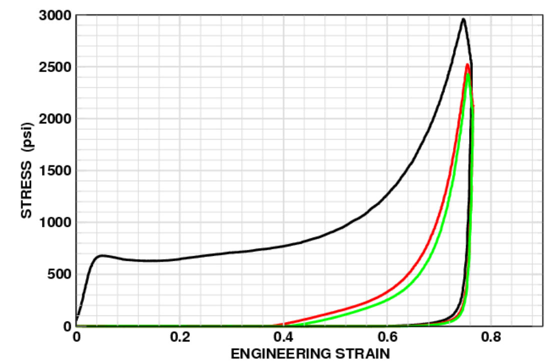
$$\dot{\boldsymbol{\sigma}} = \dot{\boldsymbol{\sigma}}_r + \dot{\boldsymbol{\sigma}}_f$$

$$\dot{\boldsymbol{\sigma}}_r = \mathbf{E}_r : \dot{\boldsymbol{\varepsilon}}^e = \mathbf{E}_r : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{in})$$

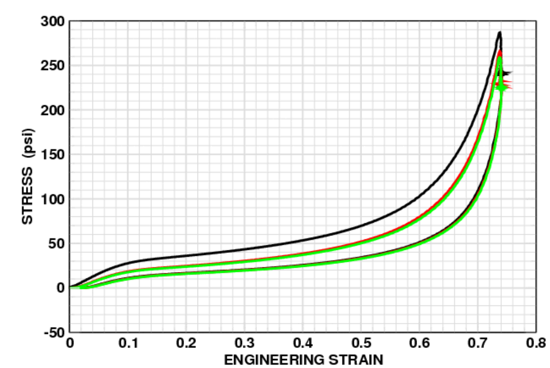
$$\dot{\boldsymbol{\varepsilon}}^{in} = \dot{\lambda}\,\mathbf{g} = e^h \left(\frac{\sigma^*}{a} \right)^n \mathbf{g}$$

$$\sigma^* = \sqrt{\bar{\sigma}^2 + \frac{a^2}{b^2} p^2}$$





Rigid at -53.9 °C



Flexible at 21.1°C

FLEXIBLE ~ MOSTLY JUST NON-LINEAR ELASTIC

$$\dot{\boldsymbol{\sigma}}_f = \mathbf{E}_f(\theta,\phi) : \dot{\boldsymbol{\varepsilon}}$$

$$\mathbf{E}_f = 2G(\theta,\phi)\mathbf{P}^d + 3K(\theta,\phi)\mathbf{P}^{sp}$$

Next Step Include Effect of Damage on Elastic Moduli

Flex Foam Model Parameters and State Variable Names

Flex Foam Model Parameters

```
begin parameters for model flex_foam
    youngs modulus        =  2400.0
    poissons ratio        =  0.050
    phi                   =  0.520
    flow rate             =  1.000
    power exponent        =  3.000
    dev multiplier        =  0.2
    tensile strength      =  500.0
    adam                  =  1.0
    bdam                  =  0.5

        . . . .

    youngs function                =  f_Modulus
    poissons function              =  f_Constant
    youngs phi function            =  f_E
    poissons phi function          =  f_Constant
    rate function                  =  f_Rate
    exponent function              =  f_Expo
    shear hardening function       =  f_Shear
    hydro hardening function       =  f_Hydro
    beta function                  =  f_Beta
    dmod function                  =  d_Modulus
    dpr function                   =  f_Constant
    dmod phi function              =  f_E
    dpr phi function               =  f_Constant
    damage function                =  f_Damage
end parameters for model flex_foam
```

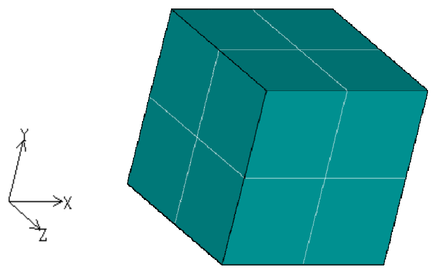
$$E = E_r \cdot E(\theta) \cdot E(\phi)$$

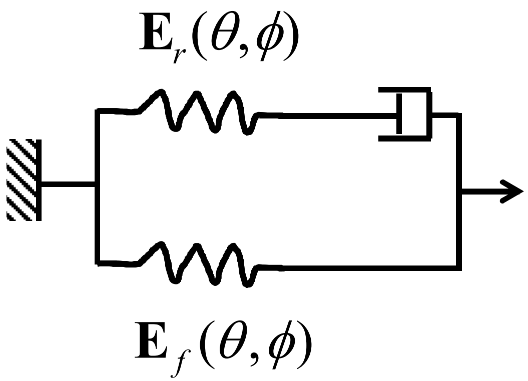
$$v = v_r \cdot v(\theta) \cdot v(\phi)$$

