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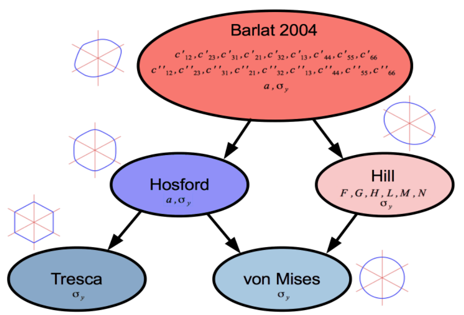

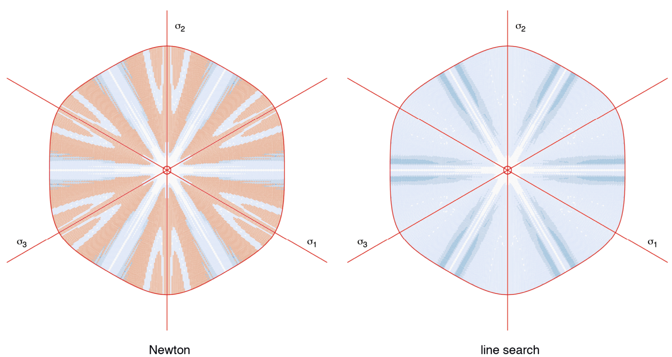

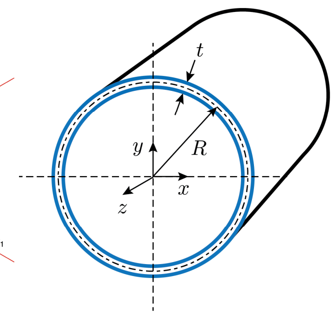

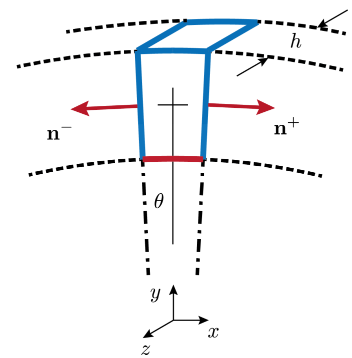

LAME: Material Modeling Strategy

William M. Scherzinger, May 1, 2017

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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LAME

- LAME is a constitutive model library that is used by the Sierra/SM code
- As a code product, it is very different from an analysis code
    - Rely on material modeling expertise at Sandia, in NW complex, and external partners
- How do we support customers?
    - Analysts
    - Application code team
    - Constitutive modelers

LAME – History

- LAME development concentrated on constitutive model developers
  - Needed to leverage expertise
  - Supported FORTRAN models
  - Effort in reproducing legacy capabilities
- While this worked well, we need to adjust to a production code environment
  - Build on what we have learned
  - Codify some practices
  - Support analysts and code development team

LAME – Current

- LAME production/development libraries
  - Production library
    - Reliable and robust
    - Documented
    - Useable
  - Development library
    - May not be robust
    - Undocumented
    - Sandbox for developing a model
- Goal is to transition models that are useful to production
  - Provides paper trail for credibility

Constitutive Model Credibility

- Model credibility – specifically constitutive model credibility – is an issue in FE modeling
  - Commercial codes have a huge user base
  - Laboratory codes are different
- How do we improve model credibility?
  - How do we use the model?
  - Do we know what the model does?
  - Do we understand how the model works?
  - Does the model do what we expect?

Production Library

- What makes a model a production model?
  - Necessary for our work
  - Support

- Documentation
  - Theory
  - Implementation
  - Verification
  - User Input/Output

Sierra/SM – documentation – manuals

LAME Material Models Manual

SAND 2016-9920 O
Library of Advanced Materials for Engineering (LAME) 4.42

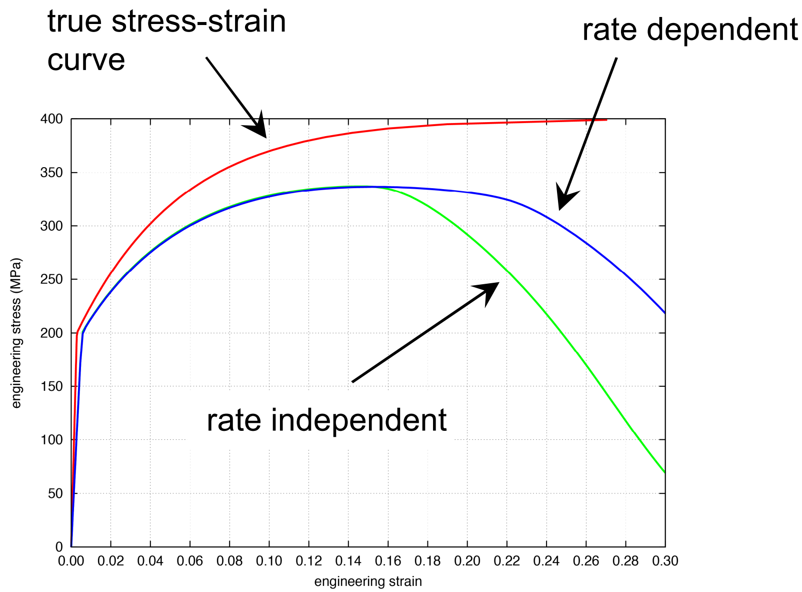
Verification

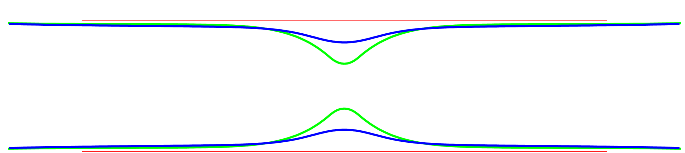
- How can we verify a model?
- First, look at strain and stress
  - Tensors (6 dimensional)
  - We can only test a limited number of strain/stress paths
- Second, look at model features
  - Models are all different
  - **No single solution to verification**
  - Requires some expertise in material modeling, continuum mechanics, analysis

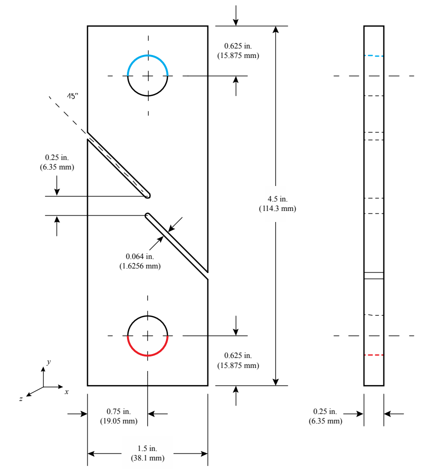
Improvements

What else can we do?

- Theory
- Implementation
- Verification
- User Input/Output
- Overview
- Calibration
- Examples







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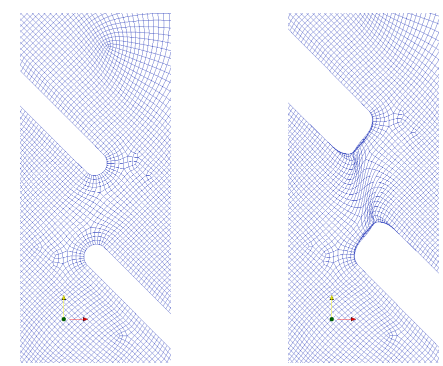
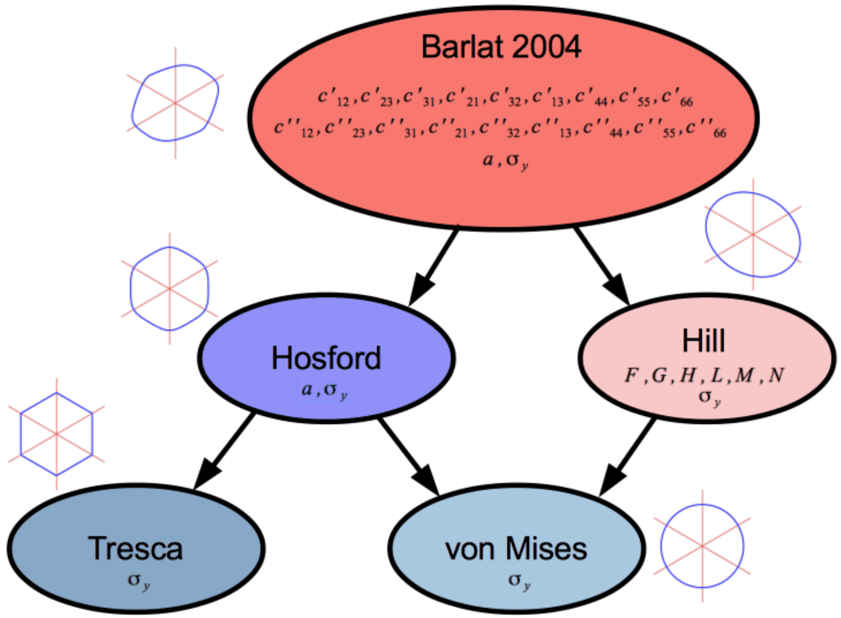


Capability Development

- A family of plasticity models
- Yield surface with associated flow
- Hardening model
- Rate dependence
- Temperature dependence
- Failure

Plasticity Models

- Yield surface – this is how we define our family of models



Plasticity Models

- The general form we will use for the yield function is as follows

$$f = \phi\left(\boldsymbol{\sigma}\right) - \bar{\sigma}\left(\bar{\varepsilon}^p\right) = 0$$

effective stress — isotropic hardening

  - This defines a surface in stress space – the yield surface
  - Assume associated flow

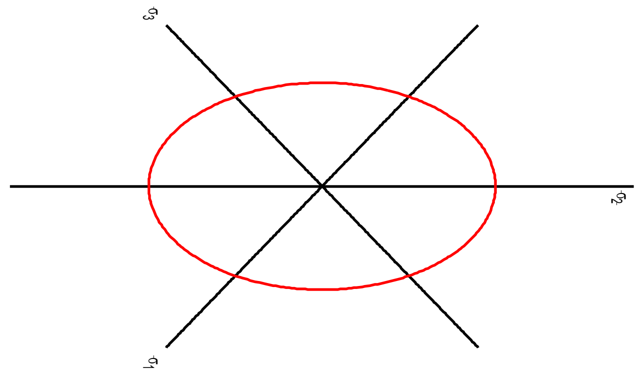
$$\bar{\sigma}\dot{\bar{\varepsilon}}^p = \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}^p = \boldsymbol{\sigma} : \gamma \frac{\partial \phi}{\partial \boldsymbol{\sigma}} \quad \rightarrow \quad \gamma = \dot{\bar{\varepsilon}}^p$$

Plasticity Models

- Von Mises

$$\phi = \sqrt{\frac{3}{2}\mathbf{s} : \mathbf{s}}$$

$$\mathbf{s} = \boldsymbol{\sigma} - \frac{1}{3}\left(\mathrm{tr}\boldsymbol{\sigma}\right)\ \mathbf{I}$$

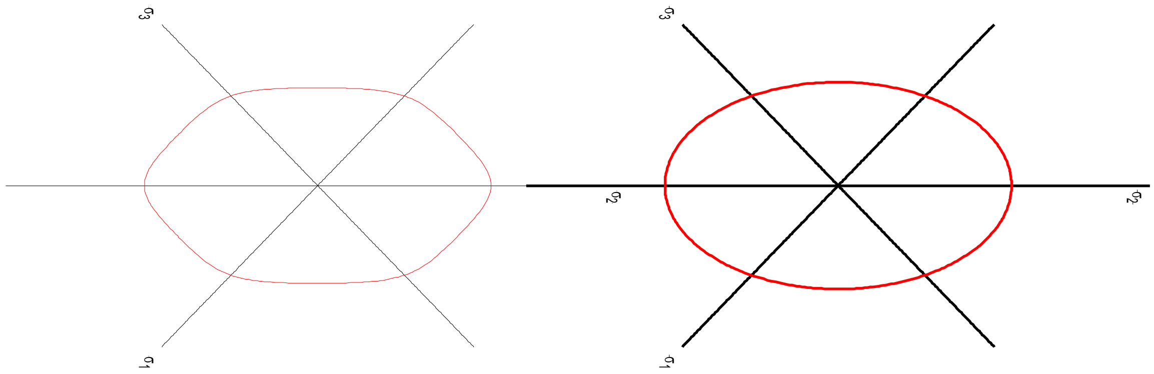


Plasticity Models

- Hosford

$$\phi = \left\{ \frac{1}{2} \left[|\sigma_1 - \sigma_2|^a + |\sigma_2 - \sigma_3|^a + |\sigma_3 - \sigma_1|^a \right] \right\}^{1/a}$$

$$\boldsymbol{\sigma} = \sum_{i=1}^{3} \sigma_i \hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_i$$



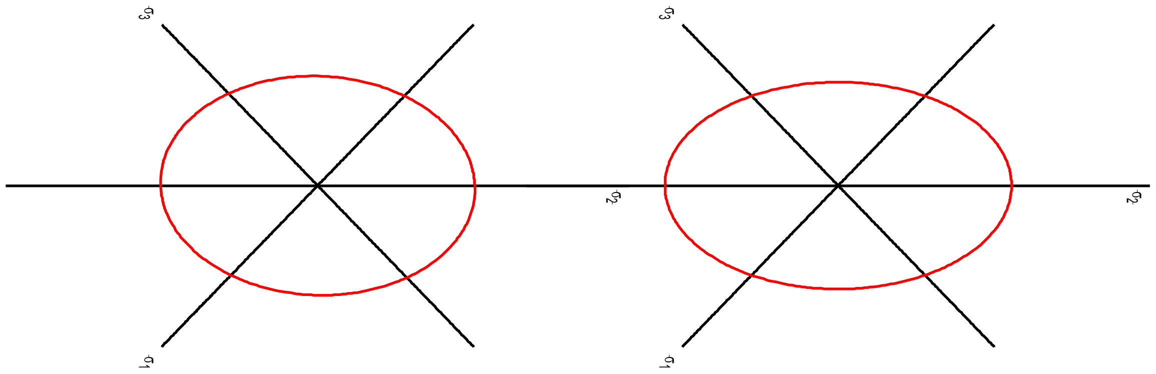
Plasticity Models

- Hill

$$\phi^2(\boldsymbol{\sigma}) = F\left(\hat{\sigma}_{22} - \hat{\sigma}_{33}\right)^2 + G\left(\hat{\sigma}_{33} - \hat{\sigma}_{11}\right)^2 + H\left(\hat{\sigma}_{11} - \hat{\sigma}_{22}\right)^2$$

$$+ 2L\hat{\sigma}_{23}^2 + 2M\hat{\sigma}_{31}^2 + 2N\hat{\sigma}_{12}^2$$

$$\phi = \sqrt{\frac{3}{2}\boldsymbol{\sigma} : \mathbf{P} : \boldsymbol{\sigma}}$$



Plasticity Models

- Barlat *

$$\mathbf{s}' = \mathbf{L}' : \boldsymbol{\sigma} \quad ; \quad \mathbf{s}'' = \mathbf{L}'' : \boldsymbol{\sigma}$$

$$\phi\left(\boldsymbol{\sigma}\right) = \left\{ \frac{1}{4} \left[|s_1' - s_1''|^a + |s_1' - s_2''|^a + |s_1' - s_3''|^a \right.\right.$$

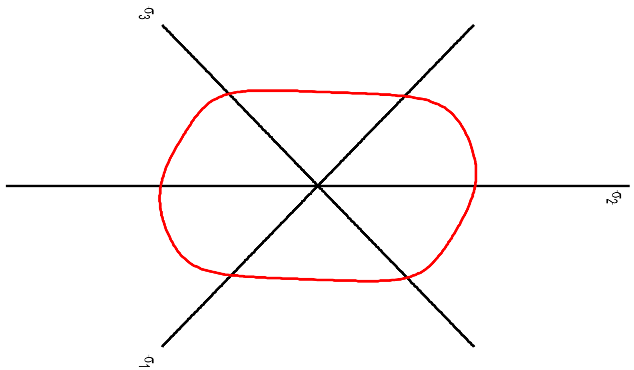
$$+ |s_2' - s_1''|^a + |s_2' - s_2''|^a + |s_2' - s_3''|^a$$

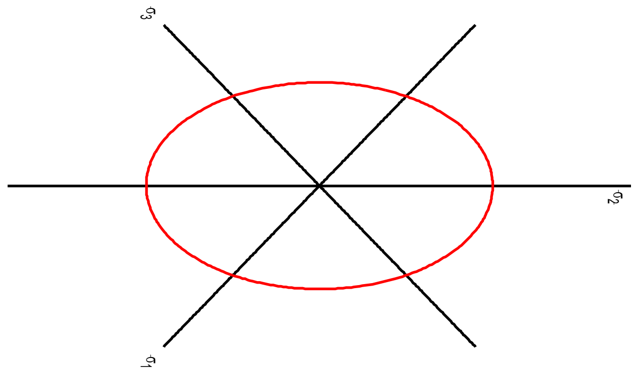
$$\left.\left. + |s_3' - s_1''|^a + |s_3' - s_2''|^a + |s_3' - s_3''|^a \right] \right\}^{1/a}$$

* Barlat et. al., “Linear transformation based anisotropic yield functions”, IJP, v. 21, 2005.

