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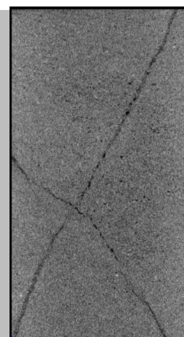

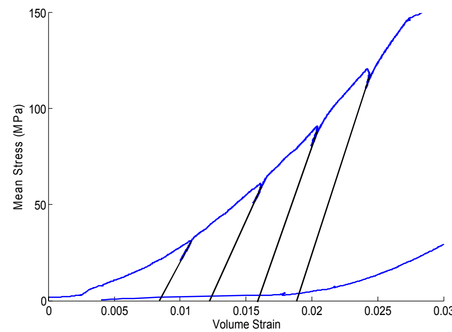

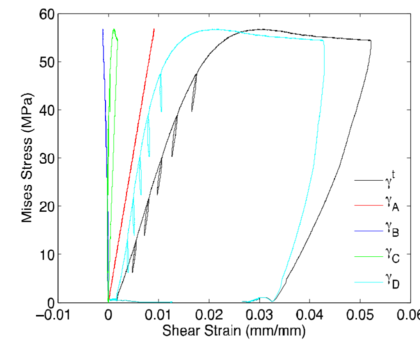

Strain Separation Methods for Porous Sandstone

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Motivation

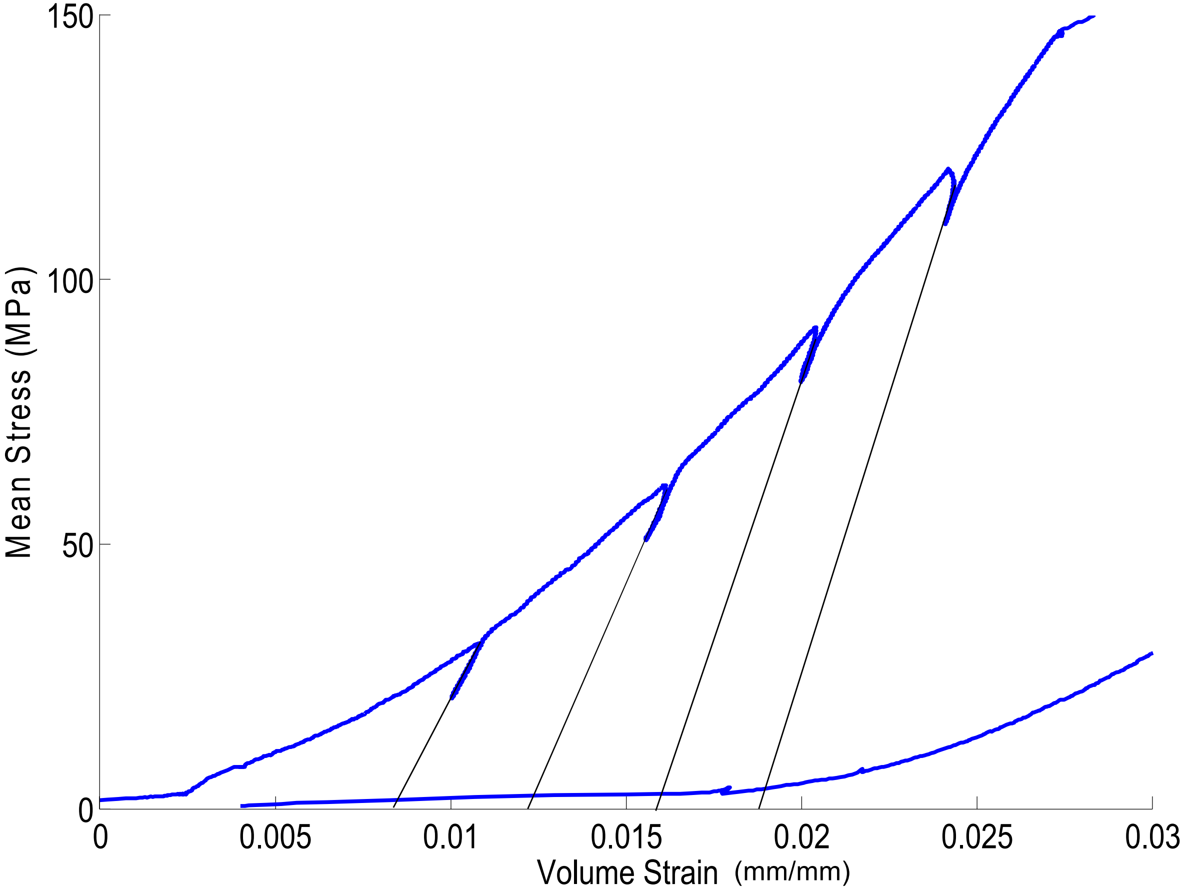
- In order to investigate localization models experimental data must be carefully reduced to develop constitutive parameters
  - Simple separation of strain into elastic and plastic components from a single constant modulus, while straightforward and a reasonable first approximation, needs to be more rigorous for thorough evaluation
- This process is subjective to test conditions, and material dependencies. For this work stress and plastic strain dependence were included.