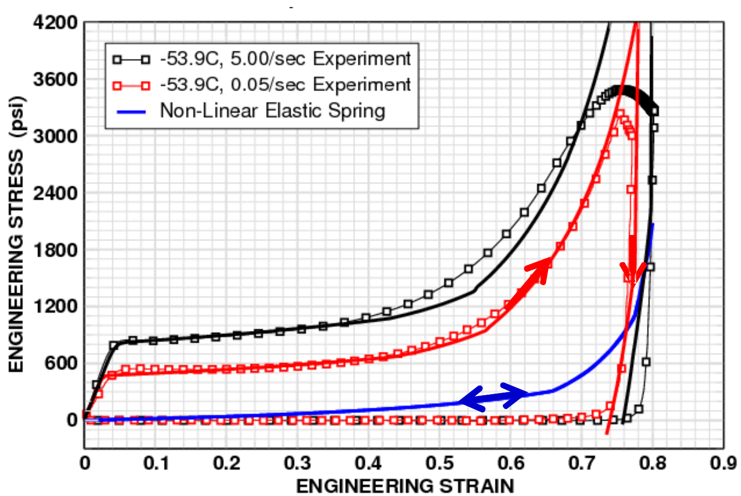
State Variables

damage
denergy
dstrain
emax
epvol
eqps
fa
fb
iter
phi
pwork
vstrain

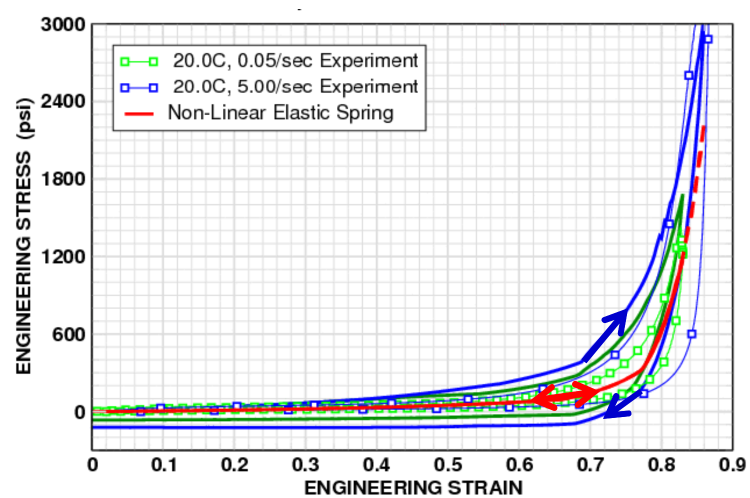
15 pcf Flexible Polyurethane Foam
Comparison of Model Predictions with Experiments







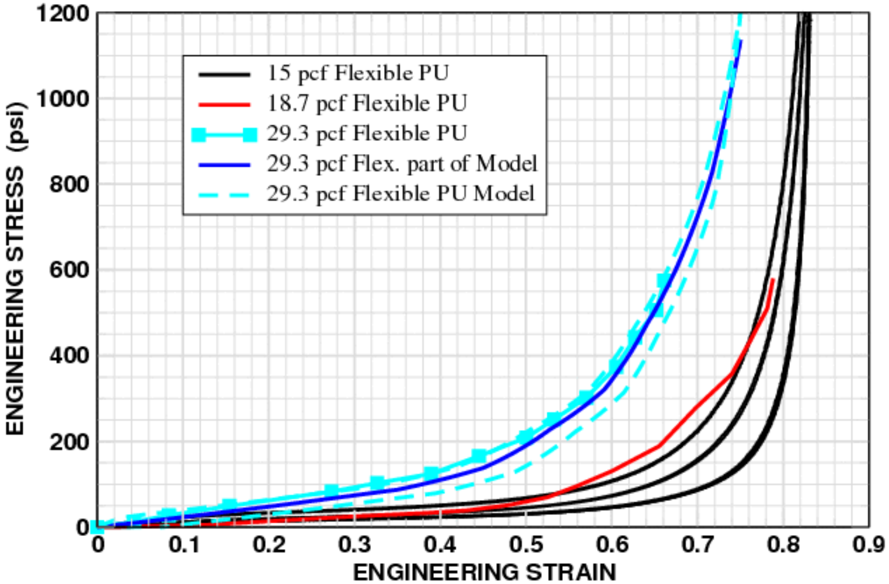
-53.9 °C

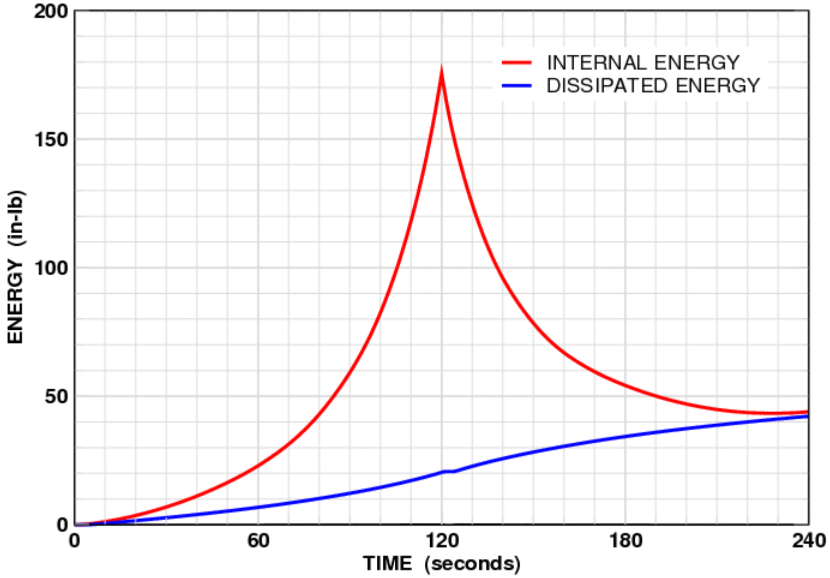


20 °C

Uniaxial Compression

Predicted Energy Dissipation with Flex Foam Model





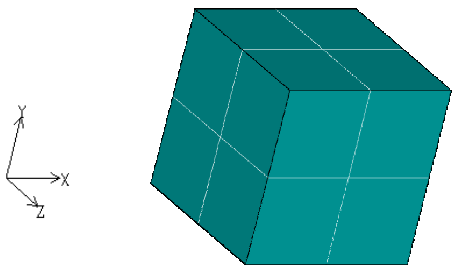
$$Pwork = \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}^{in}$$