Plasticity Models

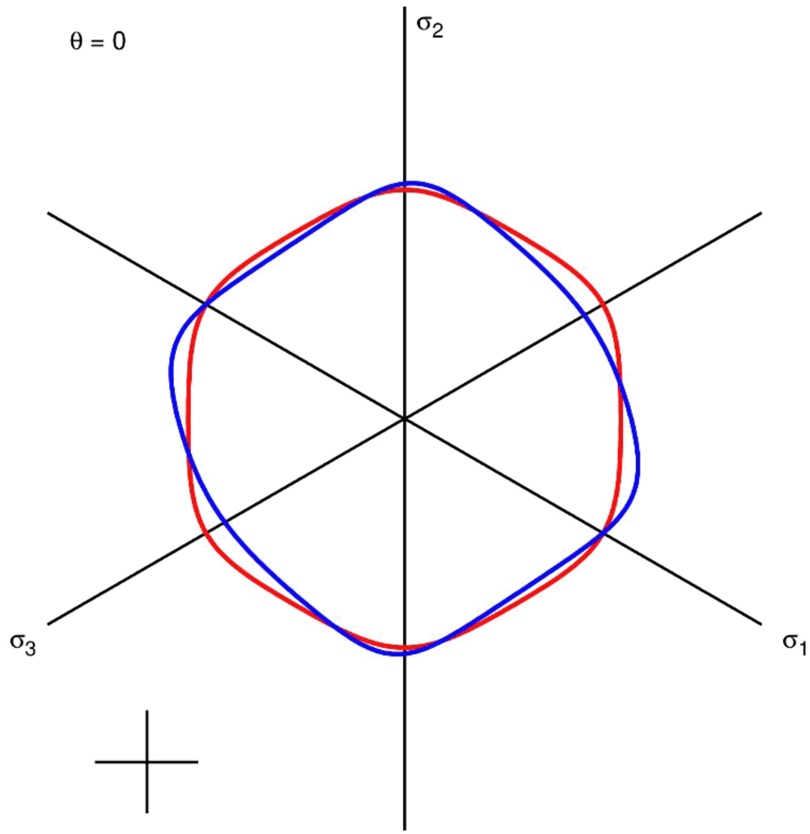
- Barlat *

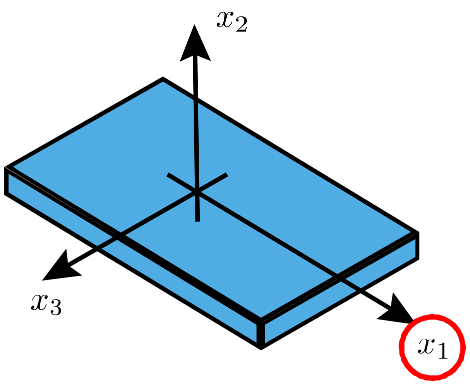




* Barlat et. al., “Linear transformation based anisotropic yield functions”, IJP, v. 21, 2005.

Hosford and Barlat Model





Integration

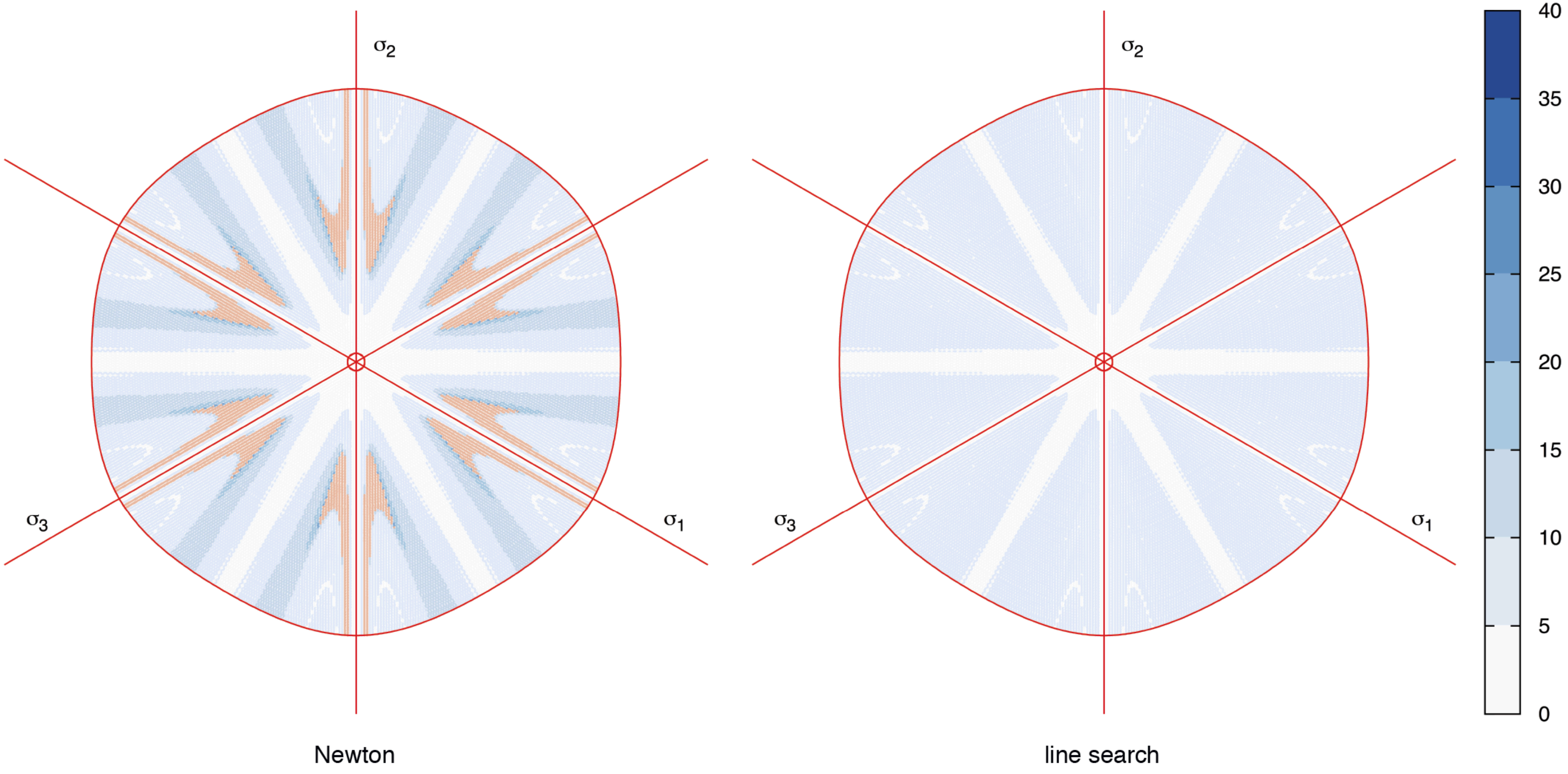
- How do we implement these models?

- Backward Euler algorithm with Newton-Raphson algorithm

  - Von Mises reduces to radial return
  - Other models are more complex – it is **not** radial return
  - Newton-Raphson does not always work (contrary to Simo-Hughes)

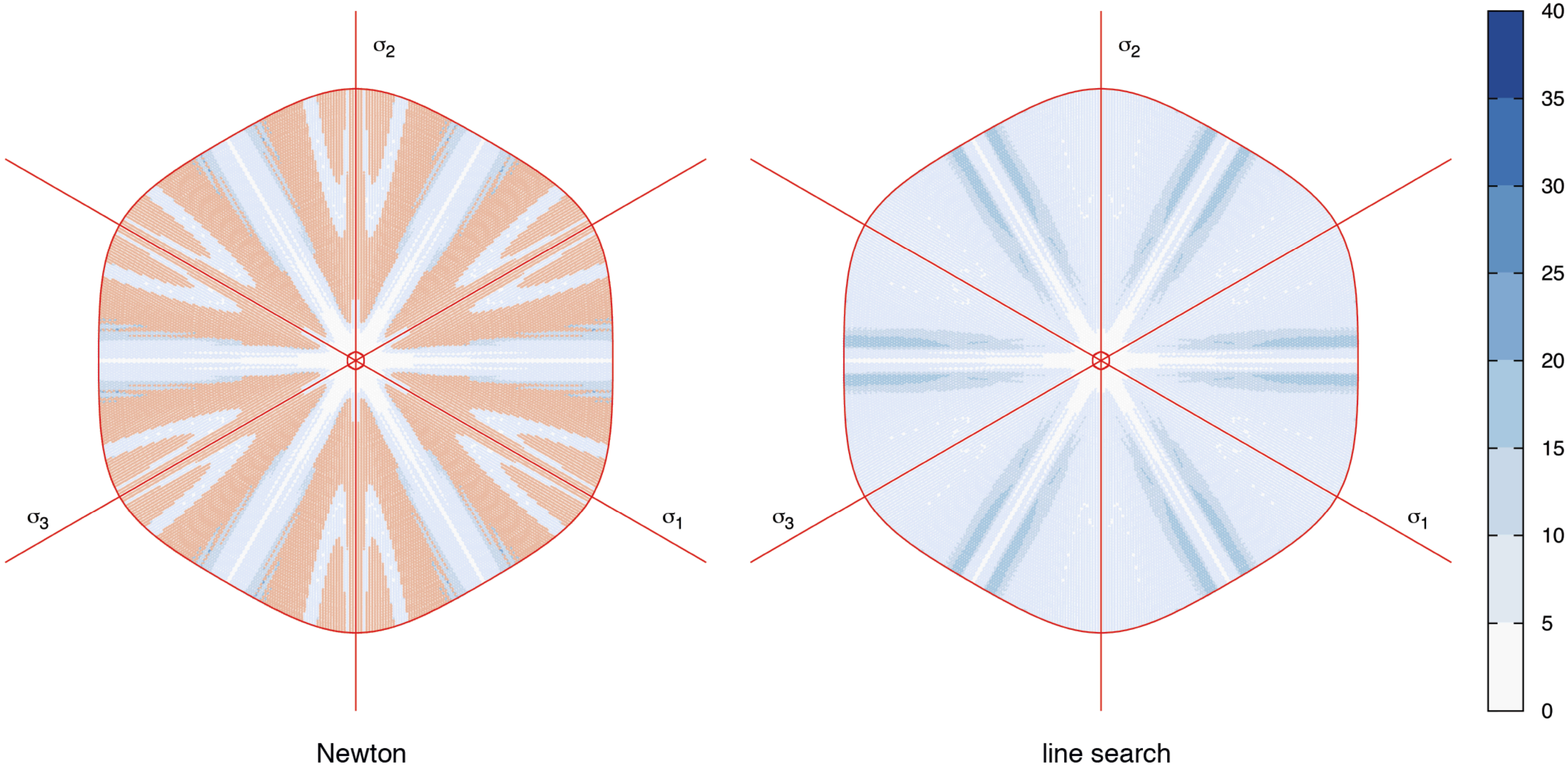
- Many other options have been proposed
  - Forward Euler with sub-stepping
  - Backward Euler with sub-stepping
  - Line search

Hosford (a=6)

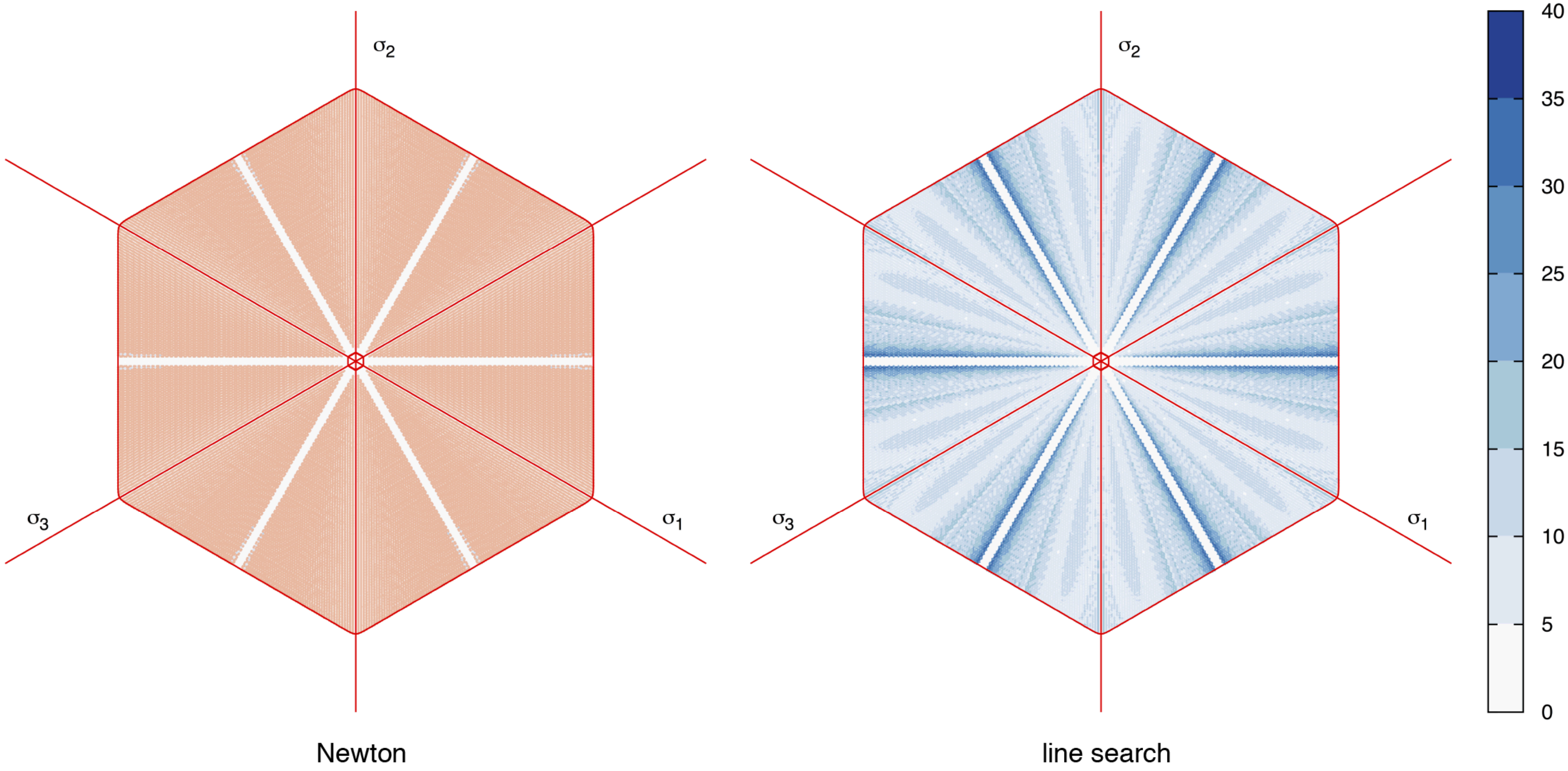


σ_2
σ_3
σ_1
Newton
σ_2
σ_3
σ_1
line search
40
35
30
25
20
15
10
5
0

Hosford (a=8)