Tests Performed

- True triaxial tests performed at 5 different Lode angles
  - 30, 14.5, 0, -14.5, -30 degrees (axisymmetric compression to axisymmetric extension)
  - Tests were performed under constant mean stress conditions
  - 5 mean stresses were tested ranging from 30 to 150 MPa in 30 MPa increments in order to map out the failure/yield surface for a range of Lode angles
- Unload loops from all tests were used to develop the strain separation process.

Strain Separation

To Determine the inelastic increment of strain



$$G(\tau, \gamma_P)$$

$$K(\sigma, \varepsilon_P)$$

$$\phi = 14.5$$

$$\sigma = 150$$

Strain Separation: Constitutive Laws

- Starting with common elastic-plastic constitutive models:

$$\varepsilon_{ij}^{t} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p}$$

  - Isotropy and usual invariant definitions provide the common elastic strain models

$$\gamma^{e} = \frac{\tau}{G} \qquad \varepsilon^{e} = \frac{\sigma}{K}$$

  - Assuming elastic property dependence in incremental form and expanding the total derivative

$$d\gamma^{t} = d\left(\frac{\tau}{G(\tau,\gamma^{p})}\right) + d\gamma^{p}$$

$$d\gamma^{t} = \frac{d\tau}{G} - \frac{\tau}{G^{2}}\left(\frac{\partial G}{\partial \tau}d\tau + \frac{\partial G}{\partial \gamma^{p}}d\gamma^{p}\right) + d\gamma^{p}$$

$$d\varepsilon^{t} = d\left(\frac{\sigma}{K(\sigma,\varepsilon^{p})}\right) + d\varepsilon^{p}$$

$$d\varepsilon^{t} = \frac{d\sigma}{K} - \frac{\sigma}{K^{2}}\left(\frac{\partial K}{\partial \sigma}d\sigma + \frac{\partial K}{\partial \varepsilon^{p}}d\varepsilon^{p}\right) + d\varepsilon^{p}$$

Strain Separation: Breakdown

$$d\gamma^{t} = \frac{d\tau}{G} - \frac{\tau}{G^2}\left(\frac{\partial G}{\partial \tau} d\tau + \frac{\partial G}{\partial \gamma^{p}} d\gamma^{p}\right) + d\gamma^{p}$$

$$d\gamma_{A} = \frac{d\tau}{G}$$

$$d\gamma_{B} = -\frac{\tau}{G^2}\left(\frac{\partial G}{\partial \tau} d\tau\right)$$

$$d\gamma_{C} = -\frac{\tau}{G^2}\left(\frac{\partial G}{\partial \gamma^{p}} d\gamma^{p}\right)$$

$$d\gamma_{D} = d\gamma^{p}$$

$$\beta = -\frac{d^{p}\varepsilon}{d^{p}\gamma} \qquad d^{p}\gamma = d\gamma_{C} + d\gamma_{D}$$

- Strain is separated into 4 forms: Elastic, elastic stress dependent, plastic strain dependent, plastic
- A,B,C are recovered upon unloading γ^{e}, however C and D are the inelastic increment of strain needed for localization theory
- A and B are found by calculating strain with the modulus without G_0 evolution

Elastic Modulus Evolution

- Plastic shear and volume strains calculated using a method developed in conjunction with Dr. Thomas Dewers
- Stress dependence develops in the form of the evolution of the modulus
- Strain dependence develops in the form of the evolution of the G_0 and K_0 parameters, other parameters are constant

$$G = G_0(1 - G_1\tau)$$

$$K = K_0(1 + K_1\sigma - K_2 e^{-K_3\sigma})$$

$$\gamma^e_{\max} + \gamma^p = \gamma^e_{\min} + \gamma^p + \frac{\tau}{G(\tau)} + \frac{\tau_{\min}}{G(\tau_{\min})}$$

$$\varepsilon^e_{max} + \varepsilon^p = \varepsilon^e_{\min} + \varepsilon^p + \frac{\sigma}{K(\sigma)} - \frac{\sigma_{\min}}{K(\sigma_{\min})}$$