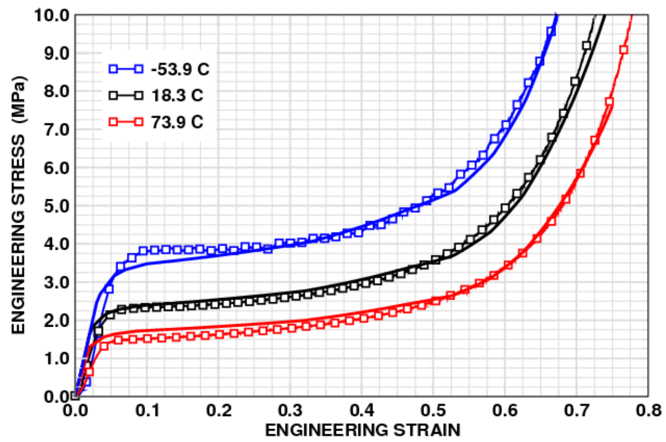
$$Denergy = \iint \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}^{in} dV dt$$

in Algebra compute:
Diss. Energy = SUM(DENERGY)

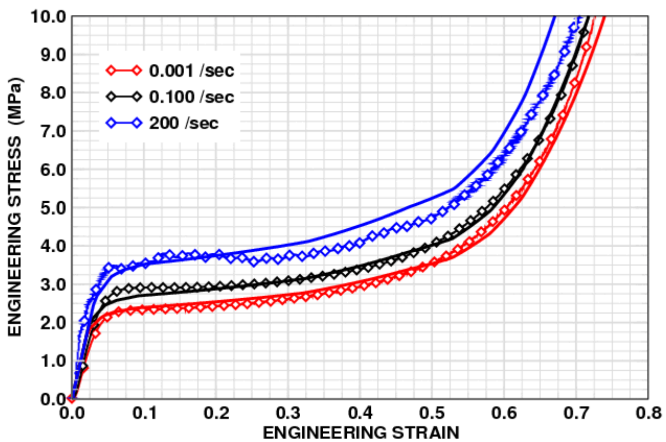
Internal Energy is global variable from ADAGIO

FR3712 Comparison of Model Predictions with Experiments

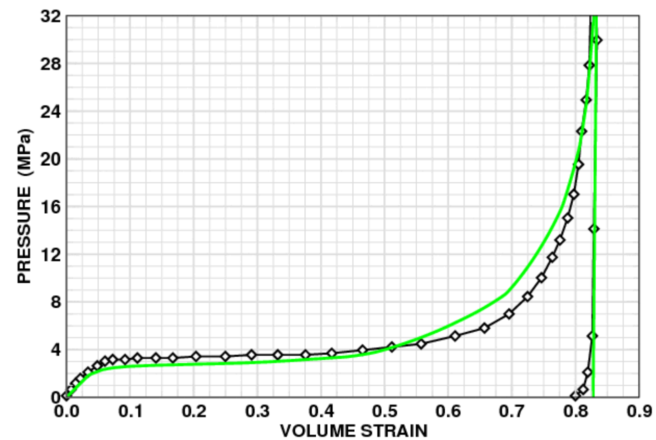




Uniaxial Compression at 0.001/second

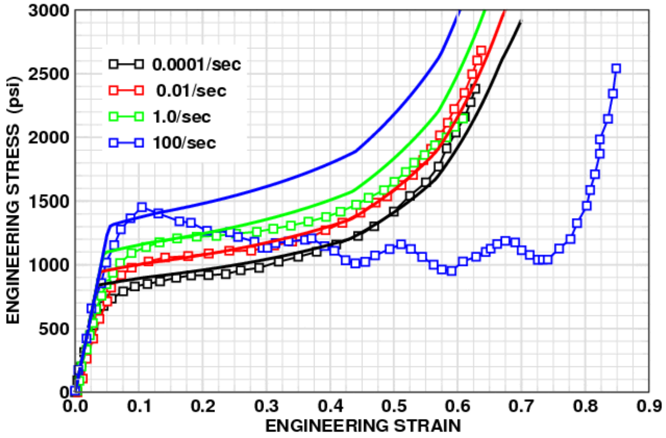


Uniaxial Compression at 18.3 C

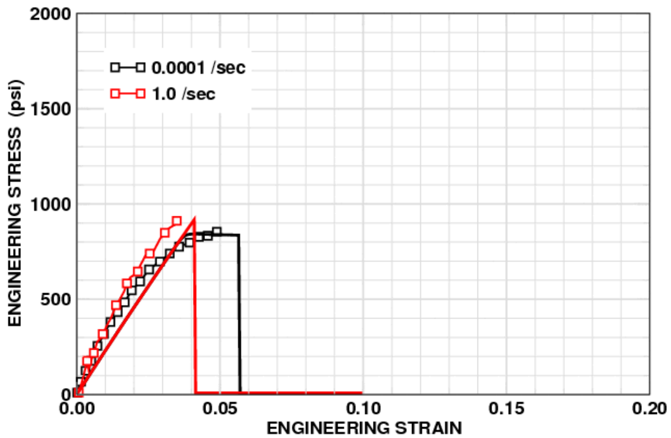


Hydrostatic Compression at 20.0 C

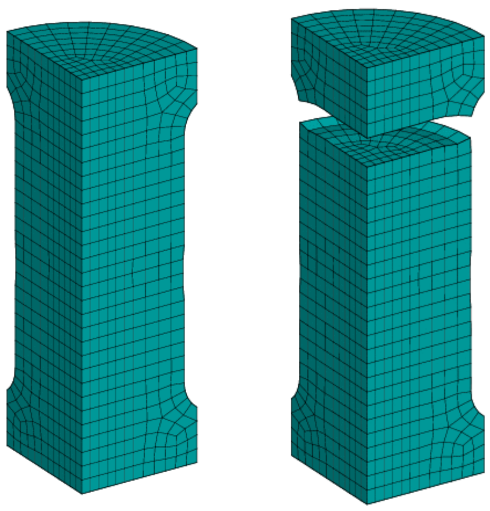
PMDI20 Comparison of Model Predictions with Experiments