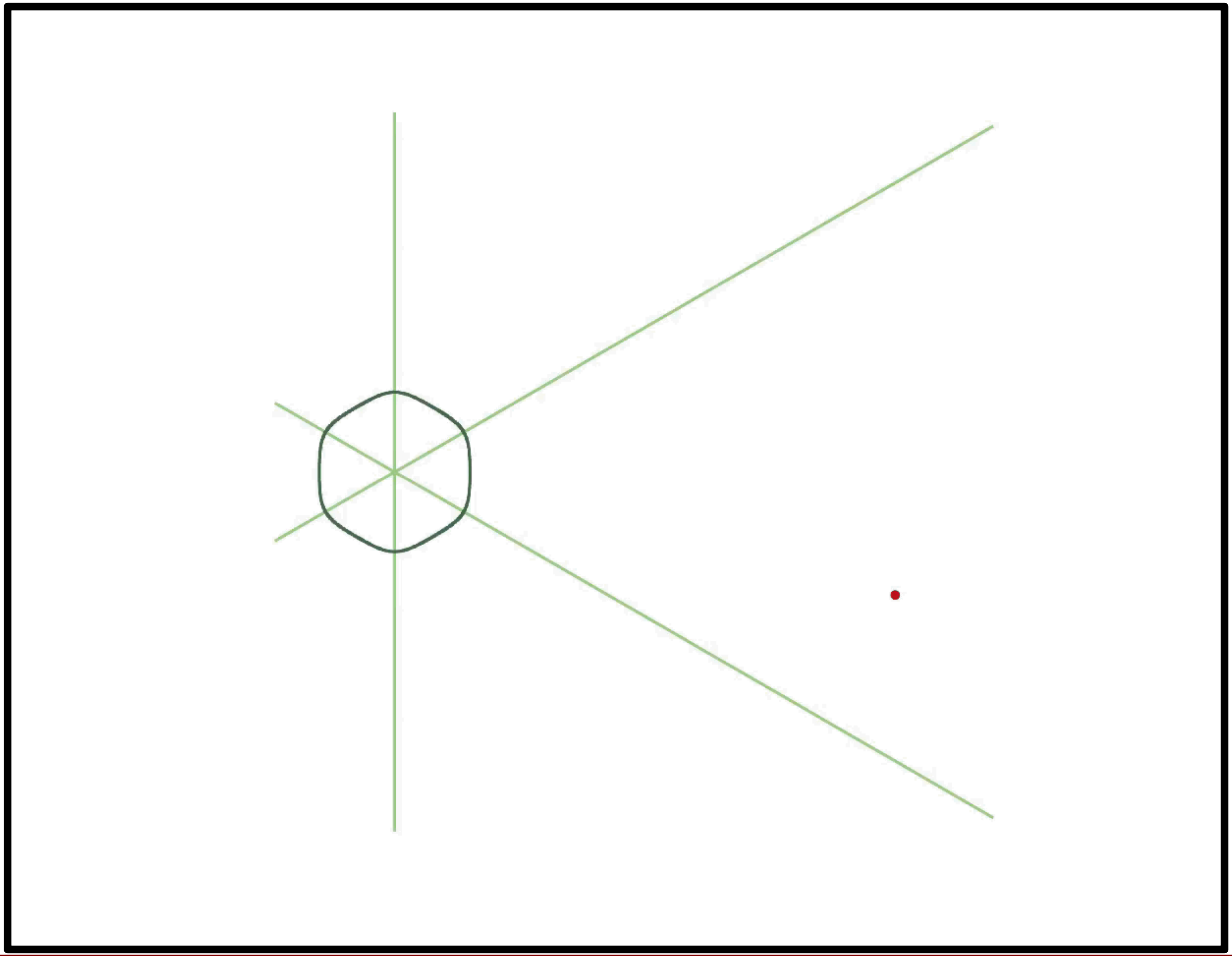


Hosford (a=100)



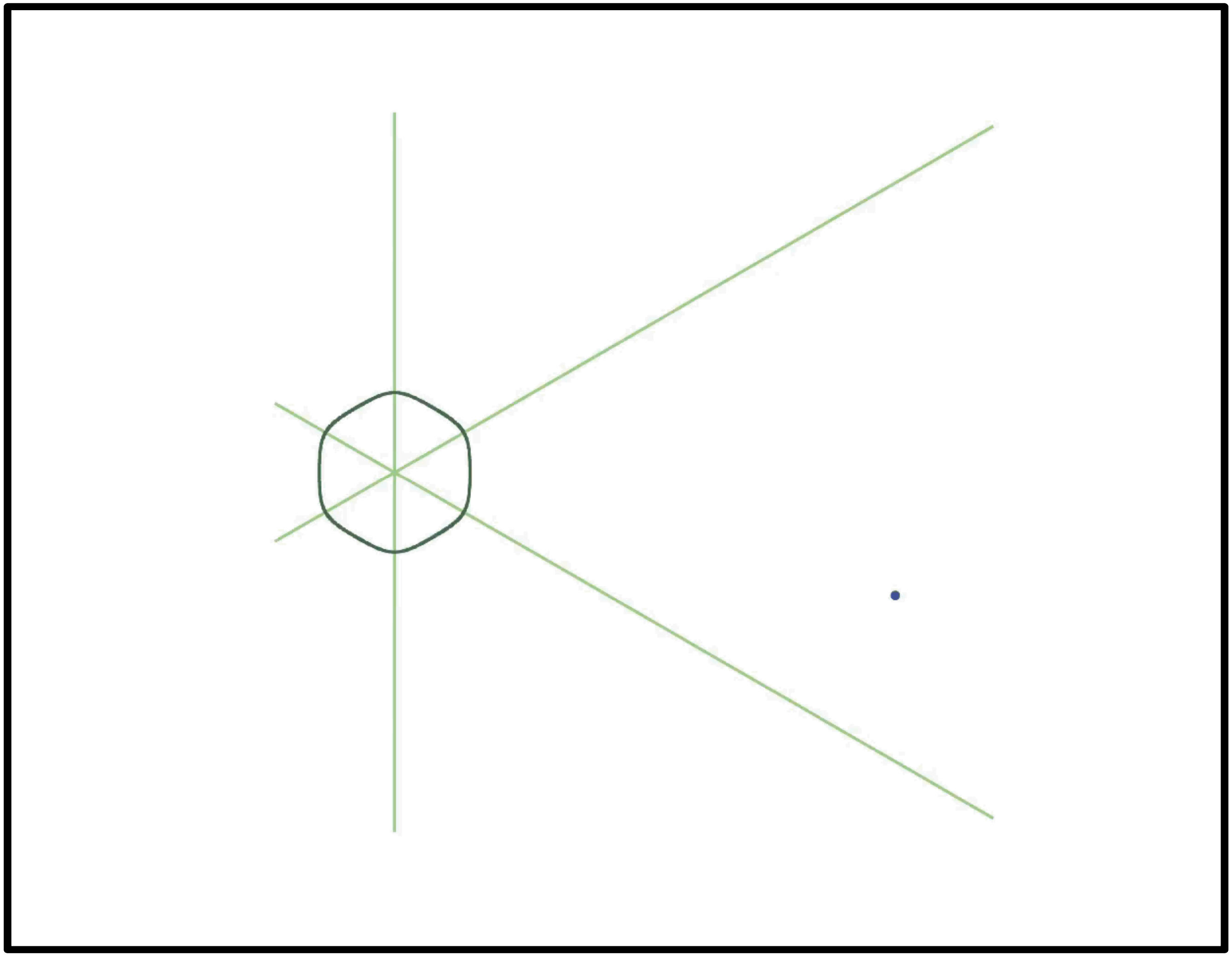
Hosford (a=8)

Newton algorithm



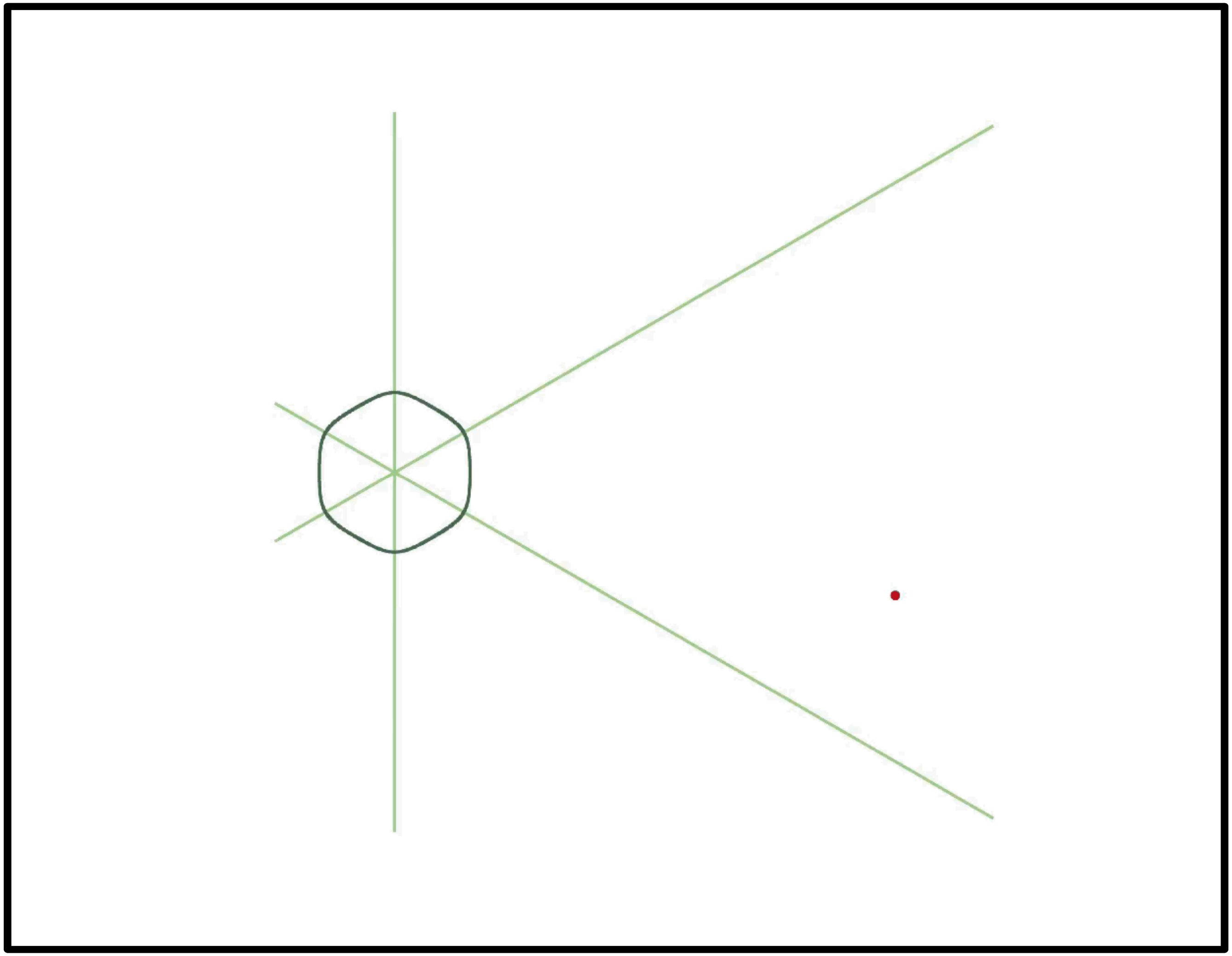
Hosford (a=8)

line search algorithm



Hosford (a=8)

Newton and line search algorithms



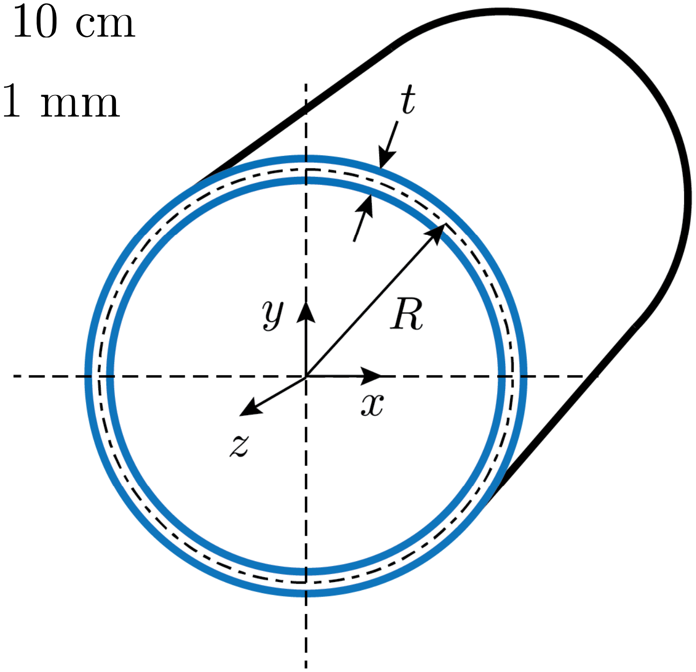
Example Problem

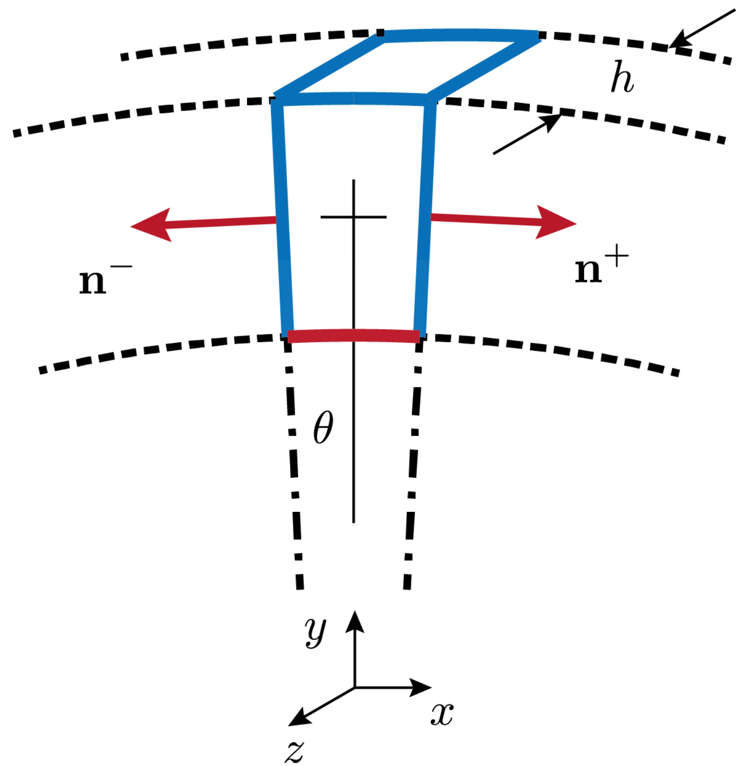
Example Problem

2090-T3 Aluminum

$R = 10$ cm

$h = 1$ mm



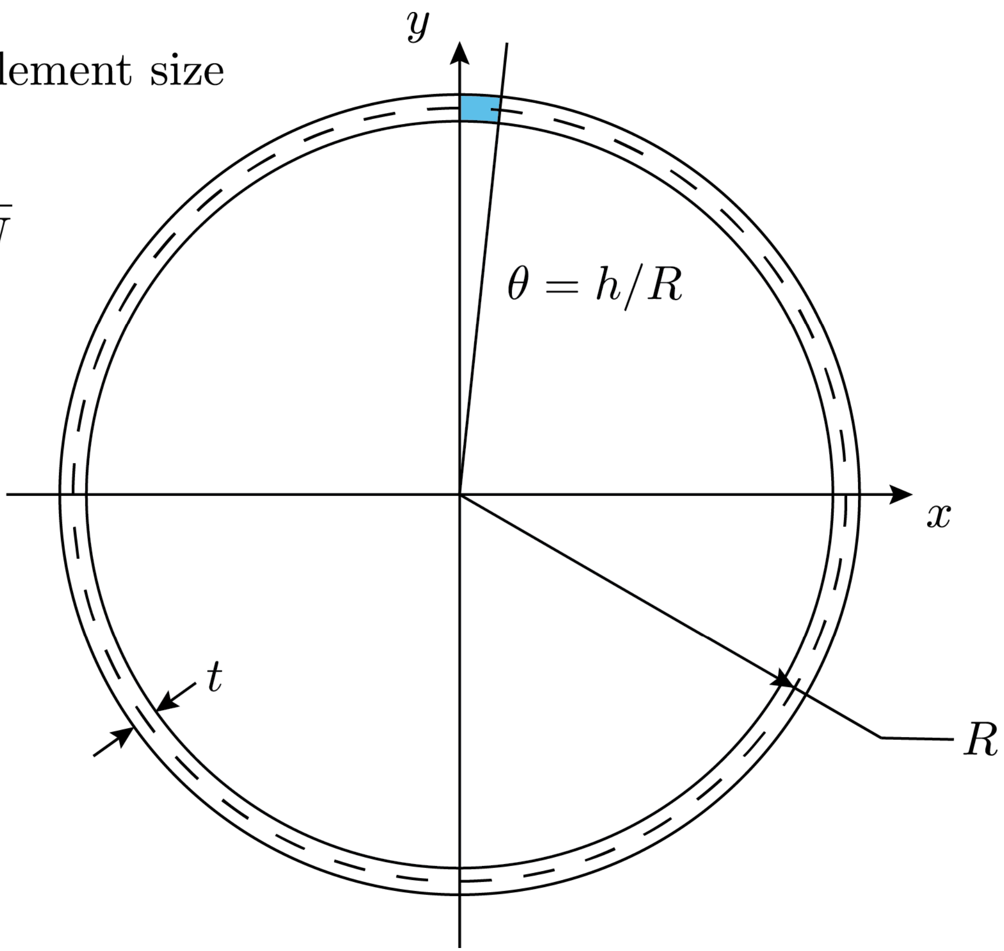


$$\bar{\sigma} = 200\,(1 - \exp(-20\,\bar{\varepsilon}^p))\ \text{MPa} \quad \rightarrow \quad \sigma_y = 200\ \text{MPa}$$