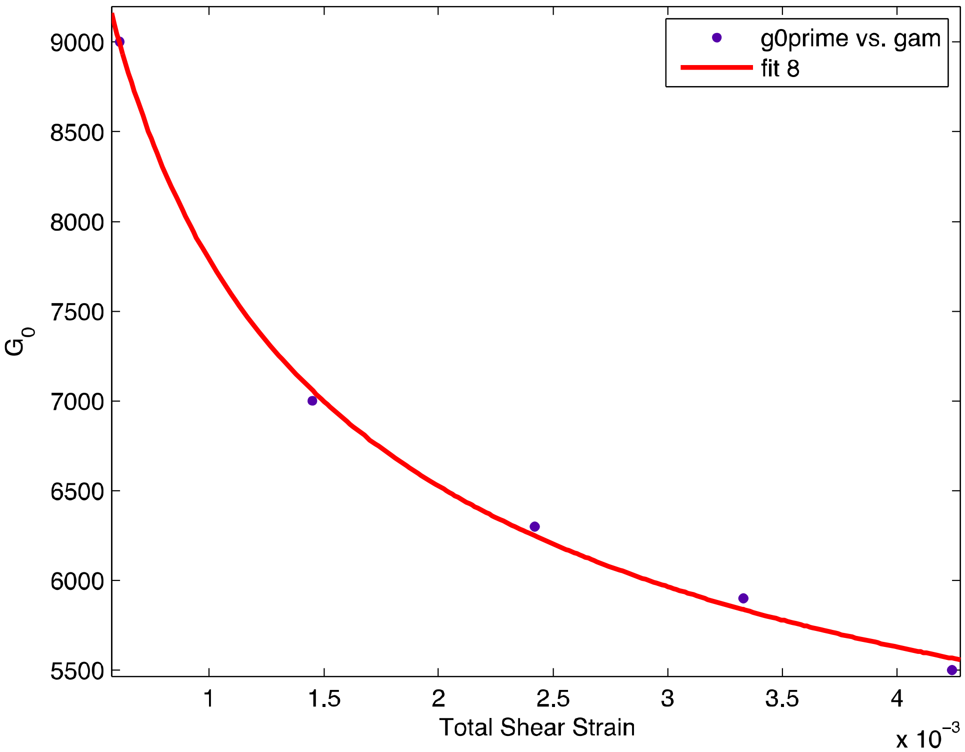
Elastic models based off work of Zimmerman et al. (1986), and Kaselow and Shapiro (2004)

G_0 and K_0 Evolution

- For a given test G_0 and K_0 evolved
- G_0 and K_0 were fit with a power function
- Plastic strains were found by subtracting elastic strain from total strain.