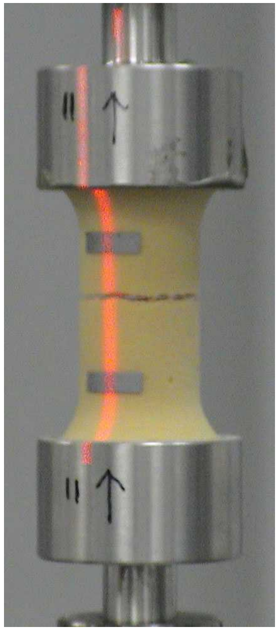


Uniaxial Compression at 21.1 C

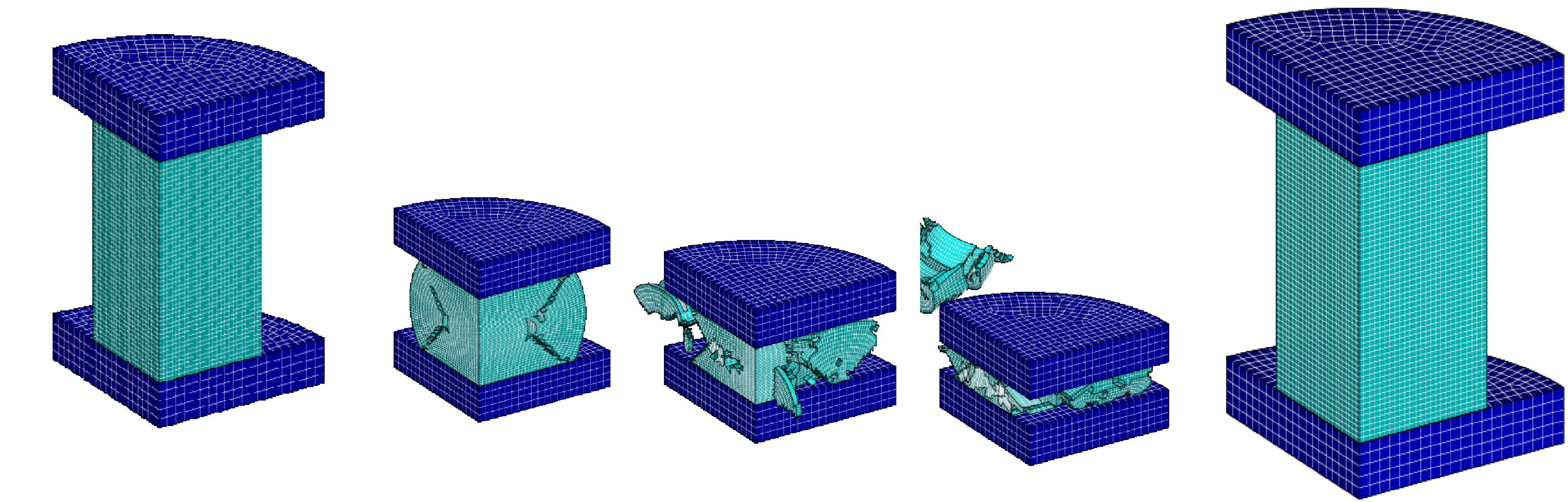


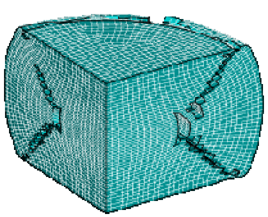
Uniaxial Tension at 21.1 C

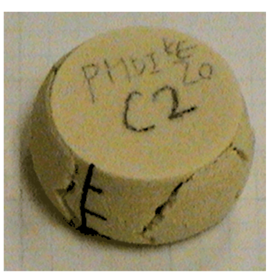


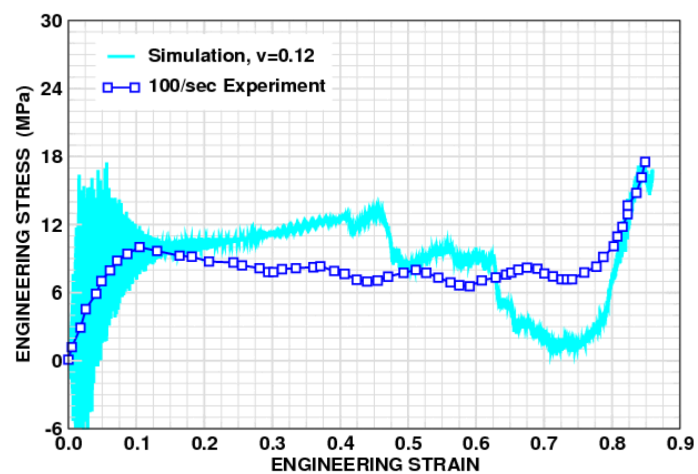


PMDI20 Comparison of Model Predictions with Experiments

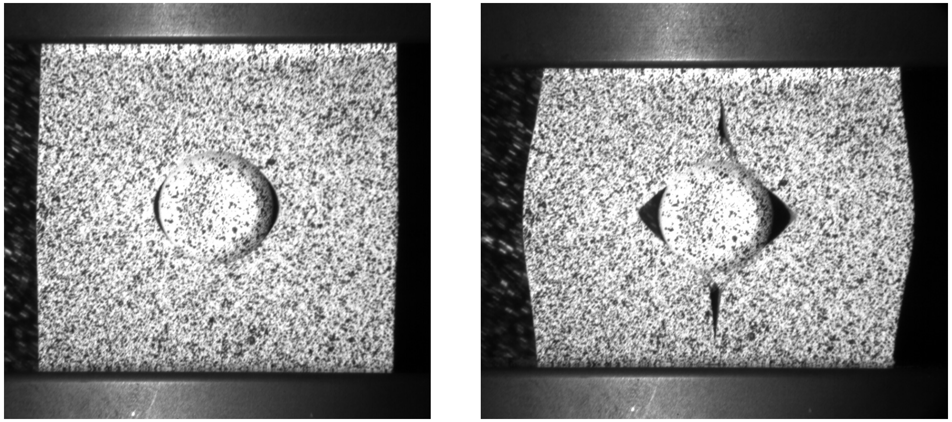