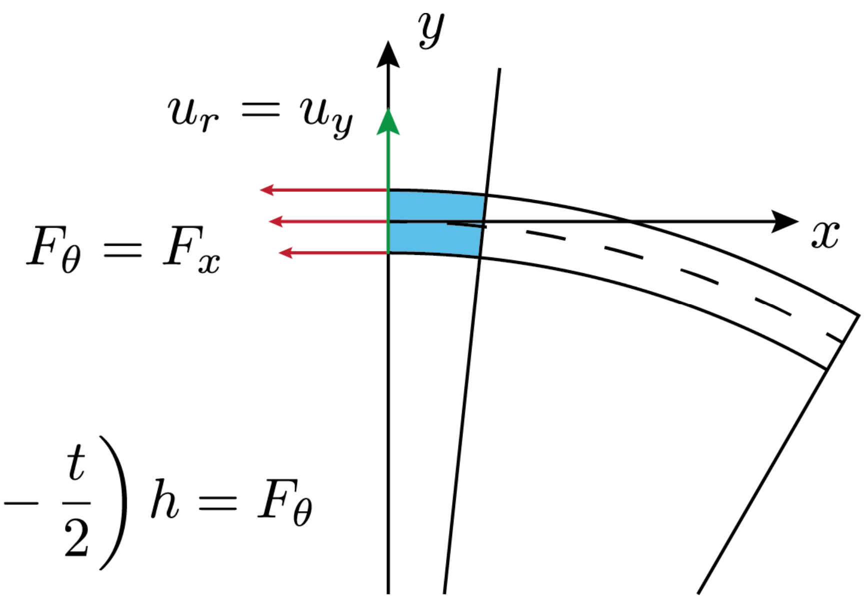
Example Problem

$h -$ element size

$$h = \frac{t}{N}$$

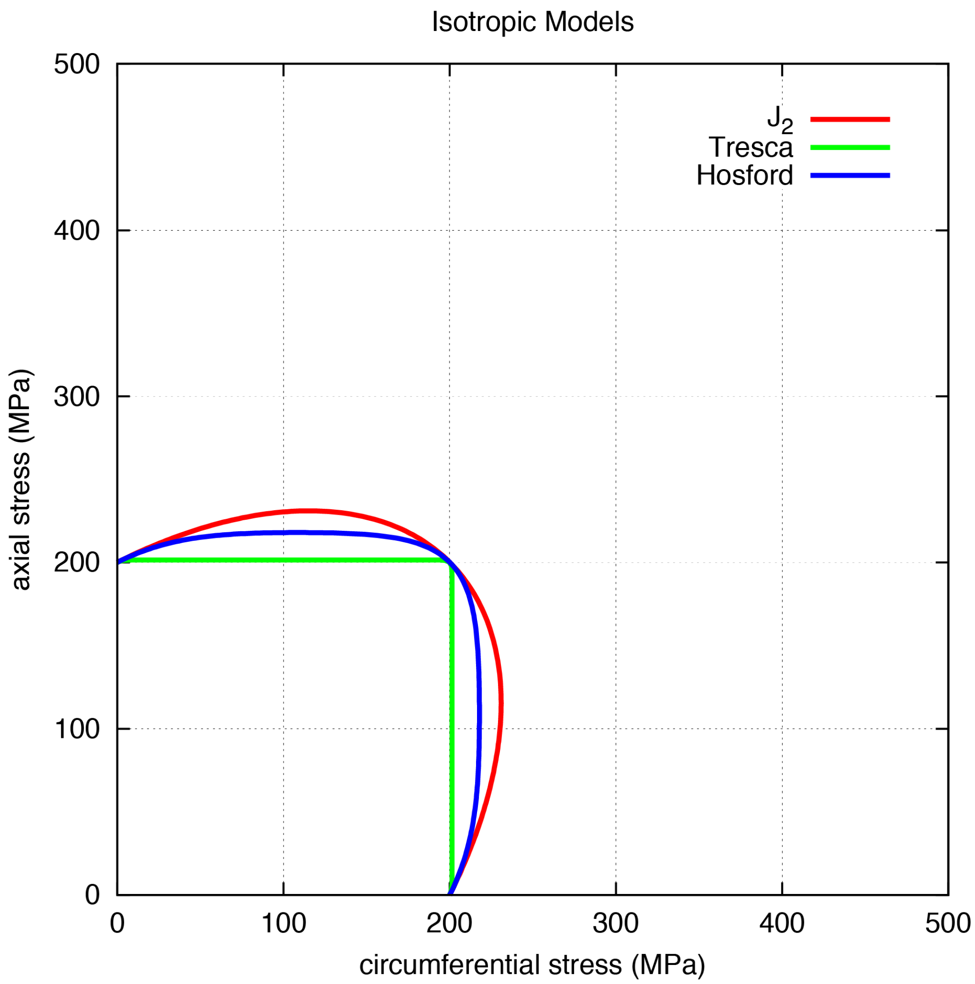


Example Problem

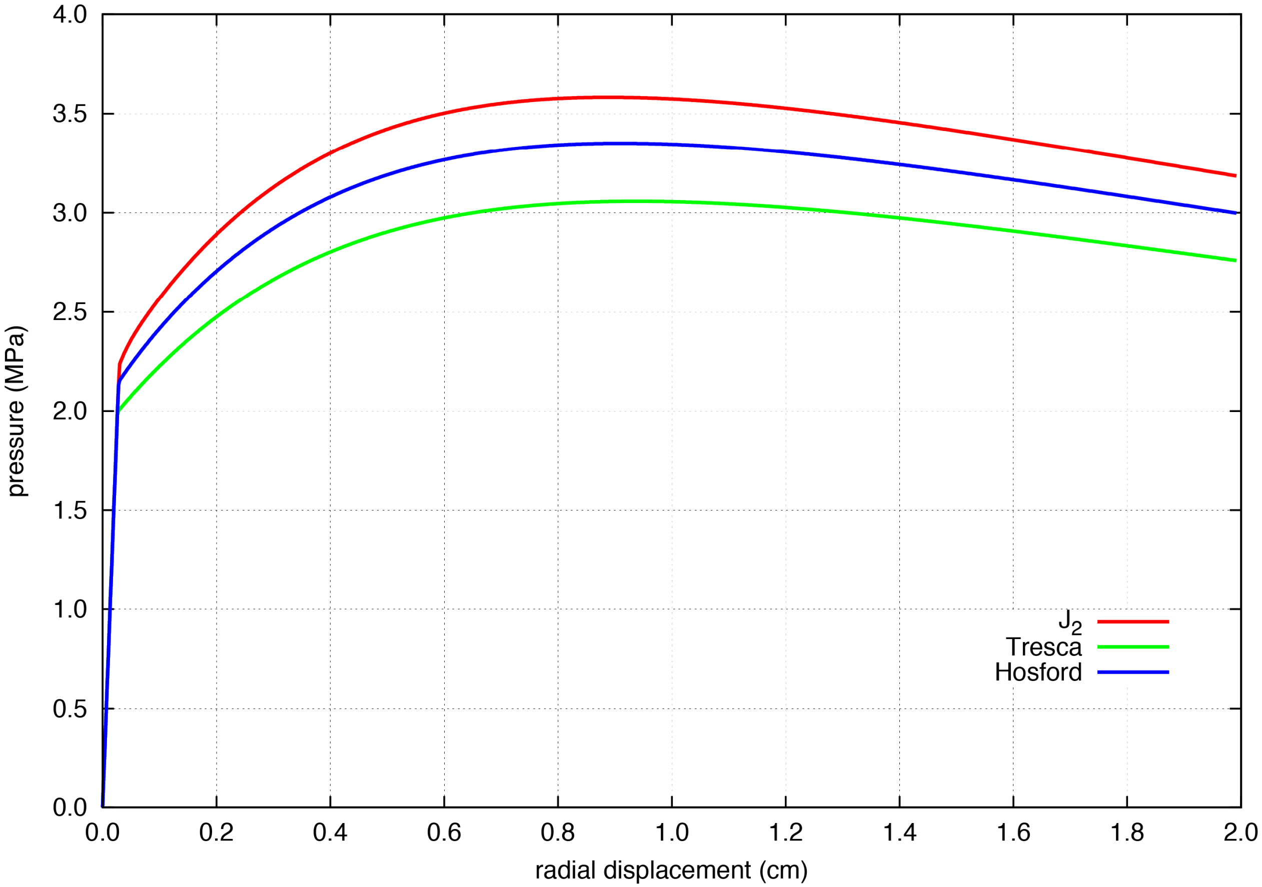


$$p\left(R + u_r - \frac{t}{2}\right)h = F_\theta$$

Yield Surface – Isotropic Models

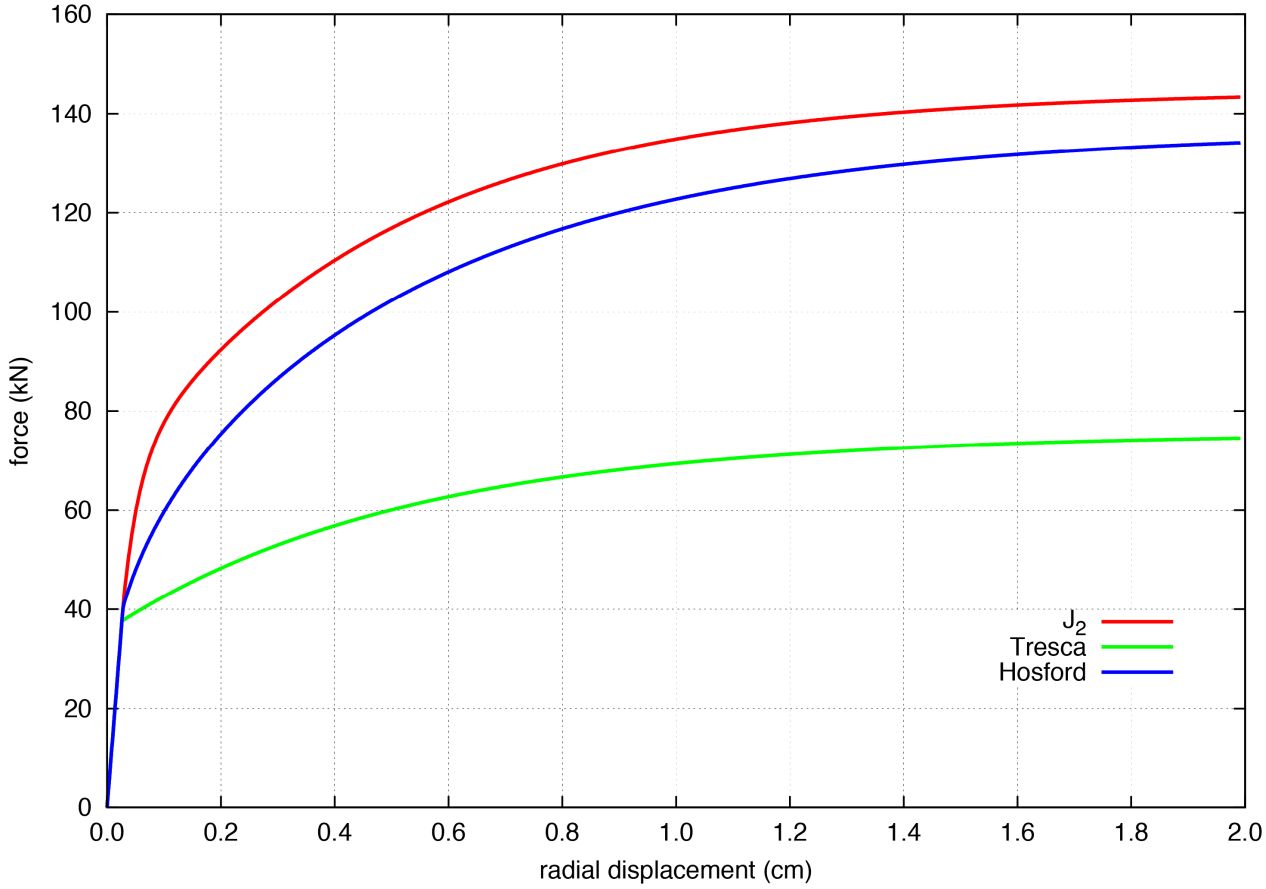


Pressure



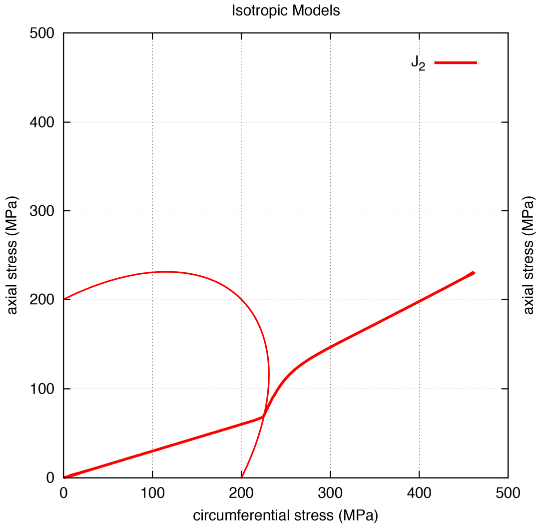
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
pressure (MPa)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
radial displacement (cm)
J_2
Tresca
Hosford

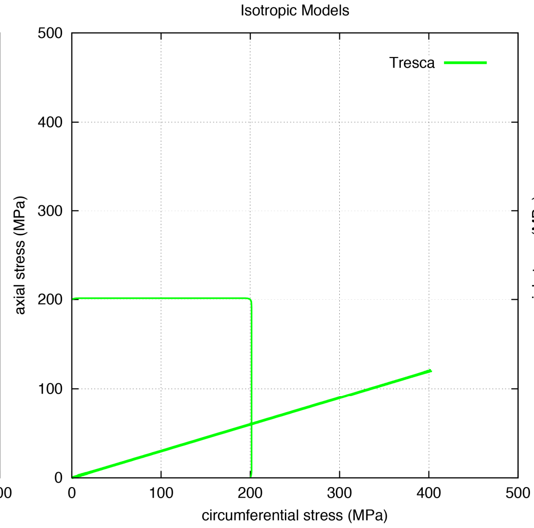
Axial Load

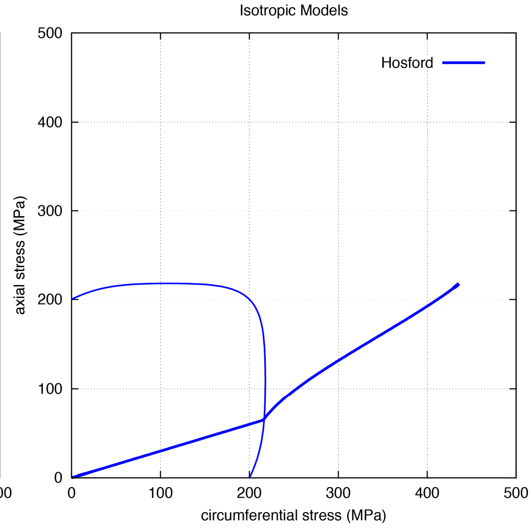


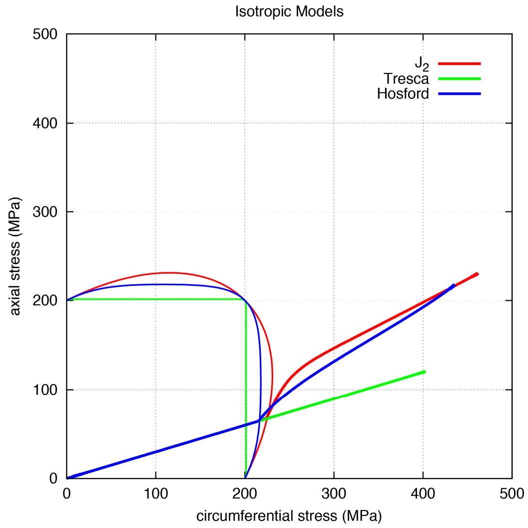
force (kN)
160
140
120
100
80
60
40
20
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
radial displacement (cm)
J_2
Tresca
Hosford