$$G_0 = 3233\gamma^{-0.1498}$$

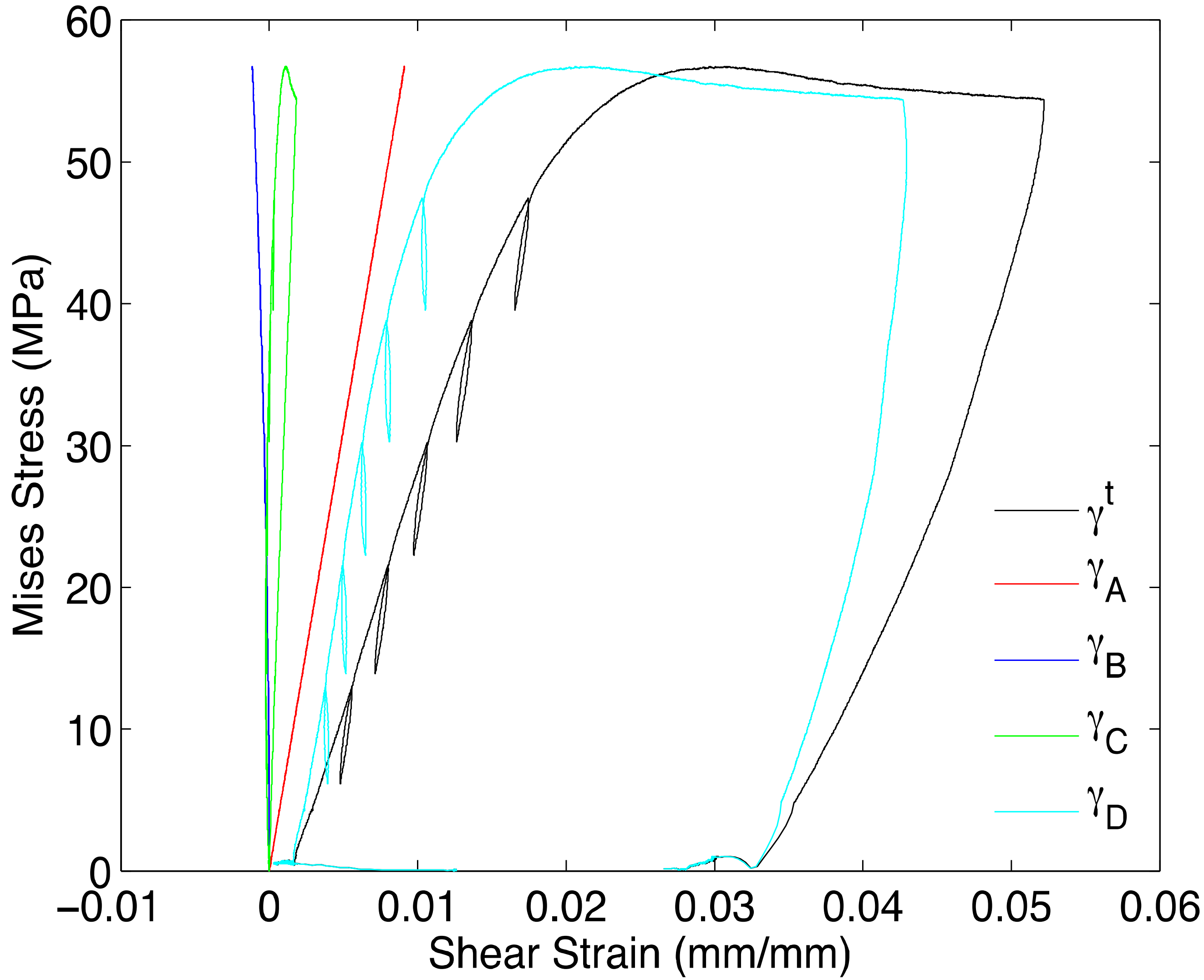
$$K_0 = 4960\varepsilon^{-0.1602}$$



$$\phi = 30$$

$$\sigma = 75$$

Separated Strains



Application

$$\theta = \frac{\pi}{4} + \frac{1}{2}\arcsin\left[\