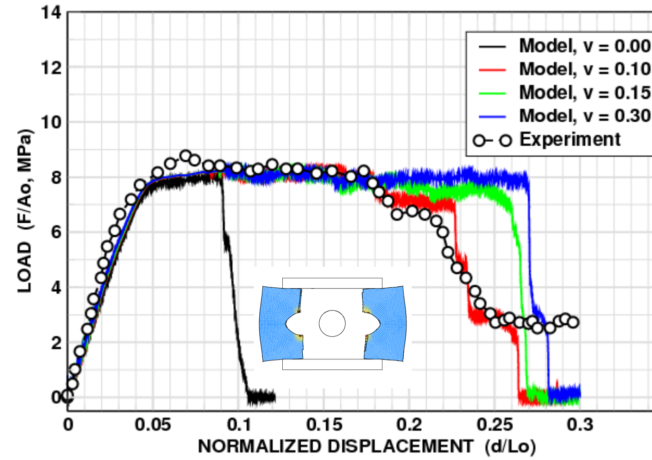


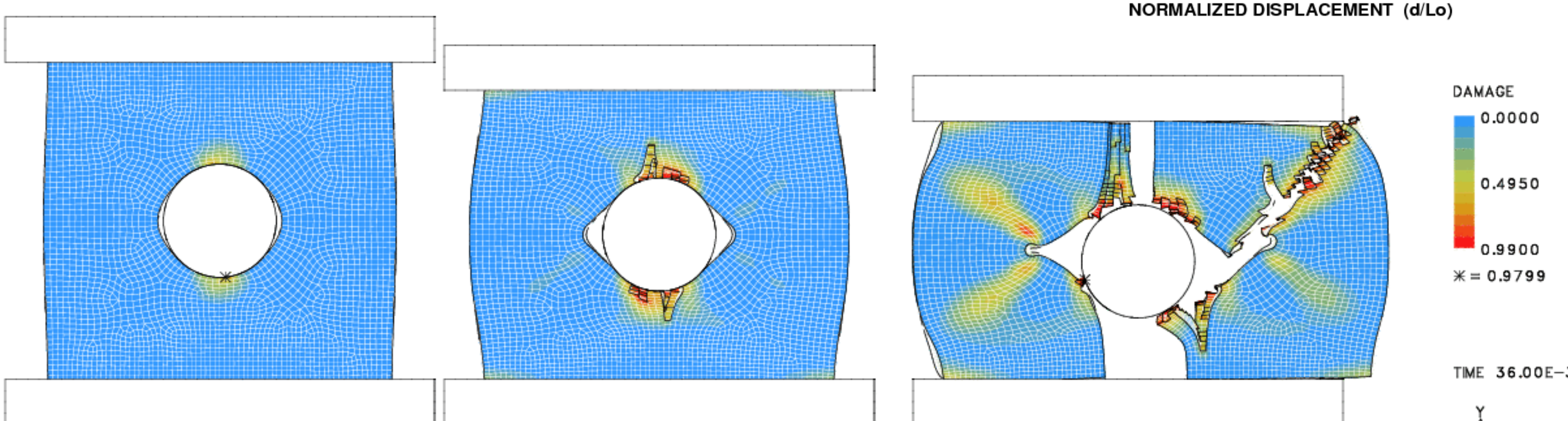




Uniaxial Compression of PMDI Foam Block with Steel Rod







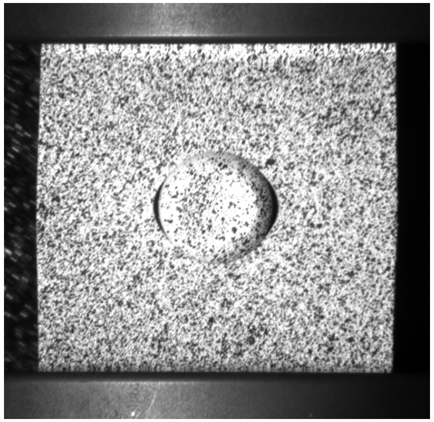
7% compression
Peak load

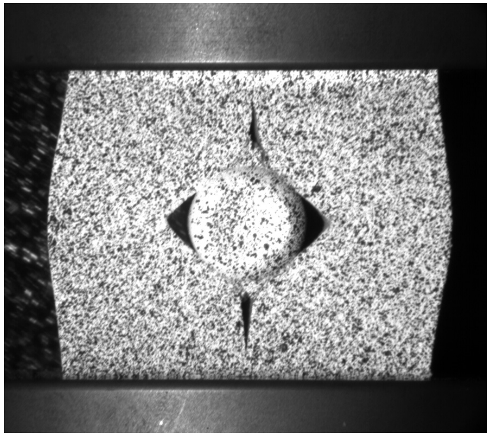
15% compression

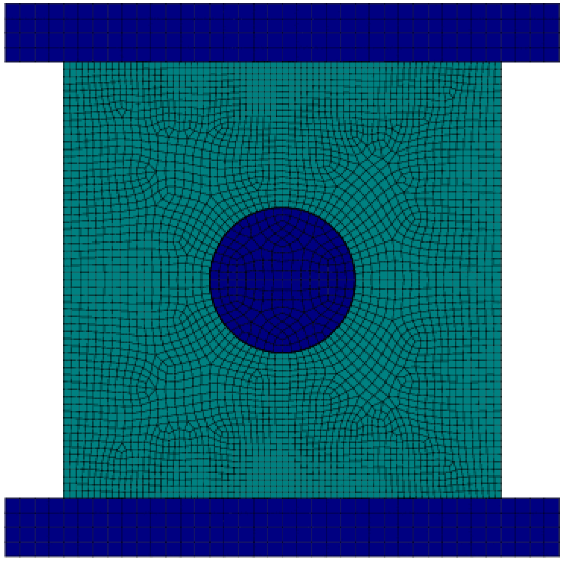
24% compression

Prediction Depends on Friction

Uniaxial Compression of PMDI Foam Block with Steel Rod