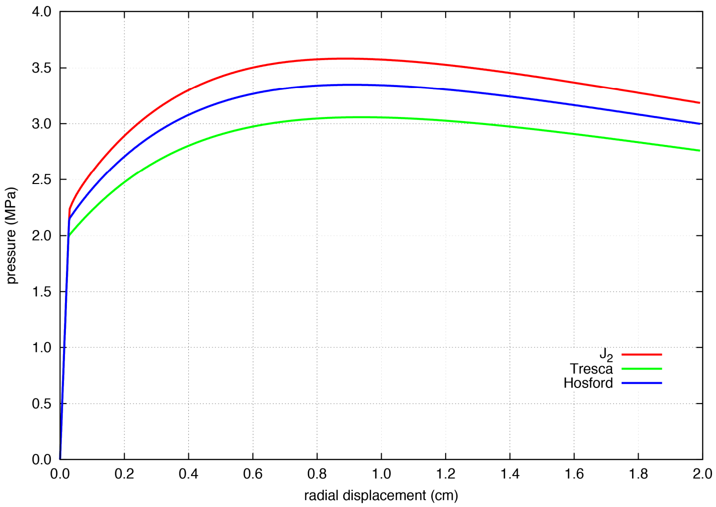
Stress Paths – Isotropic Models



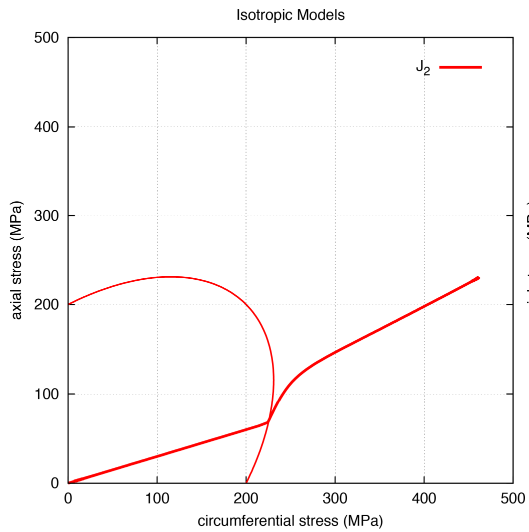


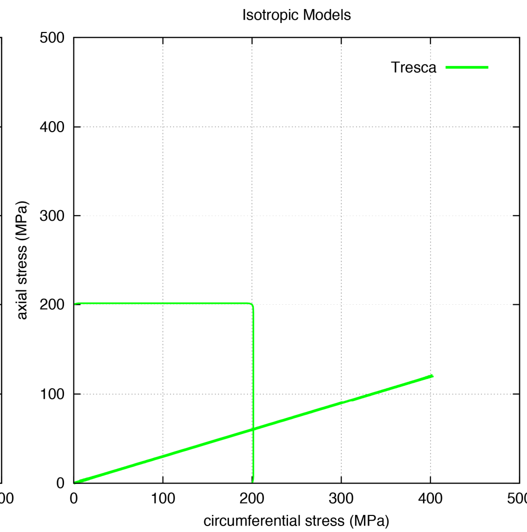


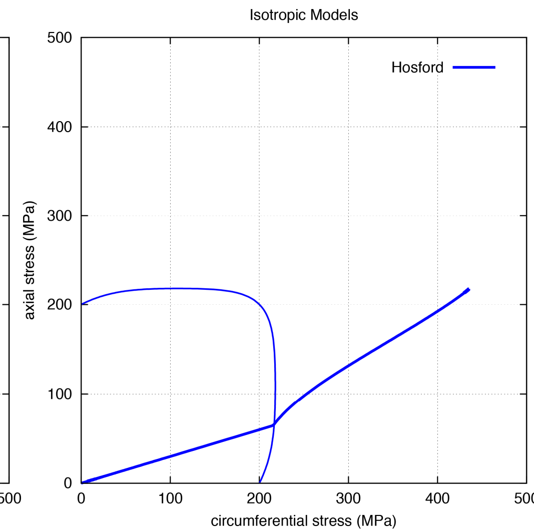


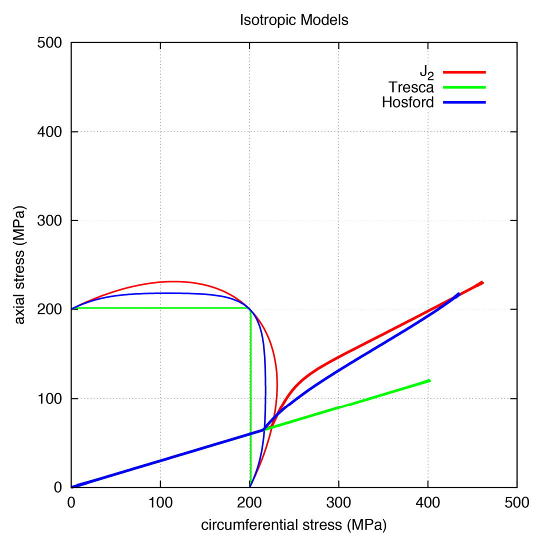


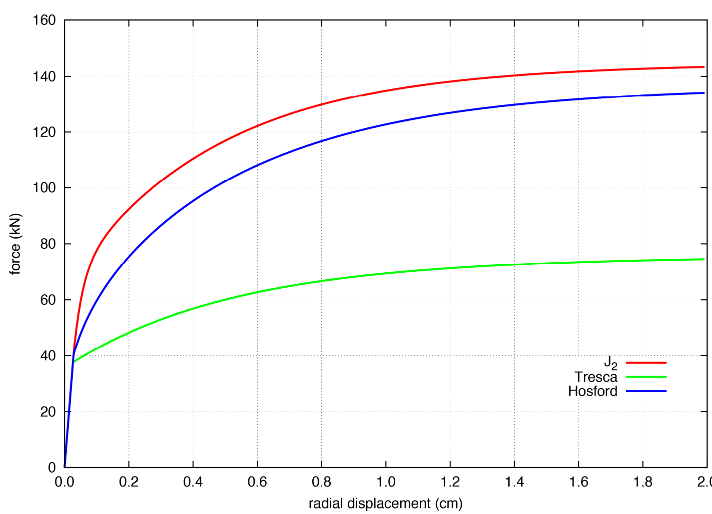
Stress Paths – Isotropic Models



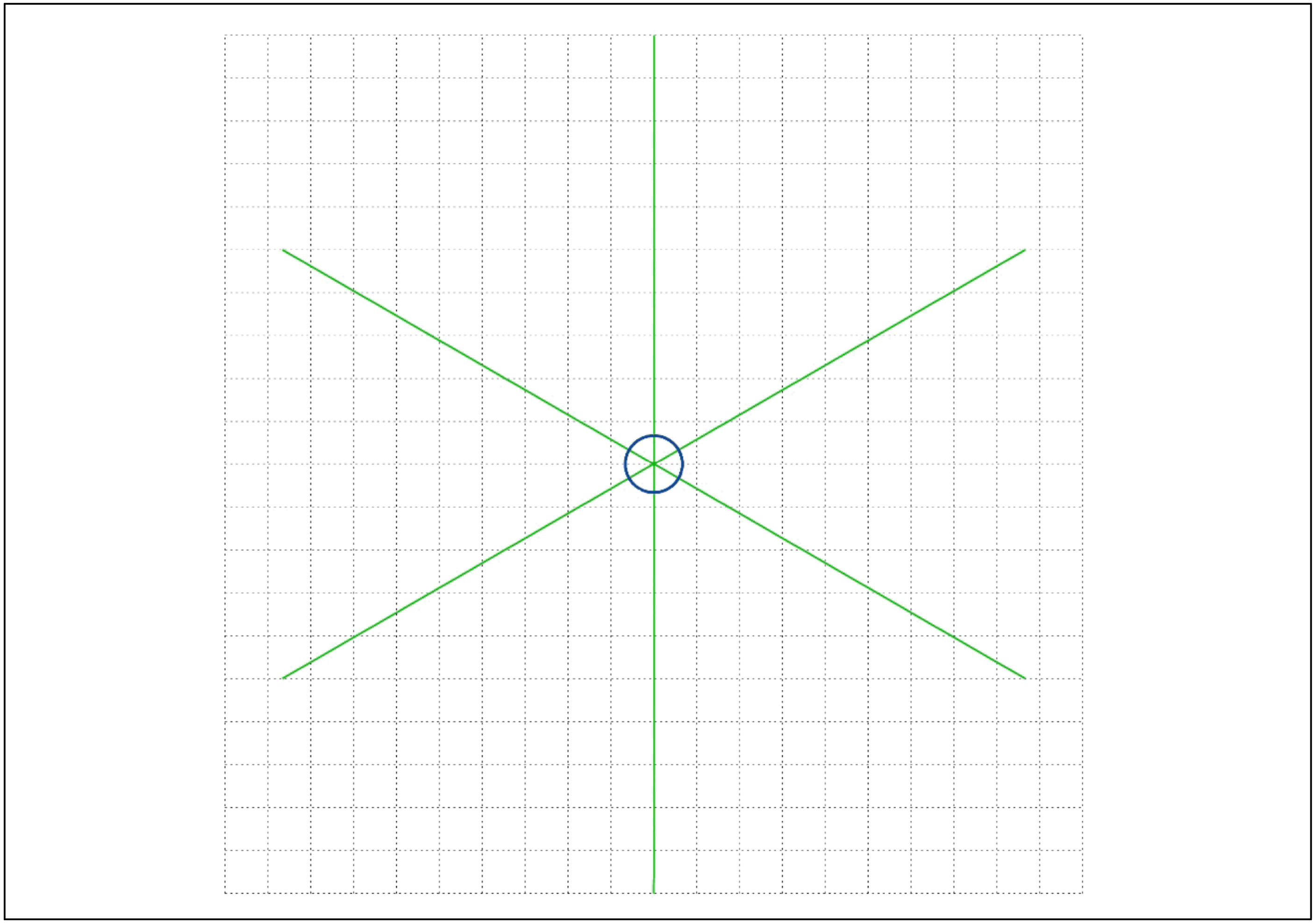




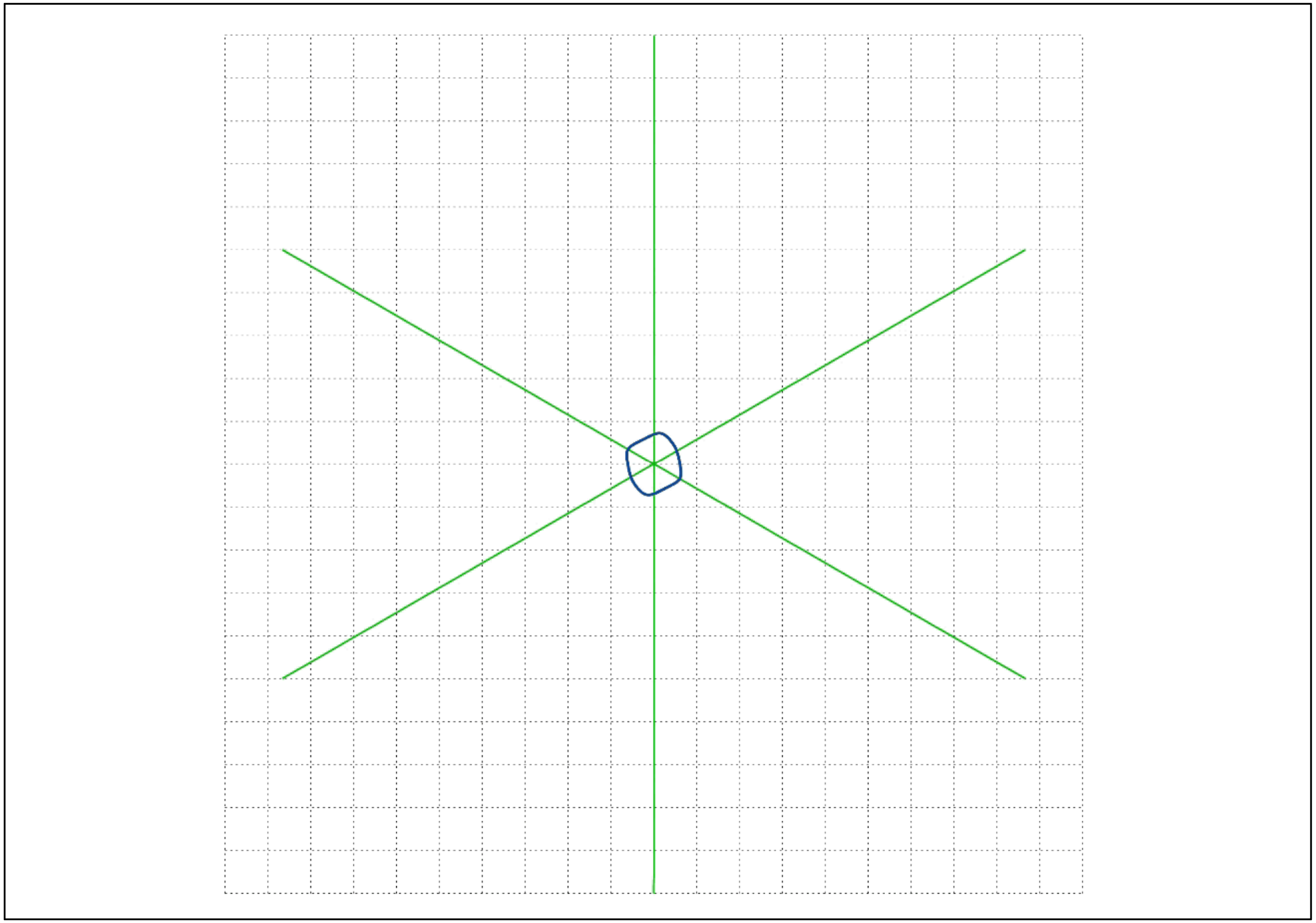




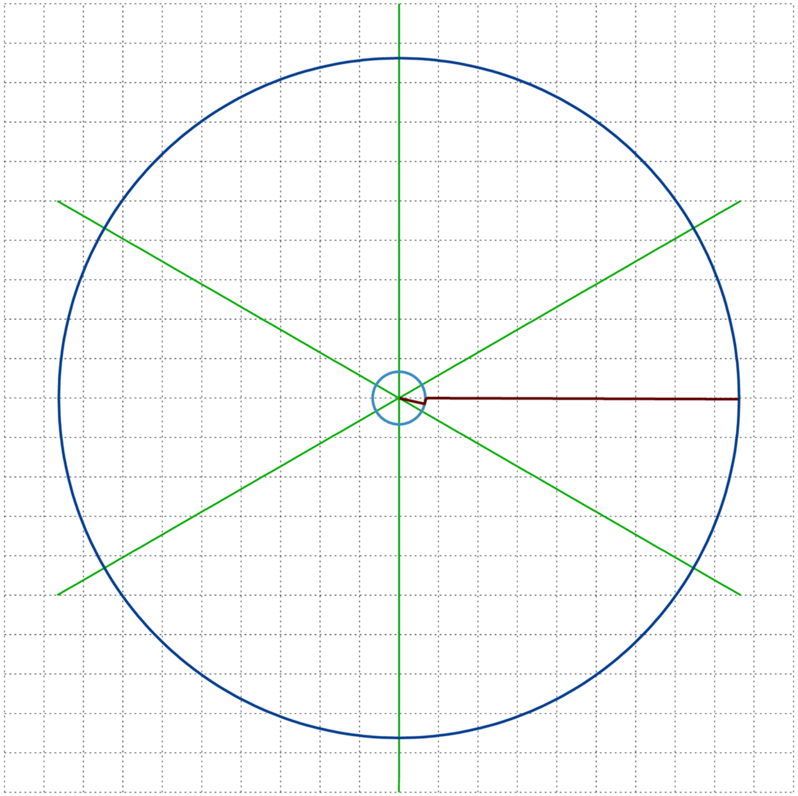
Stress Path – J2 Model

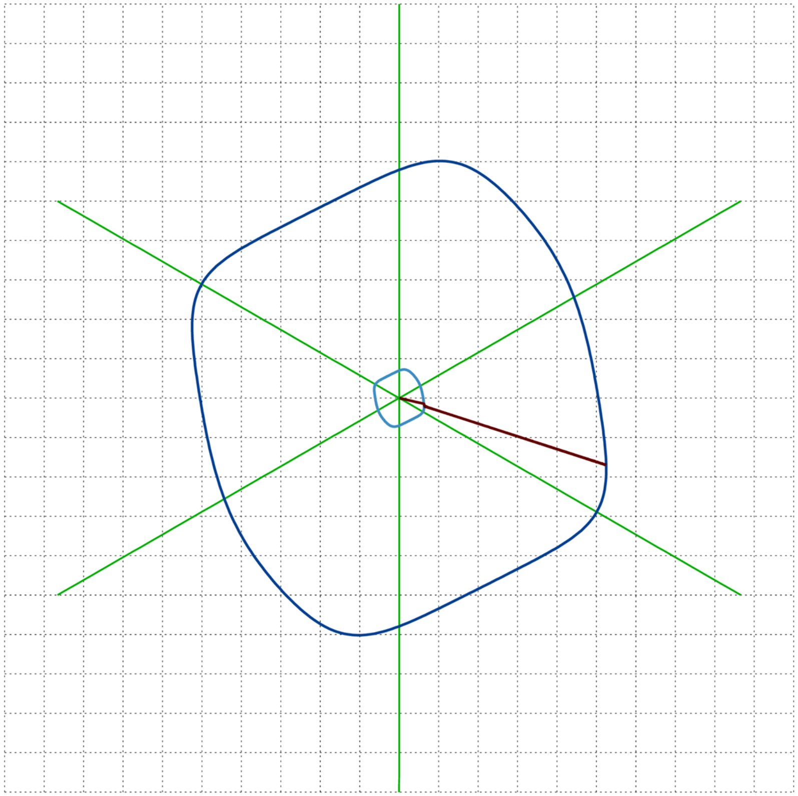


Stress Path – Barlat Model



Stress Path – Comparison





Capability Development

- Yield surface with associated flow
  - von Mises (isotropic)
  - Hosford (isotropic)
  - Hill (anisotropic)
  - Barlat (anisotropic)
- Hardening model
  - Linear
  - Power-Law
  - Voce
  - User defined
- Rate dependence
  - Johnson-Cook
  - Power-Law Breakdown
- **Temperature dependence**
  - Thermodynamics
  - Coupled with rate dependence
- **Failure**

Where We Are

- We have implemented a family of plasticity models that allow for different yield surface descriptions
  - Changes how a material/structure yields
  - Changes plastic flow
- We have implemented a capability for the analyst to use any hardening law
- We have implemented a number of viscoplastic options
- We are looking into modeling temperature dependence and failure

Where We Want to Go

- Goal is to provide comprehensive toolset to the analyst
- Incorporate thermal effects in the proper thermodynamic setting
- Add a class of failure criteria
  - Does not consider damage or coupled models
- Model yield surface evolution
- Look at using “family of yield surfaces” for UQ
  - Plasticity isn't just hardening anymore!