frac{\frac{2}{3}(1+\nu)(\beta+\mu) - N_{II}(1-2\nu)}{\sqrt{4-3N_{II}^2}}\right]$$

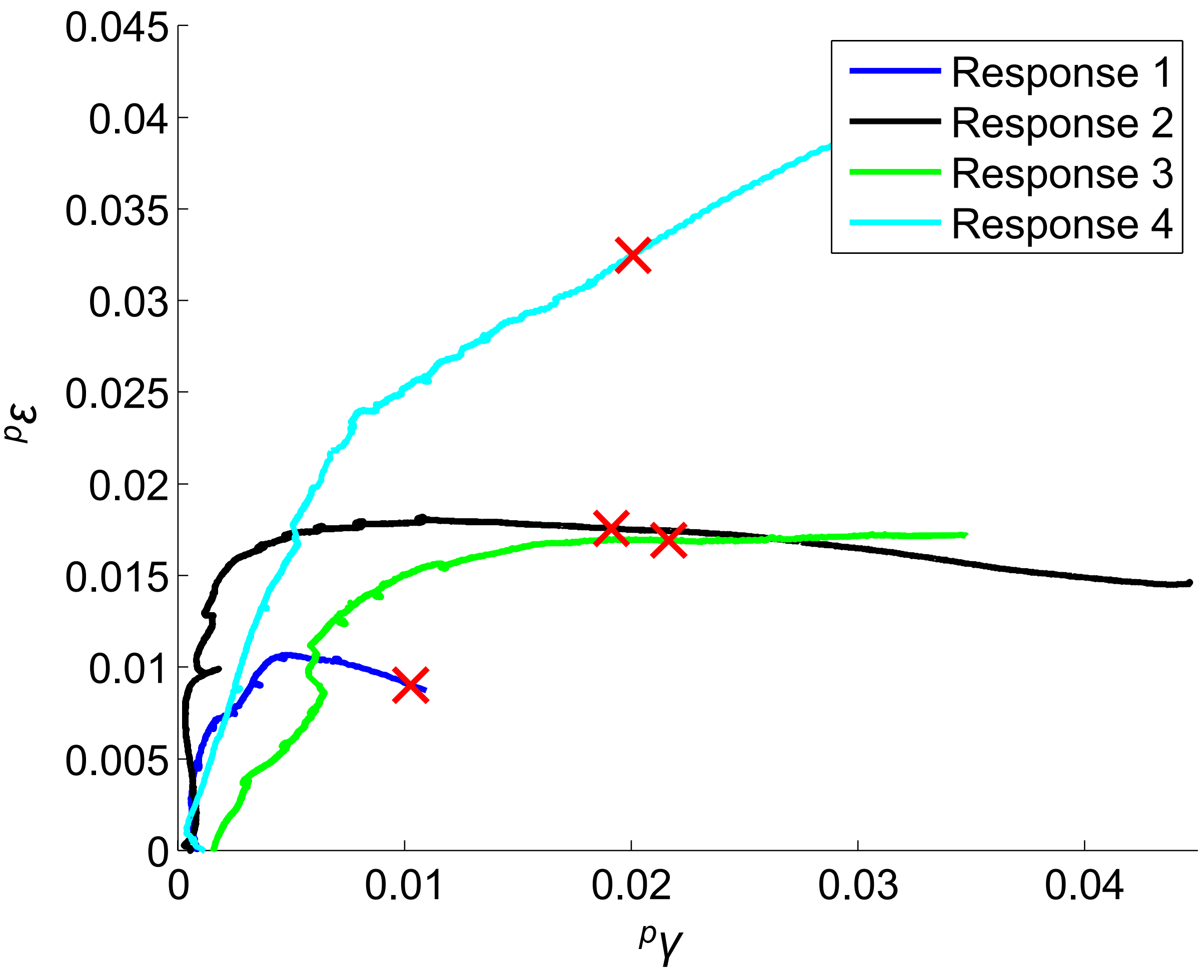
When:

$$-\frac{3(N_I + \nu N_{II})}{1+\nu} \le \beta + \mu \le -\frac{3(N_{III} + \nu N_{II})}{1+\nu}$$