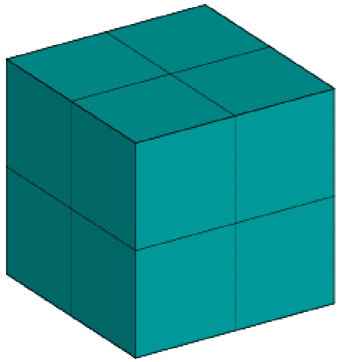


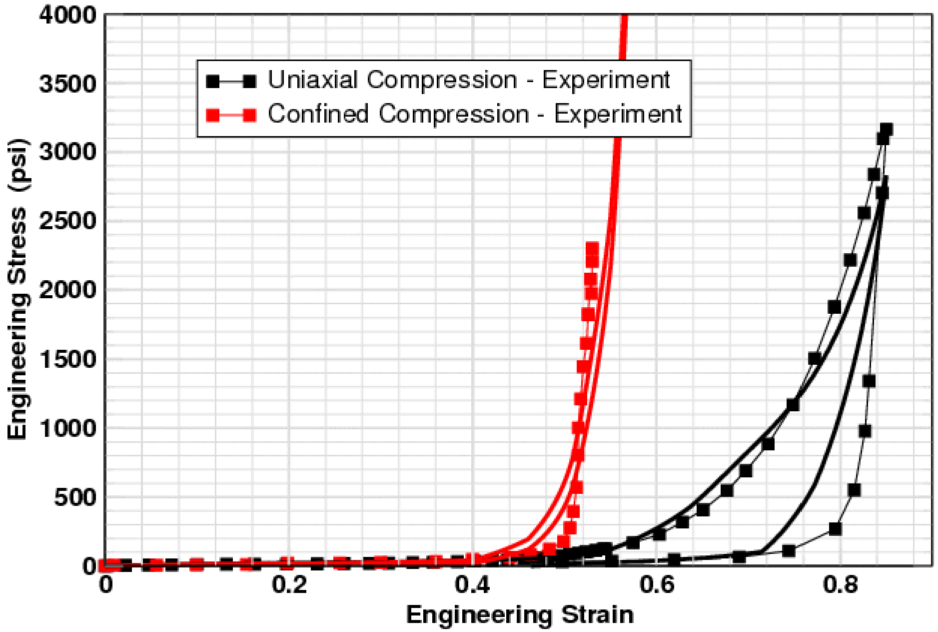


Comparison of Observed and Predicted Deformation

Uniaxial Compression Cellular Silicone Foam

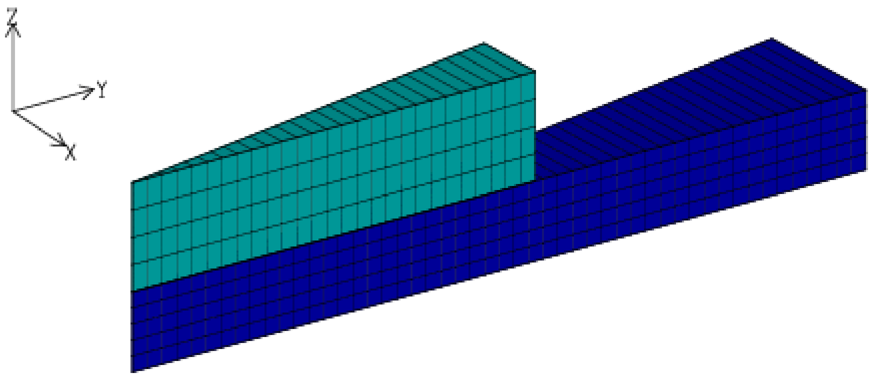
Simulation with 8-element block model

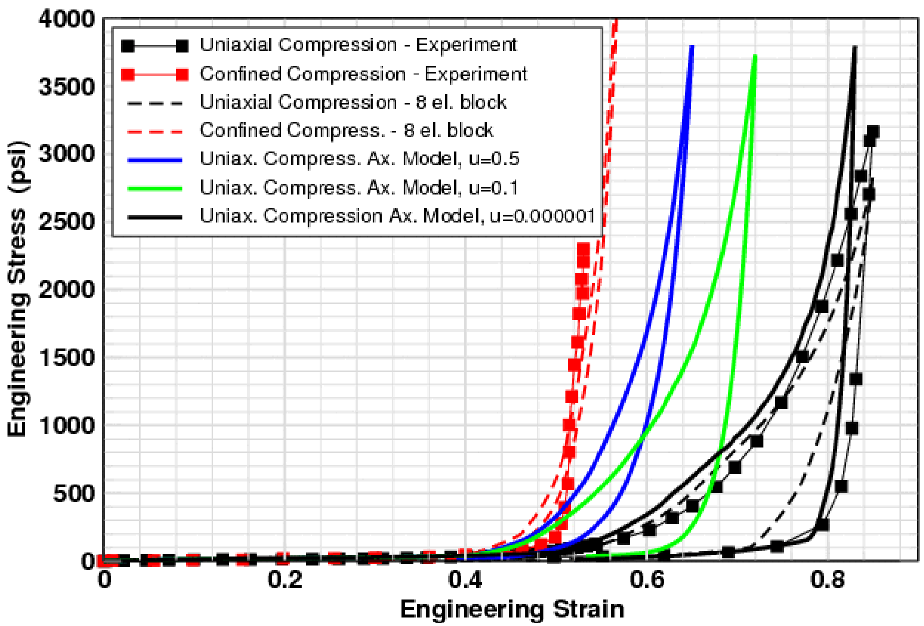


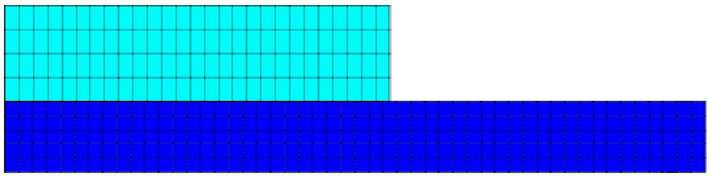