Extra Slides

Example – Rate Dependent Plasticity

- Consider the following plasticity model

$$\bar{\sigma}(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p) = \sigma_y(\bar{\varepsilon}^p)g(\dot{\bar{\varepsilon}}^p)$$

rate independent hardening

rate dependent multiplier

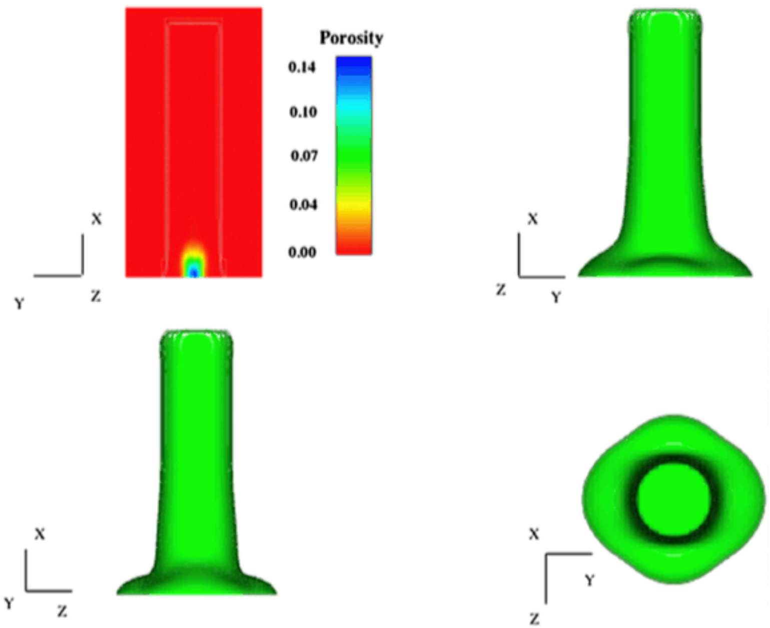
$$f(\boldsymbol{\sigma}, \bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p) = \phi(\boldsymbol{\sigma}) - \bar{\sigma}(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p)$$

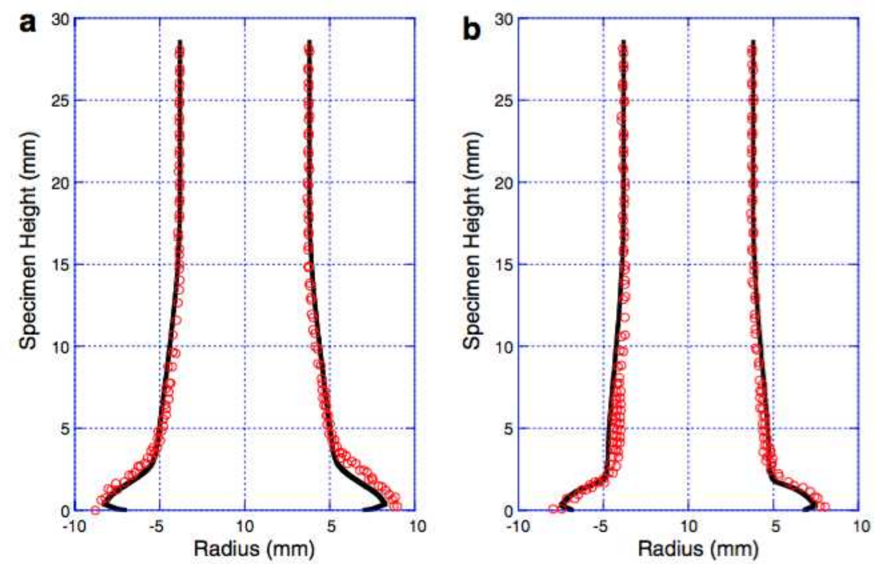
$$f \leq 0$$

How do we verify this?

Example – Rate Dependent Plasticity

Taylor impact





This shows the model runs, and it gives rate dependent behavior…
but is it the behavior we ***expect***?

Example – Rate Dependent Plasticity

- Consider a strain history for uniaxial stress: $\varepsilon(t)$
- Can I calculate the effective plastic strain history and therefore, the stress?

$$\bar{\sigma}(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p) = \sigma_y(\bar{\varepsilon}^p) g(\dot{\bar{\varepsilon}}^p) \qquad \boxed{(\varepsilon^p(t) = \bar{\varepsilon}^p)}$$

$$\varepsilon(t) = \varepsilon^e(t) + \varepsilon^p(t) \quad ; \quad \varepsilon_{ij}(t) = \varepsilon^e_{ij}(t) + \varepsilon^p_{ij}(t)$$

$$\varepsilon_{11}(t) = \varepsilon(t) \longrightarrow \varepsilon^e_{11}(t) = \varepsilon^e(t) \quad ; \quad \varepsilon^e_{22} = \varepsilon^e_{33} = -\nu \varepsilon^e(t)$$

$$\varepsilon^e = \frac{\bar{\sigma}(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p)}{E} \longrightarrow \frac{\bar{\sigma}(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p)}{E} + \bar{\varepsilon}^p = \varepsilon(t)$$

Example – Rate Dependent Plasticity

- Consider a strain history for uniaxial stress: $\varepsilon(t)$

- Can I calculate the effective plastic strain history and therefore, the stress?

$$\bar{\sigma}(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p) = \sigma_y(\bar{\varepsilon}^p) g(\dot{\bar{\varepsilon}}^p) \qquad (\varepsilon^p(t) = \bar{\varepsilon}^p)$$

$$\varepsilon(t) = \varepsilon^e(t) + \varepsilon^p(t) \quad ; \quad \varepsilon_{ij}(t) = \varepsilon^e_{ij}(t) + \varepsilon^p_{ij}(t)$$

$$\varepsilon_{11}(t) = \varepsilon(t) \longrightarrow \varepsilon^e_{11}(t) = \varepsilon^e(t) \quad ; \quad \varepsilon^e_{22} = \varepsilon^e_{33} = -\nu \varepsilon^e(t)$$

$$\varepsilon^e = \frac{\bar{\sigma}(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p)}{E} \longrightarrow \frac{\bar{\sigma}(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p)}{E} + \bar{\varepsilon}^p = \varepsilon(t)$$

Example – Rate Dependent Plasticity

- Consider a constant plastic strain rate: $\dot{\bar{\varepsilon}}^p$

$$\varepsilon^p(t) = \dot{\bar{\varepsilon}}^p t \quad ; \quad \varepsilon^e(t) = \frac{\bar{\sigma}(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p)}{E} \longrightarrow \varepsilon(t) = \varepsilon^e(t) + \varepsilon^p(t)$$

stretch ratio $\lambda(t) = \exp(\varepsilon(t))$

boundary condition $u(t) = [\lambda(t) - 1]\, L_0$

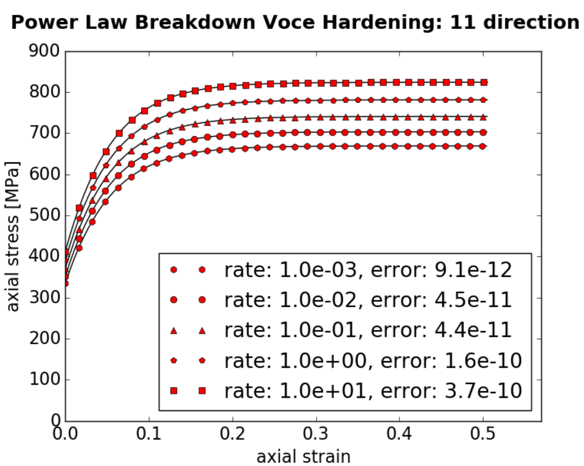
initial condition $\sigma_{11}(0) = \bar{\sigma}(0, \dot{\bar{\varepsilon}}^p)$

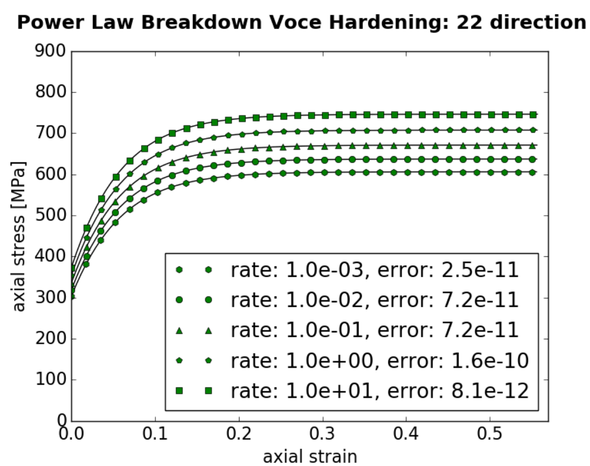
Example – Rate Dependent Plasticity

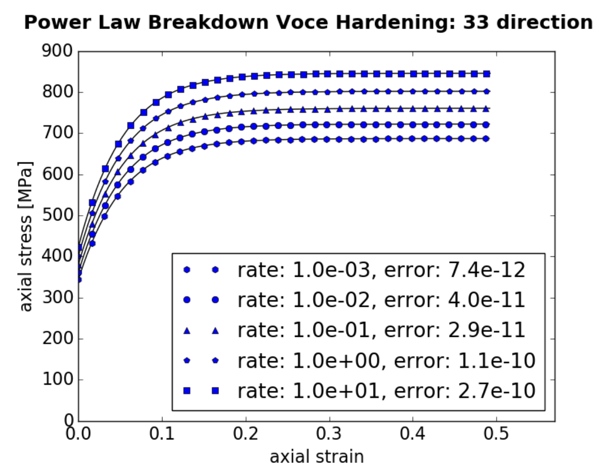
$$f(\sigma_{ij}, \bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p) = \phi(\sigma_{ij}) - \bar{\sigma}(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p) = 0$$

$$\phi^2 = F\left(\sigma_{22} - \sigma_{33}\right)^2 + G\left(\sigma_{33} - \sigma_{11}\right)^2 + H\left(\sigma_{11} - \sigma_{22}\right)^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2$$

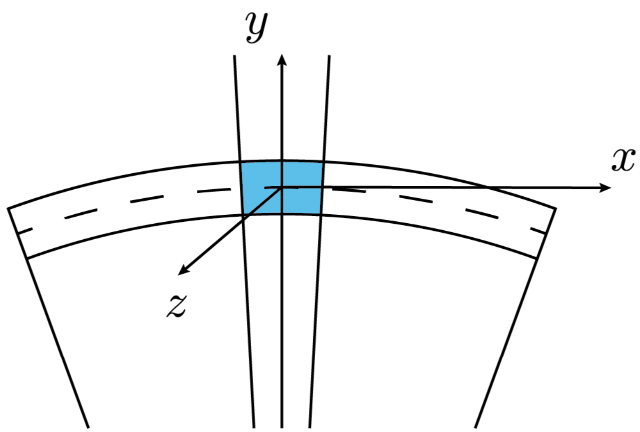
$$\bar{\sigma} = \left[\sigma_y + A\left(1 - \exp(-b\bar{\varepsilon}^p)\right)\right]\left[1 + \sinh^{-1}\left(\left(\frac{\dot{\bar{\varepsilon}}^p}{g}\right)^{1/m}\right)\right]$$