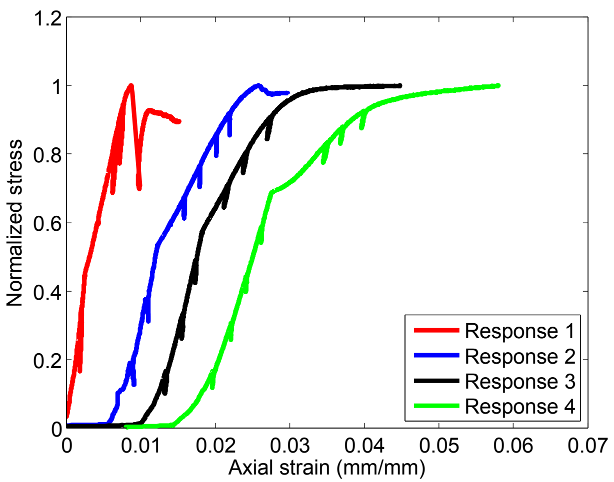
$$N_I = {(\sigma - \sigma_3)}/{\tau},\ N_{II} = {(\sigma - \sigma_2)}/{\tau},\ N_{III} = {(\sigma - \sigma_1)}/{\tau}$$

Rudnicki and Olsson (1998)

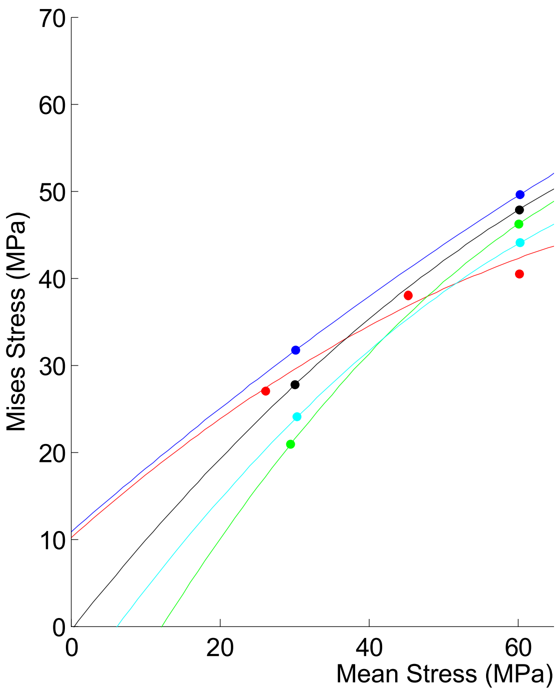
Constitutive Parameter β

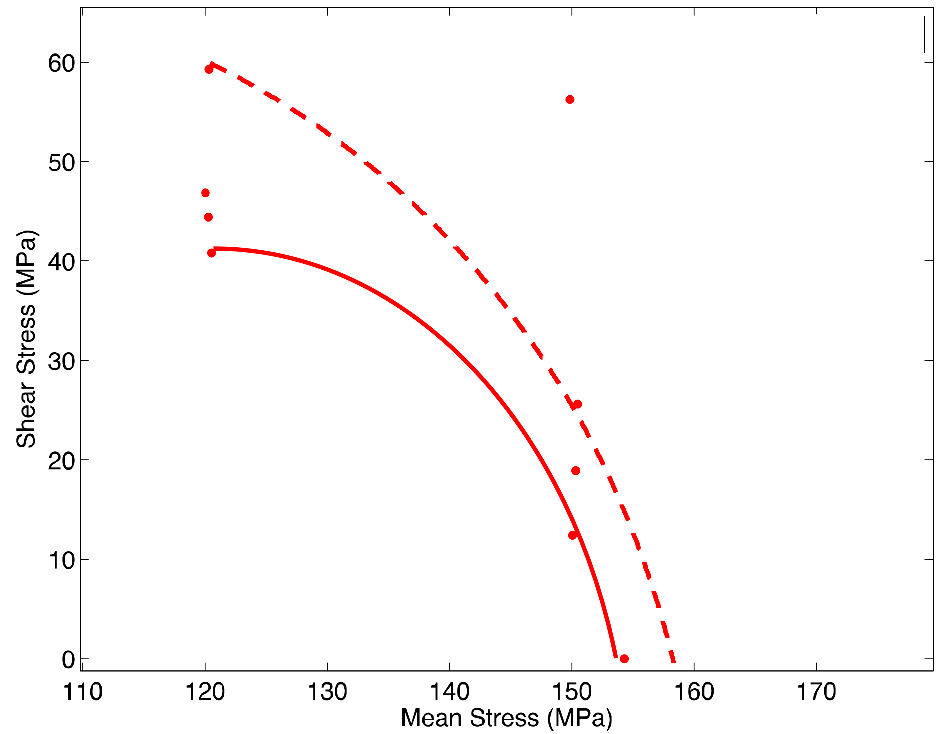