Experiment: Uniaxial Compression? of 1.10 inch diameter, 0.275 inch thick sample

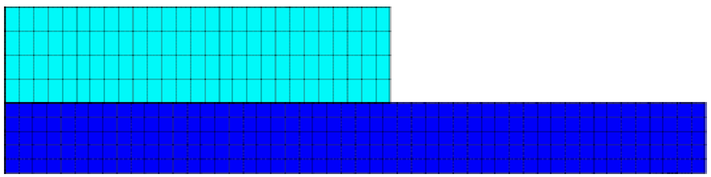
Uniaxial Compression Cellular Silicone Foam



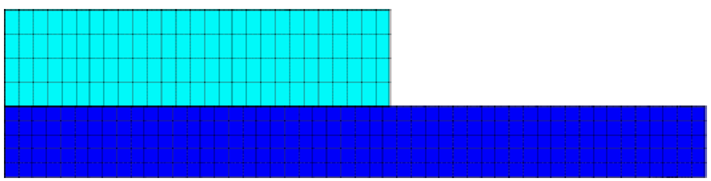




μ = 0.000001 (black curve)



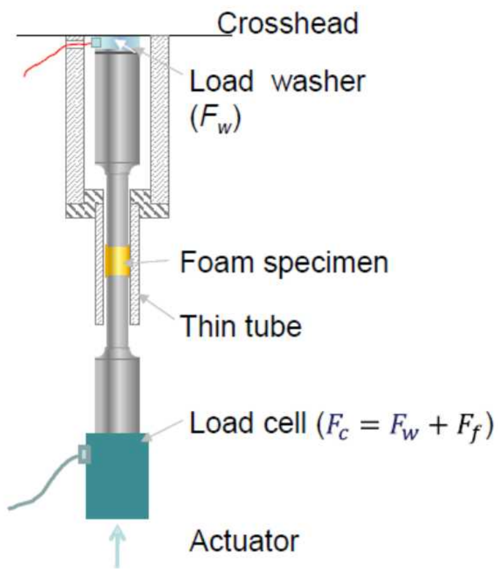
μ = 0.10 (green curve)

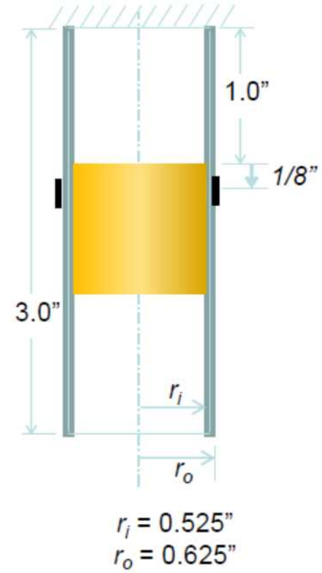


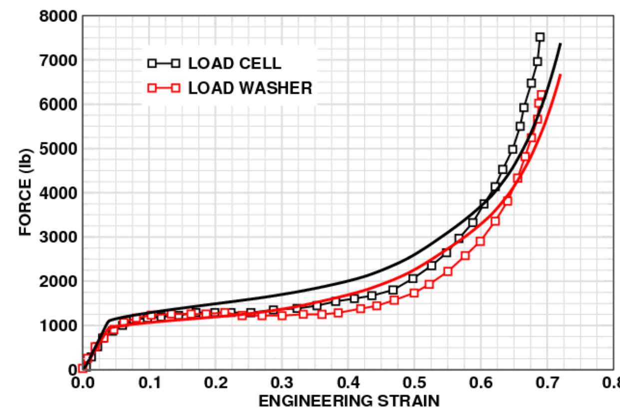
μ = 0.50 (blue curve)