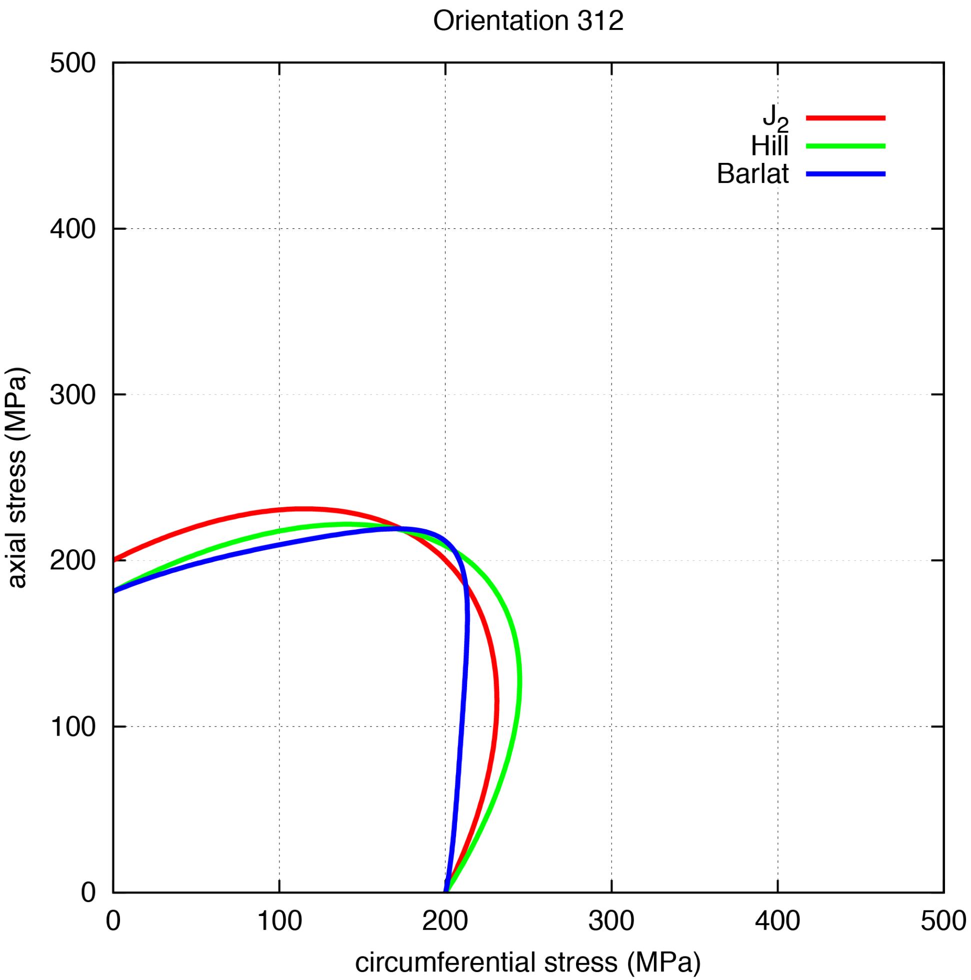
Yield Surface – Orthotropic Models



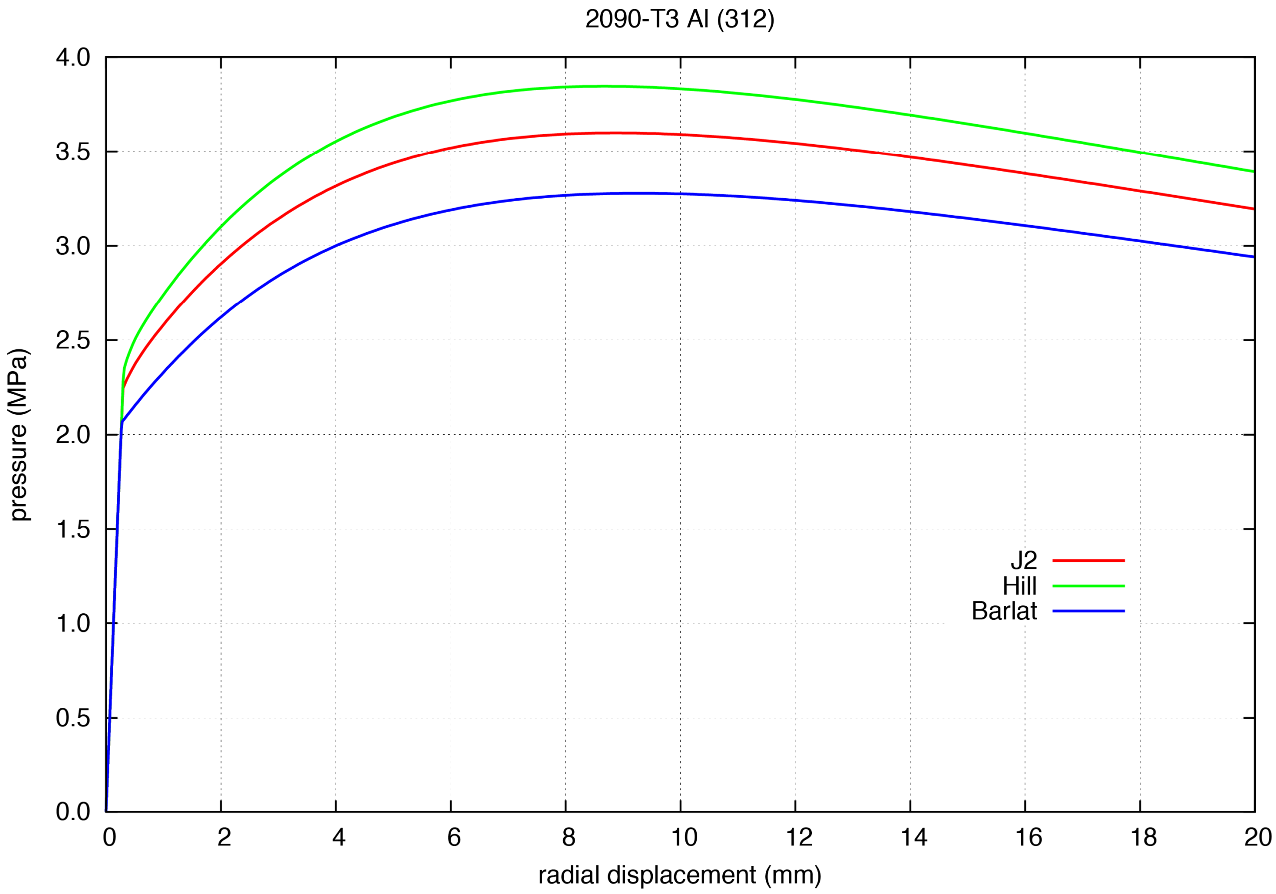
$$\sigma_{rr} = \sigma_{33}$$

$$\sigma_{\theta\theta} = \sigma_{11}$$

$$\sigma_{zz} = \sigma_{22}$$

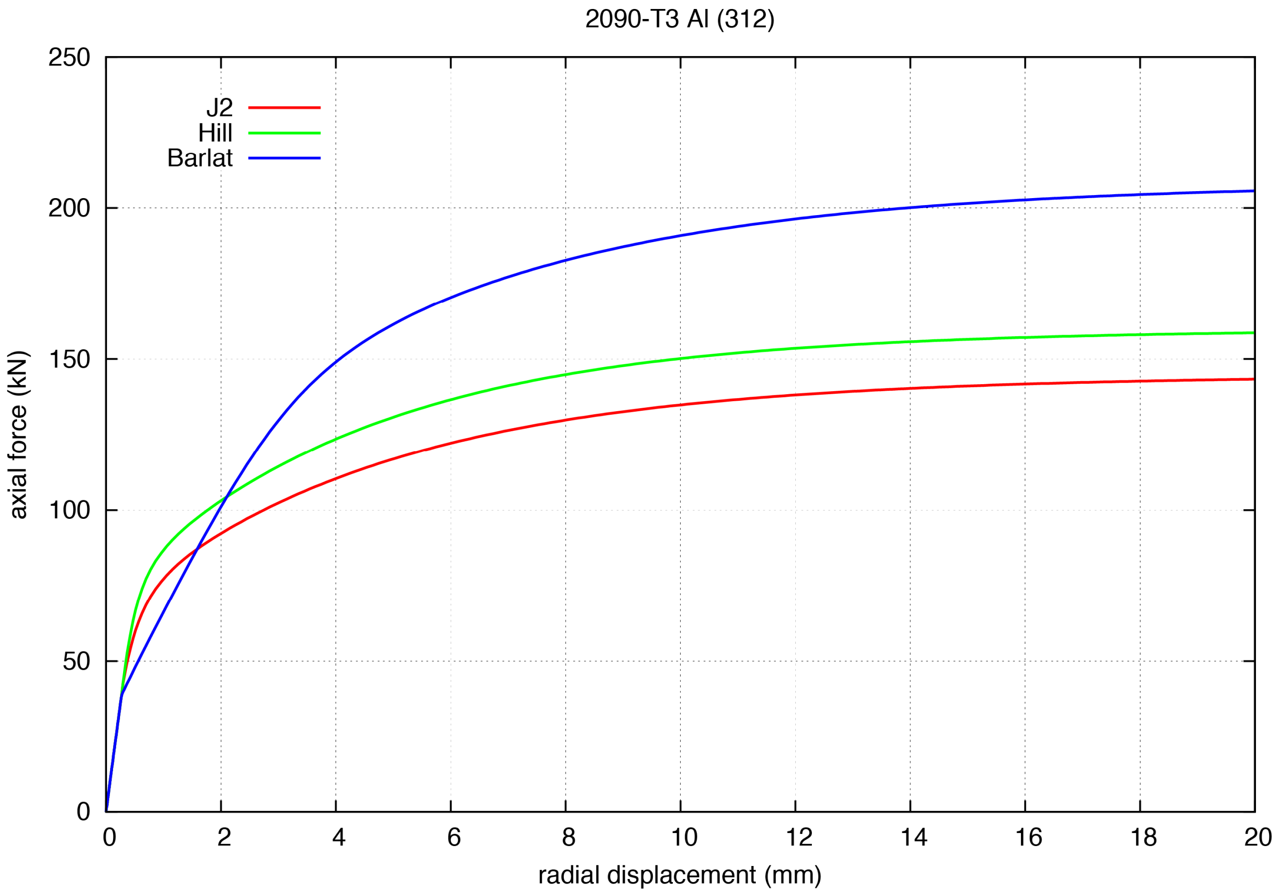


Pressure



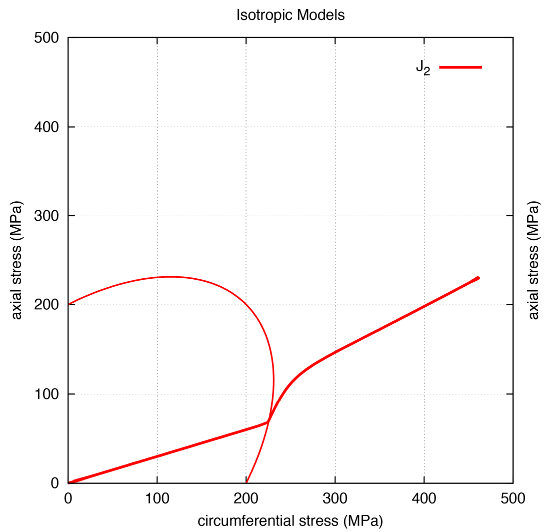
2090-T3 Al (312)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
pressure (MPa)
0
2
4
6
8
10
12
14
16
18
20
radial displacement (mm)
J2
Hill
Barlat

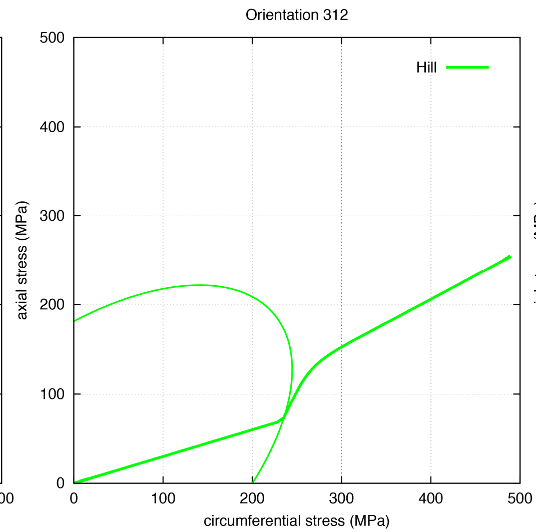
Axial Load

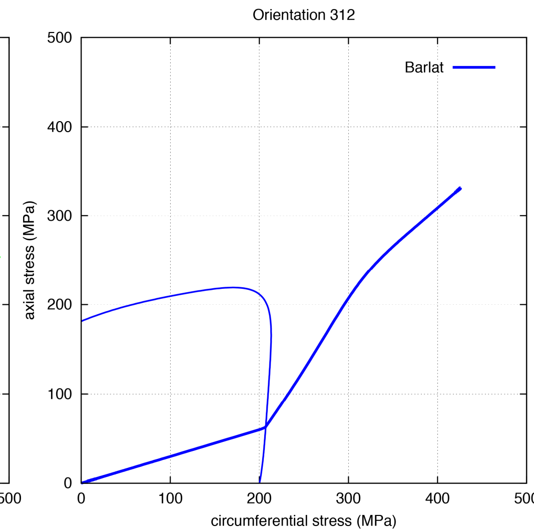


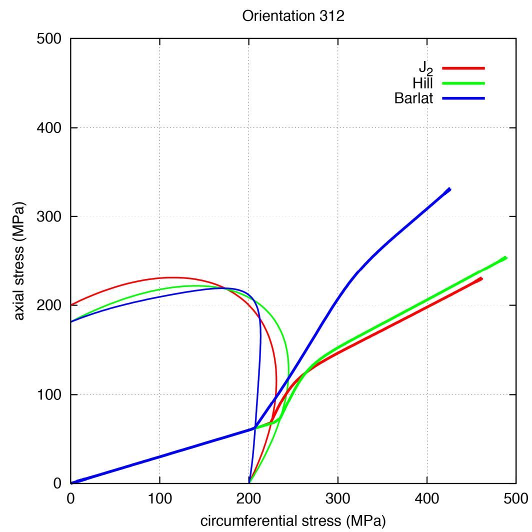
2090-T3 Al (312)
J2
Hill
Barlat
axial force (kN)
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
18
20
radial displacement (mm)

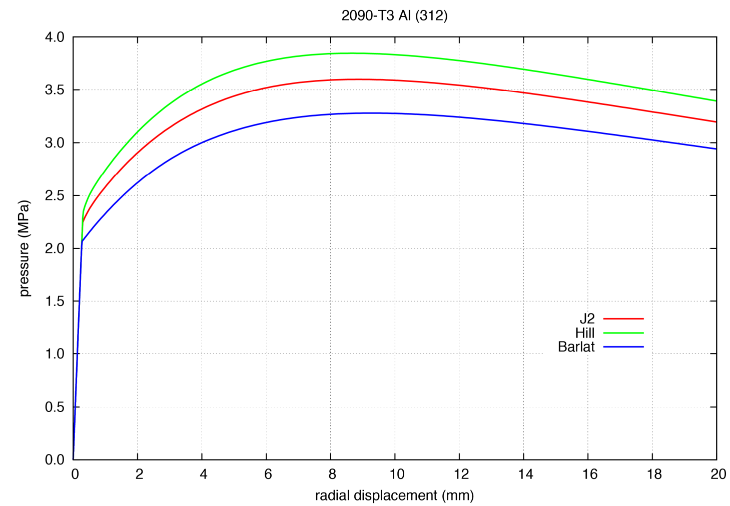
Stress Paths – Orthotropic Models











Stress Paths – Orthotropic Models

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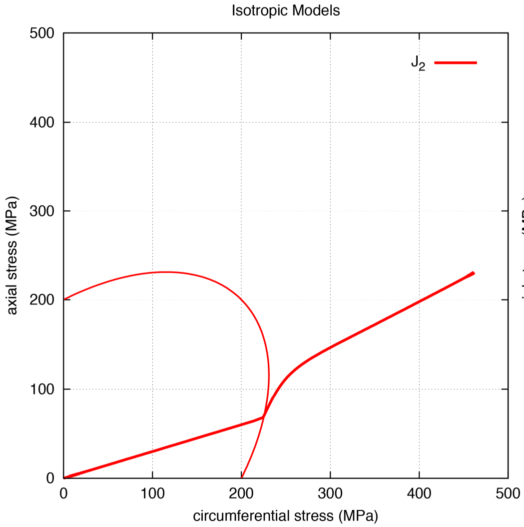
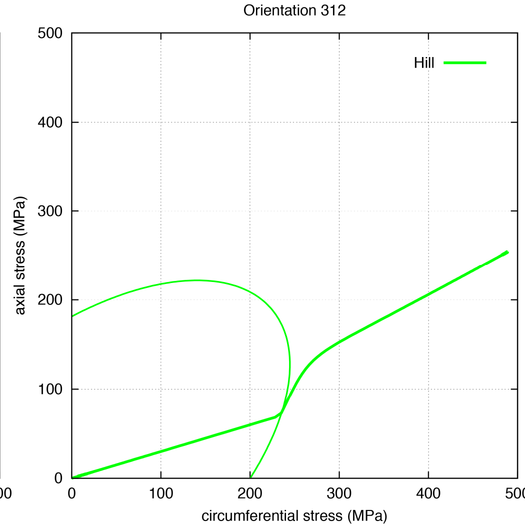
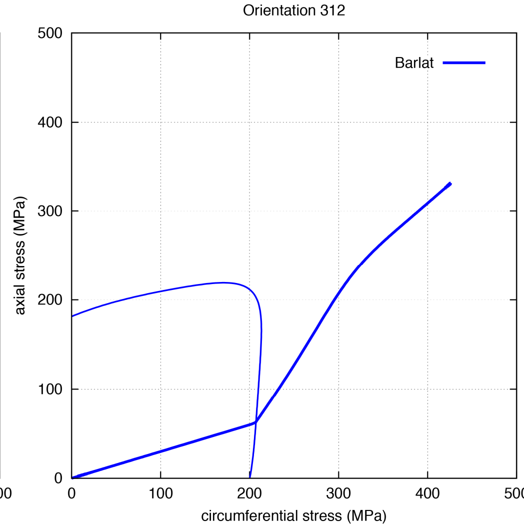
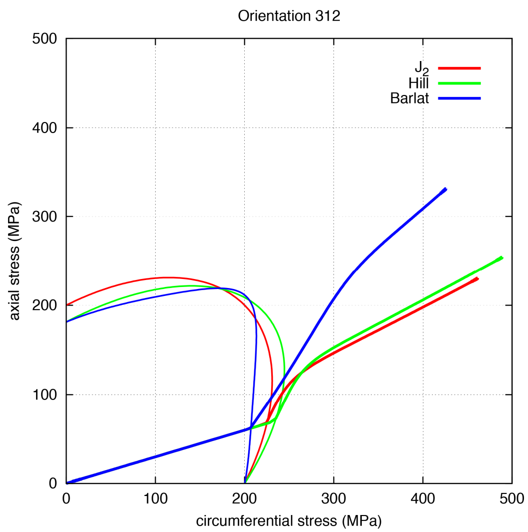
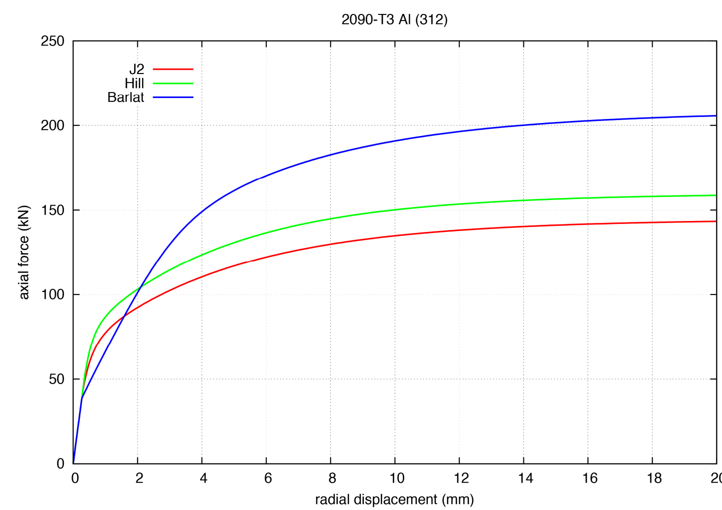