$$\beta = -\frac{d^p\varepsilon}{d^p\gamma}$$



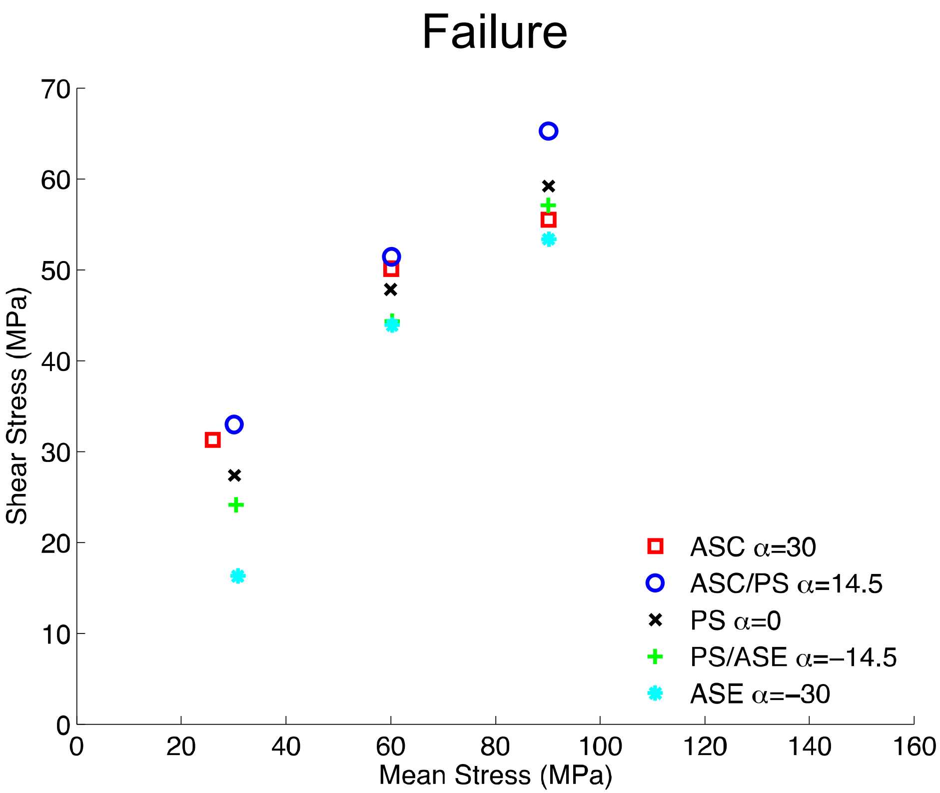
Constitutive Parameter – μ

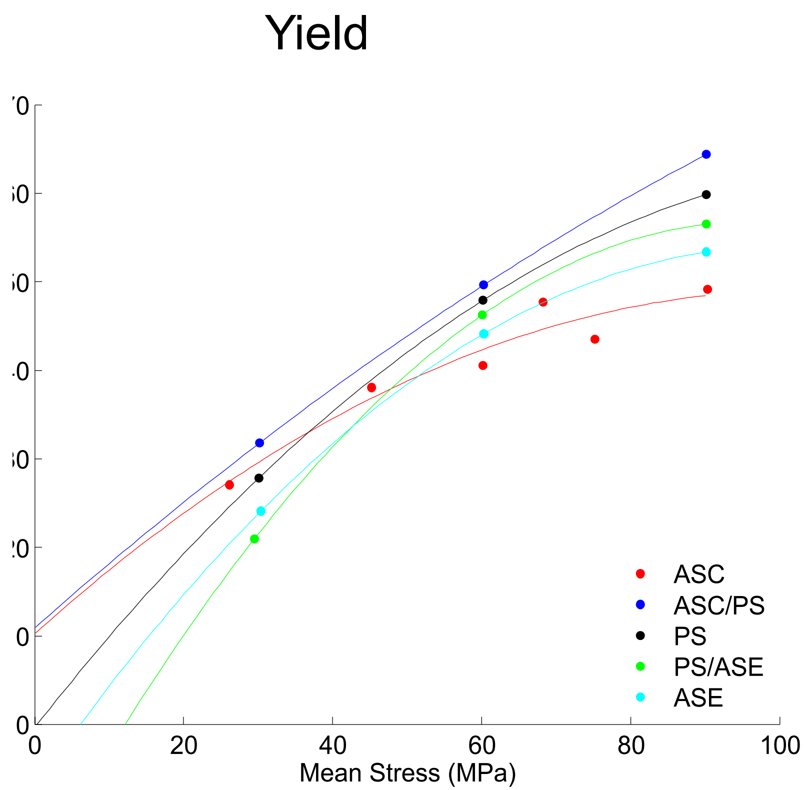




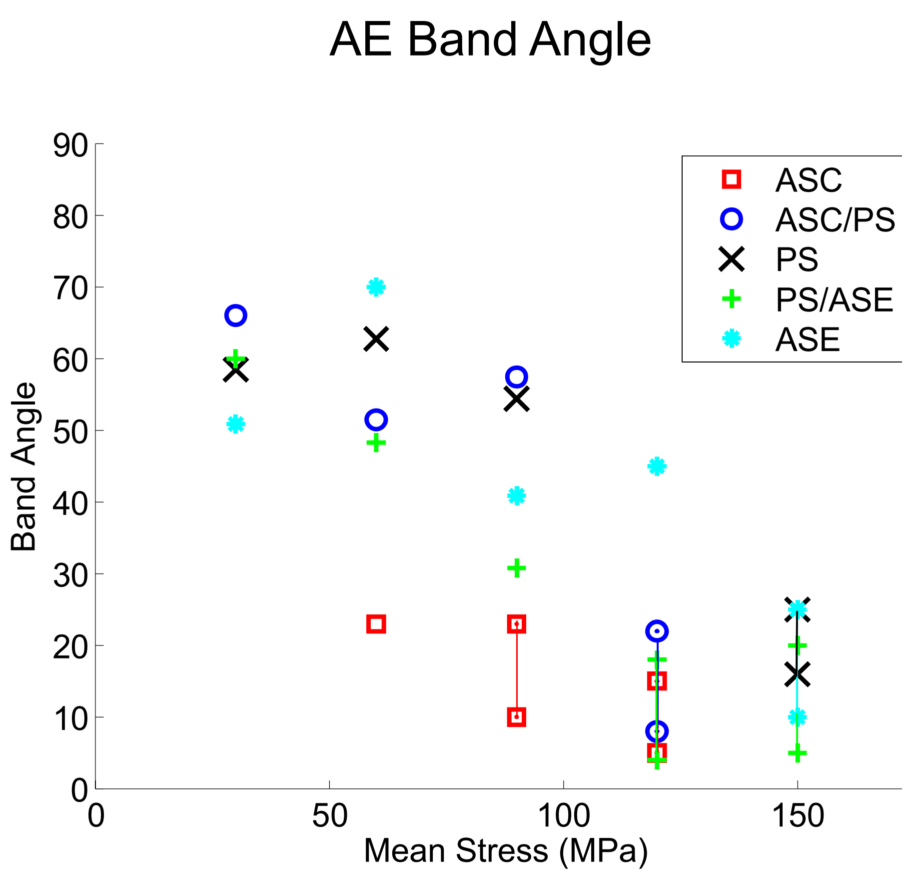
μ – contour of constant inelastic shear/volume strain