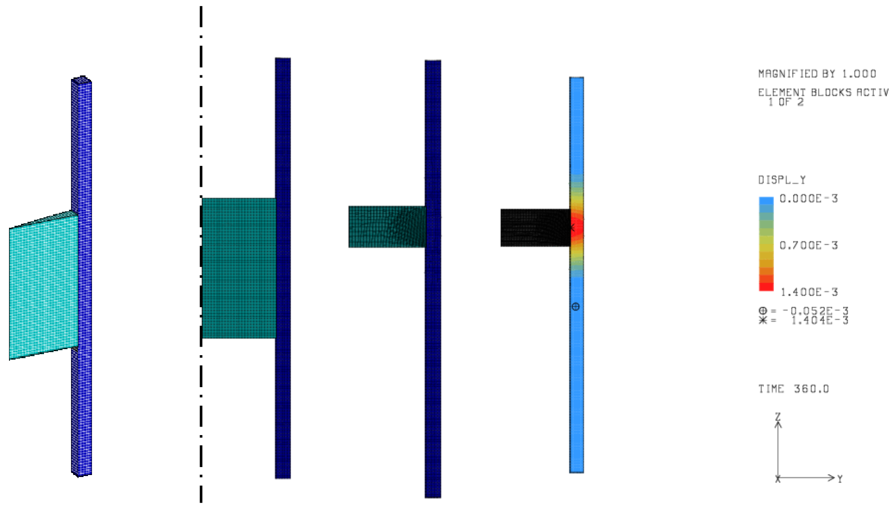
Uniaxial Compression of 1.10 inch diameter, 0.275 inch thick sample

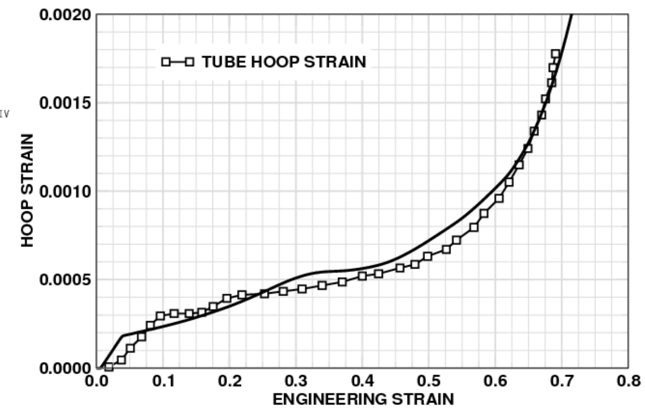
PMDI20 Comparison of Model Predictions with Experiments





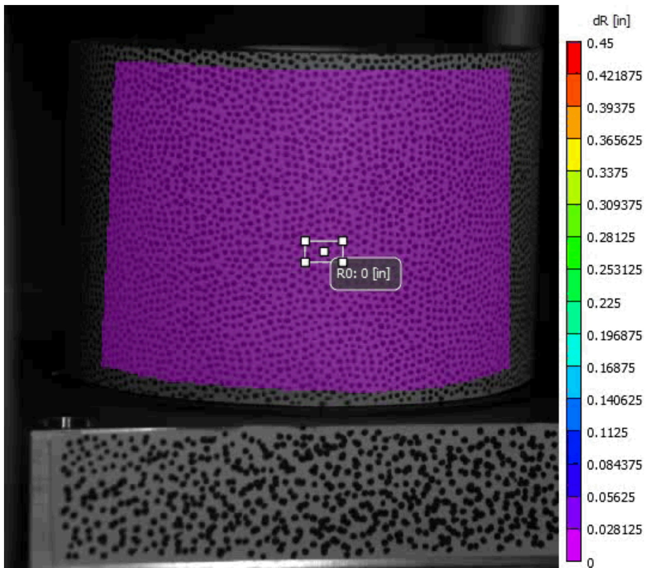


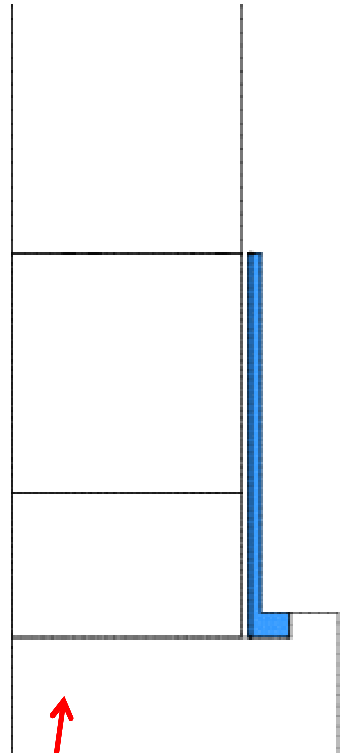


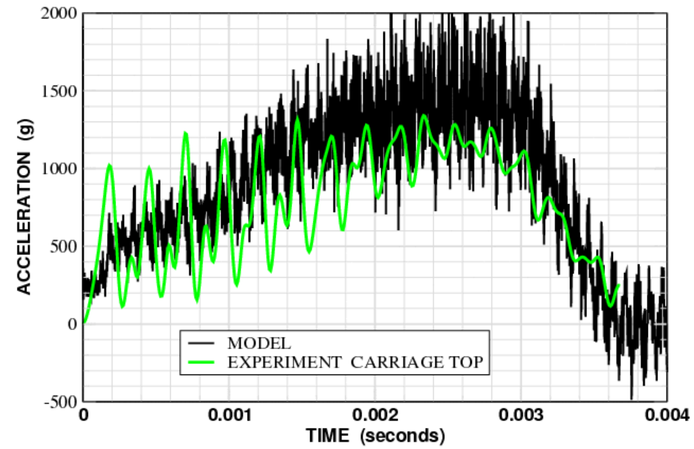


TufFoam35 Validation Experiment – Drop Table Crush Test

Sandia National Laboratories







model a bit high on peak acceleration but pulse duration/shape is good.

Experiment:
Matthew Spletzer, 1528
Wei-Yang Lu, 8343

block underneath moves but NOT in model.

Summary and Future Work

- Polyurethane foam response depends on temperature and strain-rate
- Polyurethane foam that is Flexible at room temperature can become rigid at cold temperatures.
- Flex Foam model captures change from Flexible to Rigid
- Both Flexible and Rigid foams exhibit damage when crushed
- Flex Foam model is work in progress. Future work will be to capture effects of damage on foam moduli