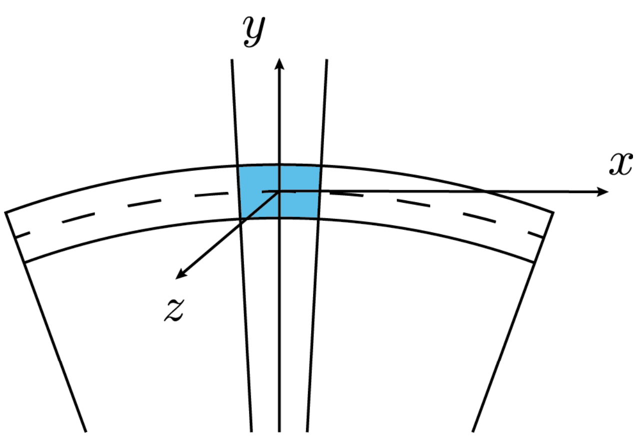








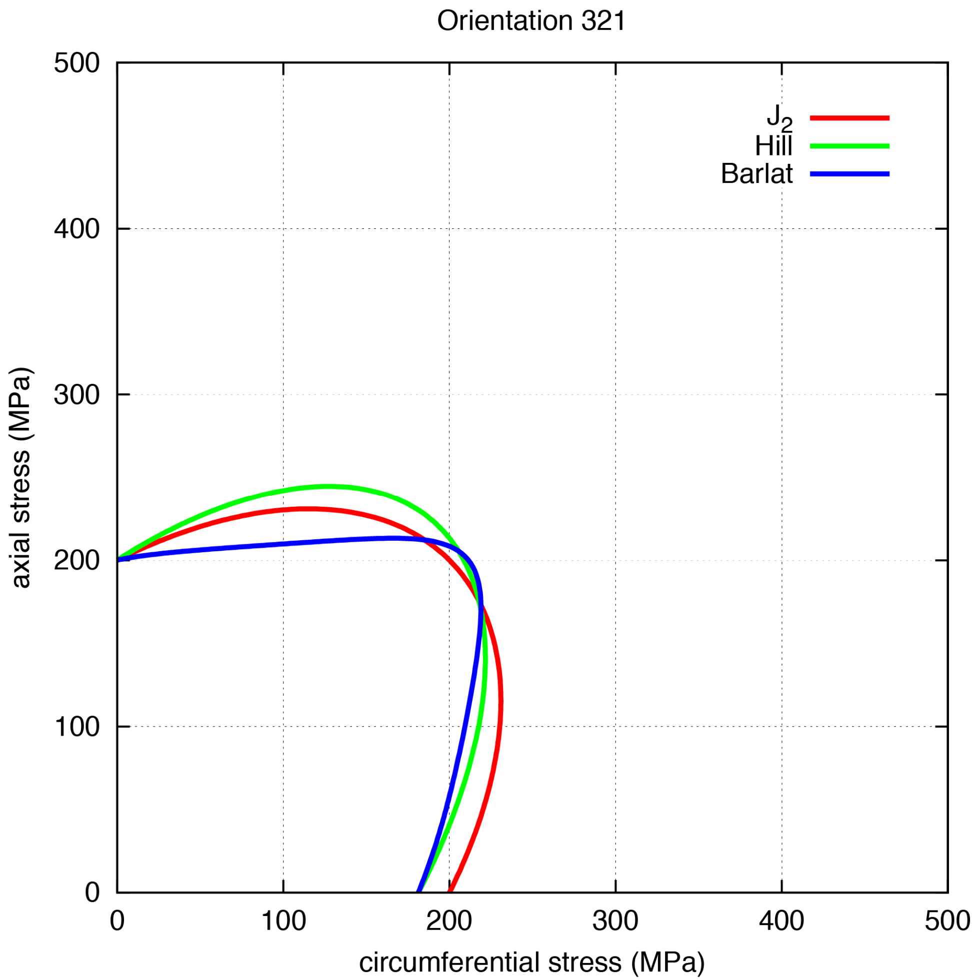
Yield Surface – Orthotropic Models



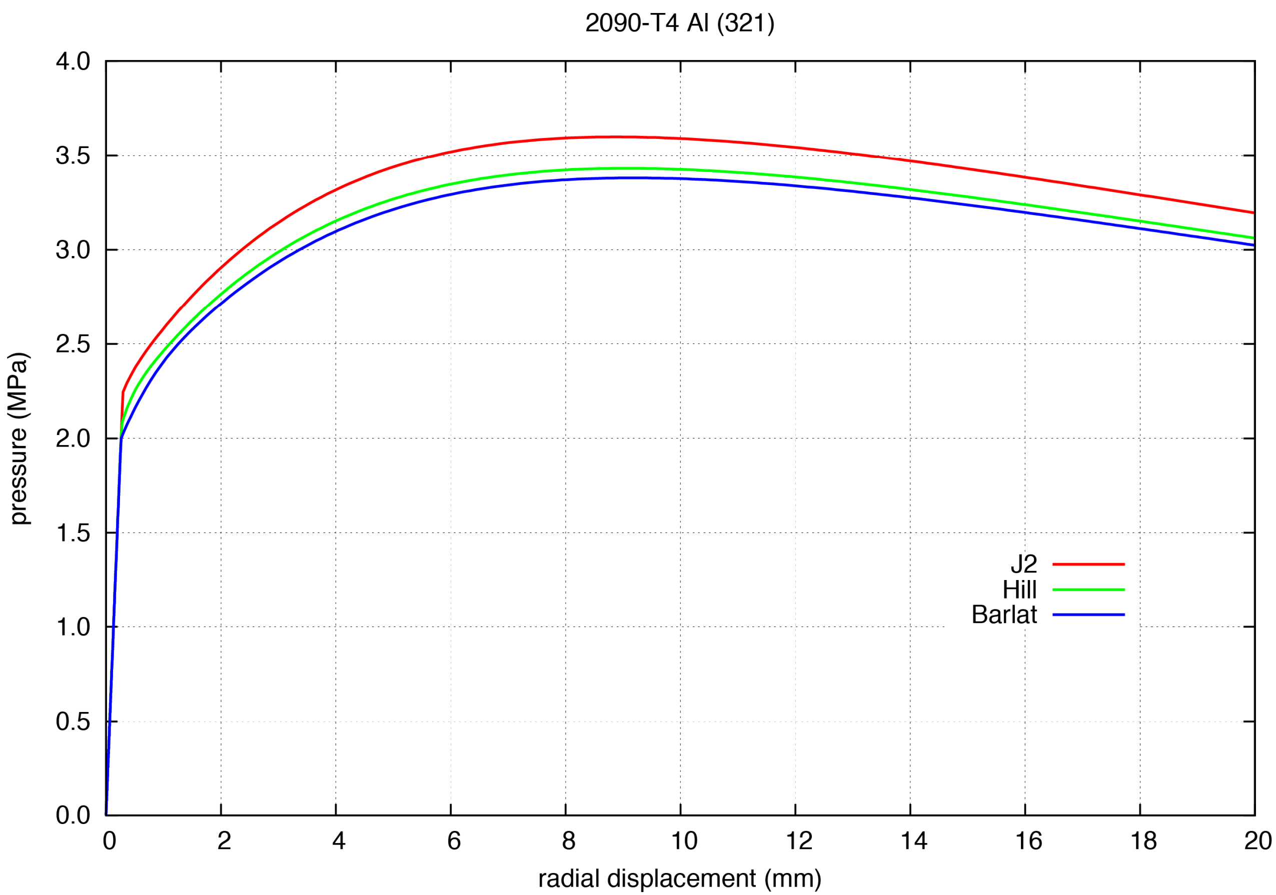
$$\sigma_{rr} = \sigma_{33}$$

$$\sigma_{\theta\theta} = \sigma_{22}$$

$$\sigma_{zz} = \sigma_{11}$$

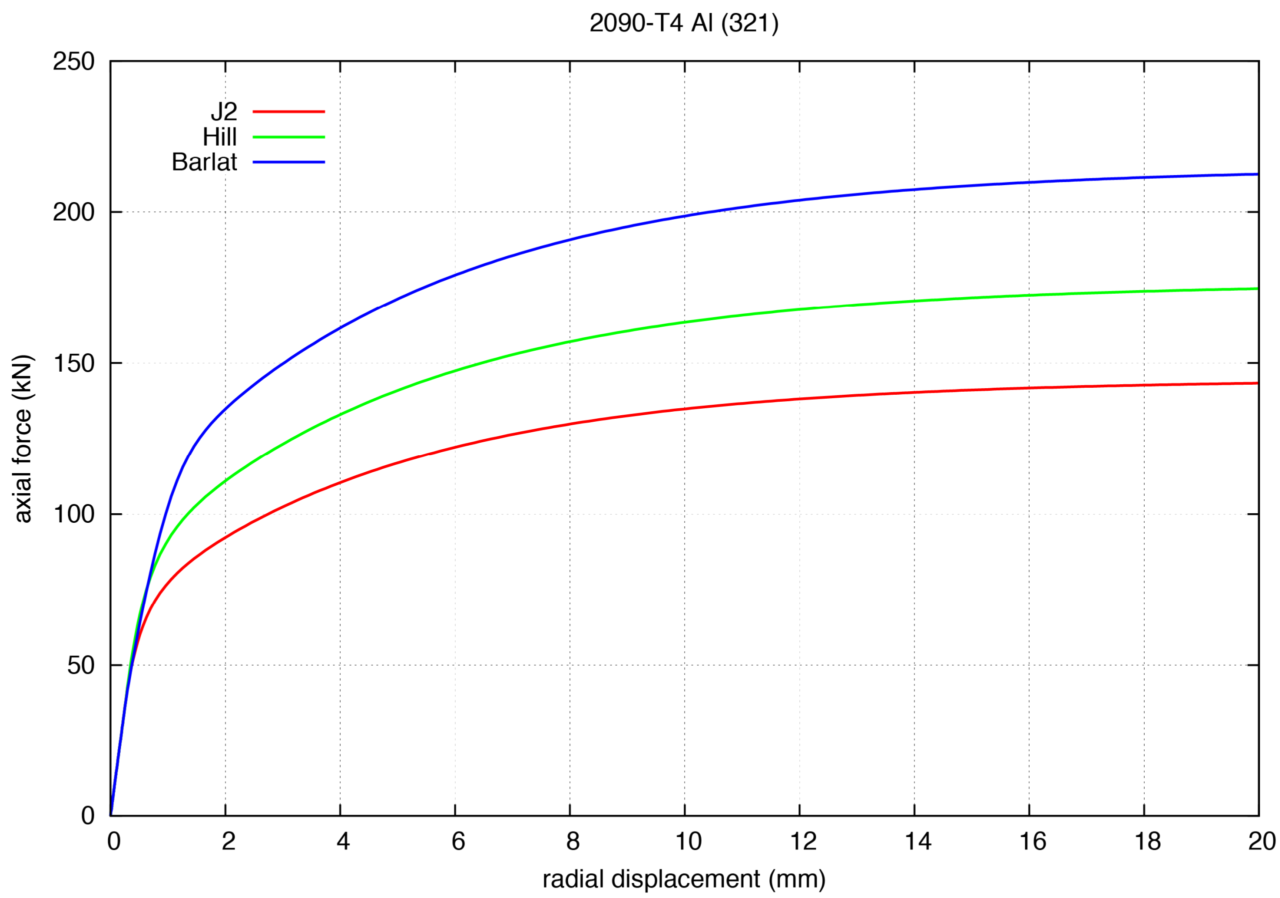


Pressure

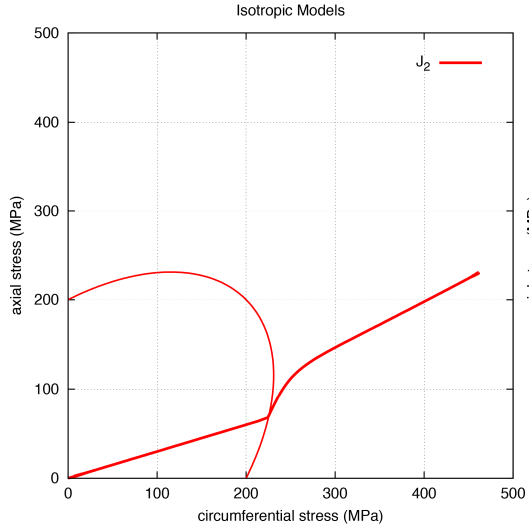


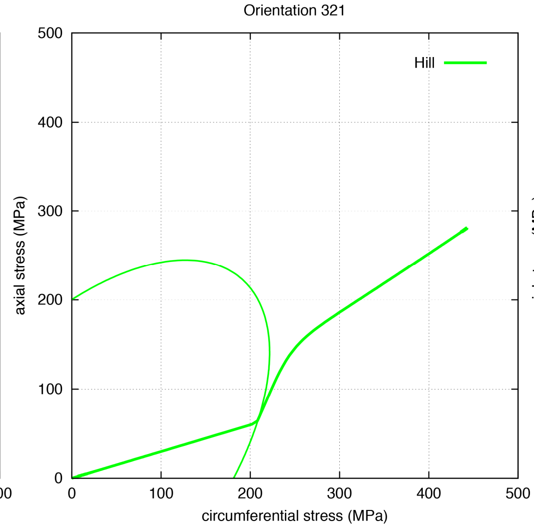
2090-T4 Al (321)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
pressure (MPa)
0
2
4
6
8
10
12
14
16
18
20
radial displacement (mm)
J2
Hill
Barlat

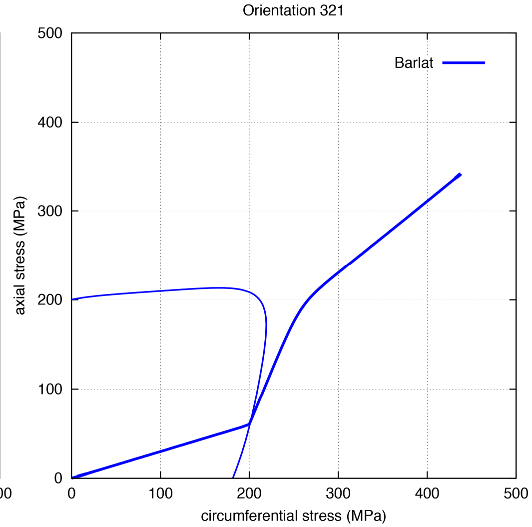
Axial Load

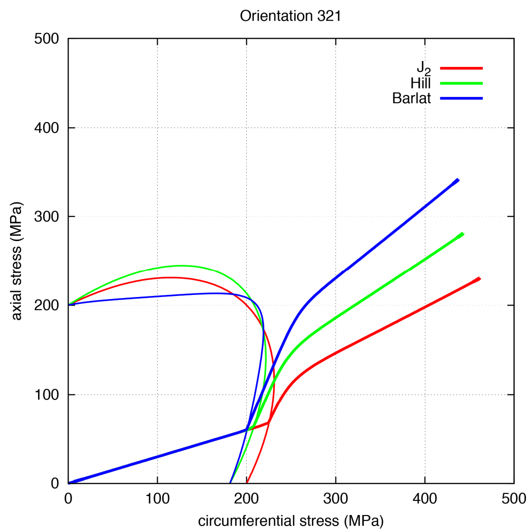

2090-T4 Al (321)
J2
Hill
Barlat
axial force (kN)
radial displacement (mm)
0
50
100
150
200
250
0
2
4
6
8
10
12
14
16
18
20

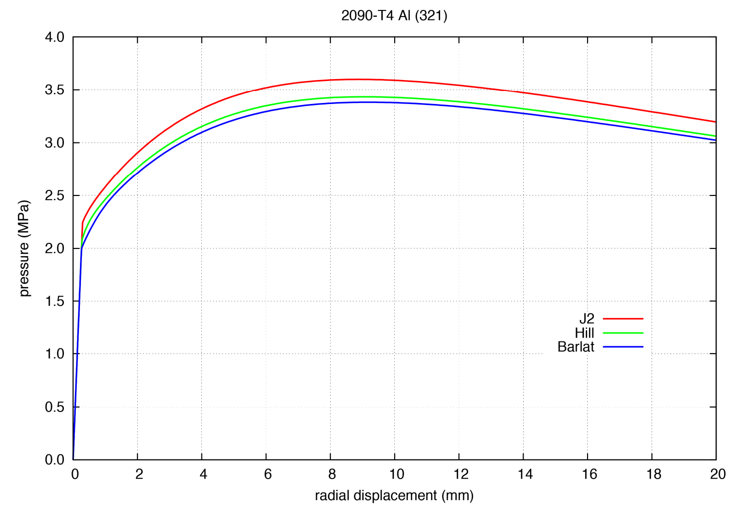
Stress Paths – Orthotropic Models











Stress Paths – Orthotropic Models