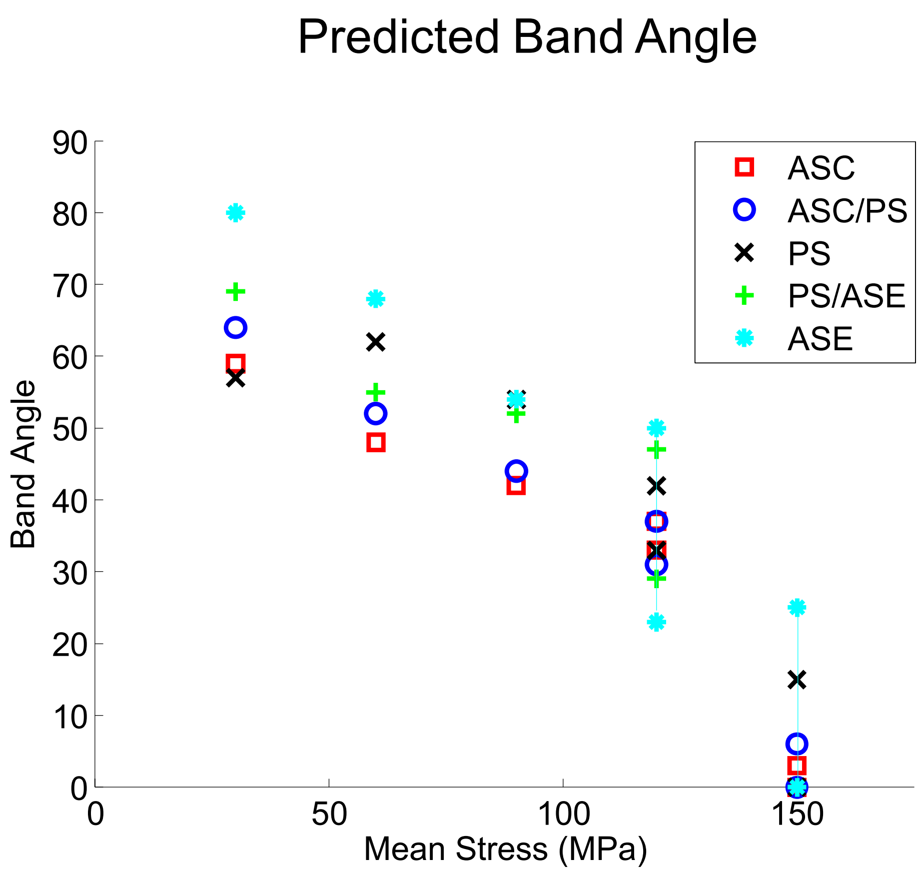
Failure/Yield Surface





Angles vs. Mean Stress





Band Angle vs. Lode Angle

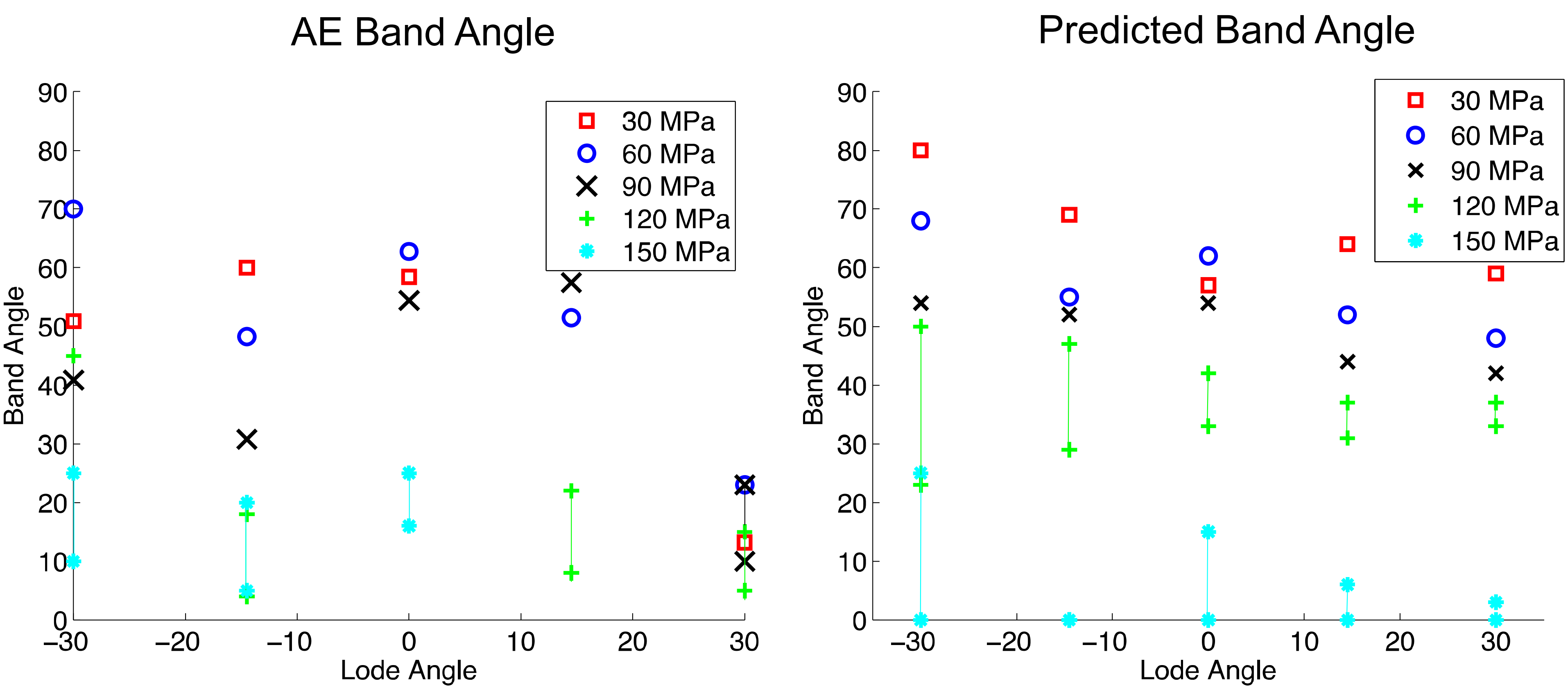


Table of Band Angles

Stress State	Mean Stress (MPa)	*β*	*μ*	Predicted θ	AE θ	Measured θ	Response Type
ASC	30	0.76	0.56	59	Conj. Bands	55-60	Shear
ASC	60	0.23	0.31	48	23	30-35	Shear
ASC	90	0.01	0.09	42	10-23	NA	CL
ASC	120	-0.29	0:-0.3	37:33	5-15	NA	CL
ASC	150	-0.66	-1.1:-3	3:0	NL	NA	NL
PS	30	0.09	0.94	57	58	61-80	Shear
PS	60	0.55	0.80	62	63	64	Shear
PS	90	0.08	0.67	54	54	58	Shear
PS	120	-0.23	0:-0.7	42:33	NL	NA	NL
PS	150	-0.75	-1.5:-4.4	15:0	16-25	NA	CL
ASE	30	0.76	0.85	80	51	65	Shear
ASE	60	0.65	0.49	68	NA*	70	Shear
ASE	90	0.04	0.13	54	41	46	Shear
ASE	120	-0.17	0:-1.9	50:23	Conj. Bands	45	Shear
ASE	150	-0.21	-1.8:-6	25:0	10-25	NA	CL

Conclusions

- Strain separation processes can be implemented to provide reasonable localization results for high porosity sandstone in comparison with experimental results for non-axisymmetric states of stress.
  - Further analysis is still required, moduli are dependent on more than their respective stress and plastic strain.
- Separation of strains allows for determination of the onset of yield
  - Yield occurs earlier with the strain separated more rigorously than if the strains are separated into purely elastic and plastic components.
  - Yield surfaces, while similar to failure surfaces, are somewhat different

Future work

- Currently working to include a pore pressure component
  - Working with both drained and undrained tests
  - Utilizing acoustic velocity monitoring to confirm elastic property evolution determined from unload loops

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