Analysis of Mancos Shale failure in light of localization theory for transversely isotropic materials

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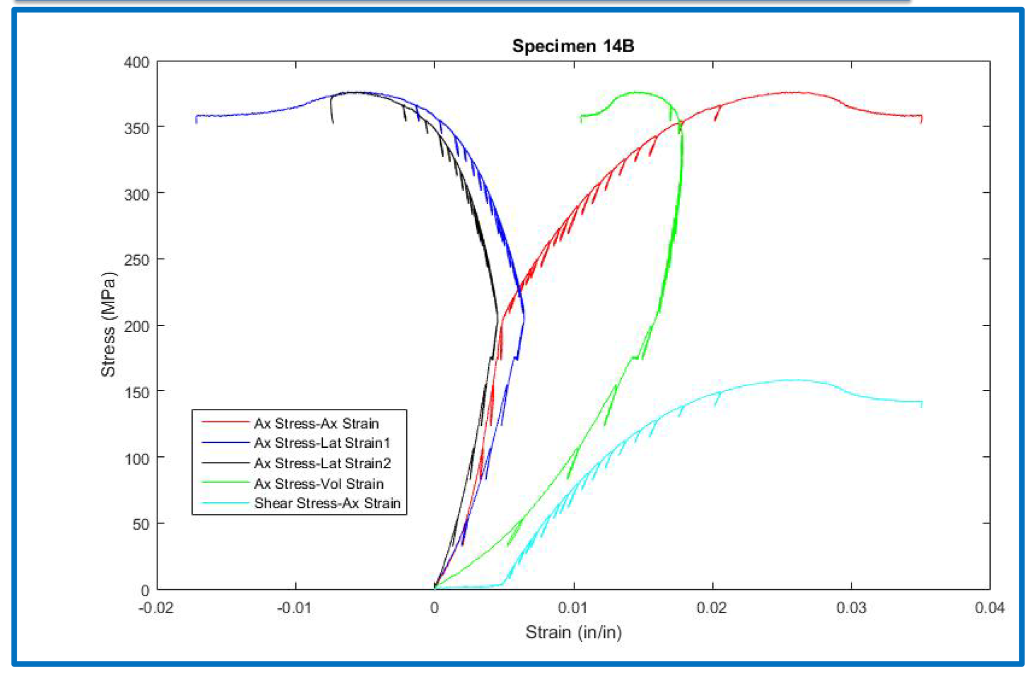
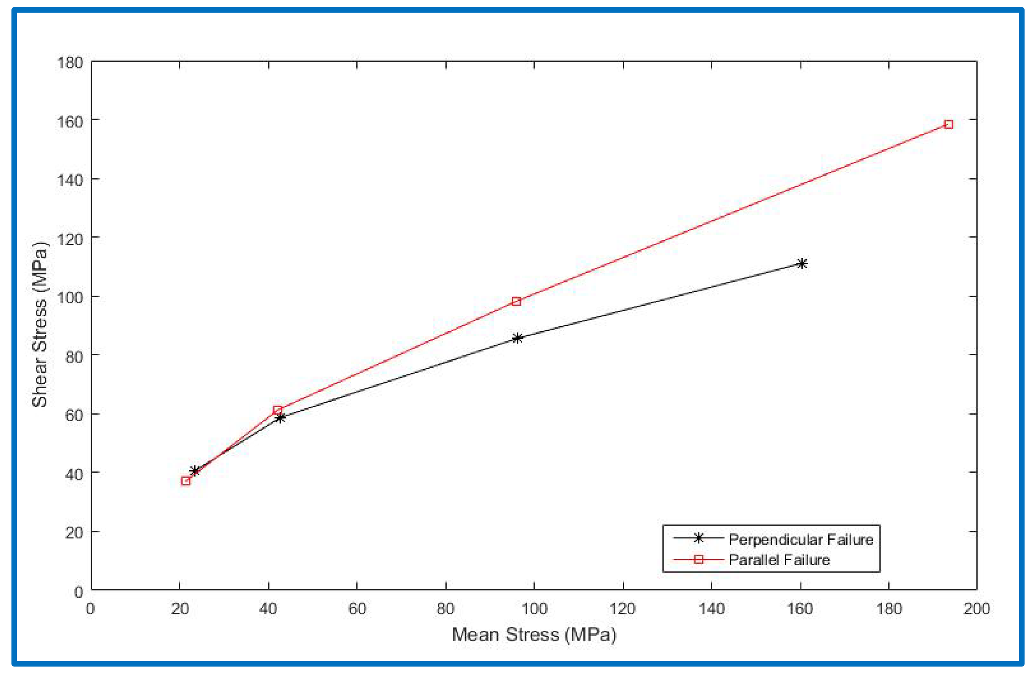
Abstract: Utilizing the localization conditions laid out in Rudnicki 2002, the failure of a series of tests performed on Mancos shale has been analyzed. Shale specimens were tested under constant mean stress conditions in an axisymmetric stress state, with specimens cored both parallel and perpendicular to bedding. Failure data indicates that for the range of pressures tested the failure surface is well represented by a Mohr- Coulomb failure surface with a friction angle of 34.4 for specimens cored parallel to bedding, and 26.5 for specimens cored perpendicular to bedding. There is no evidence of a yield cap up to 200 MPa mean stress. Comparison with the theory shows that the best agreement in terms of band angles comes from assuming normality of the plastic strain increment.

Specimen	Bedding orientation with respect to core direction	Mean Stress (MPa)	Shear Stress (MPa)
16B (UCS)	Parallel	21.42	37.09
32A (UCS)	Perpendicular	23.41	40.54
15B	Parallel	42.20	61.31
28A	Perpendicular	42.80	58.75
12B	Parallel	96.09	98.30
25A	Perpendicular	96.20	85.62
14B	Parallel	193.42	158.44
22A	Perpendicular	160.31	111.14
14A (Hydro)	Parallel	336.85	0.76
29A (Hydro)	Perpendicular	278.13	5.74

Specimen 14B





Mechanical Response:

All of the specimens tested (except hydrostatic tests) behavior dilatantly prior to failure. From posttest inspection it is apparent that failure occurred due to fracture formation. Fracture planes were steeply inclined with respect to the axial direction of the specimen regardless of the bedding orientation. Specimens loaded parallel to bedding demonstrated a higher failure stress when compared with those loaded perpendicular to bedding.

Equations:

Per Rudnicki, 2002 equations 1-3 define the predicted band angle (θ_{crit}) for three different assumptions about the material being tested.

- Equation 1 assumes that the difference between the Jaumann stress rate and the ordinary stress rate is negligible, i.e. there is only one value for shear modulus parallel to the axis of symmetry
- Equation 2 assumes the same as equation 1 but also assumes normality is satisfied, i.e. the increment of strain is normal to the yield surface.
- Equation 3 assumes the same as equation 2, but also assumes that the shear modulus is negligible with respect to the transverse modulus.

The equations in the green box are defined in terms of the following parameters:

μ - Local slope of the yield surface

r – Ratio of axial to lateral deformation defined as $r = \frac{1+{}^{2\mu}/_{\sqrt{3}}}{1-{}^{\mu}/_{\sqrt{3}}}$

v – Negative of the ratio of an increment of lateral deformation to an increment of axial deformation (Poisson's ratio in an isotropic media)

K – Transverse modulus $K = \frac{4(K_e+G/3)}{9}$

G_t – Shear modulus perpendicular to the axis of symmetry (radial direction)

Gl – Shear modulus normal to axis of symmetry (axial direction)

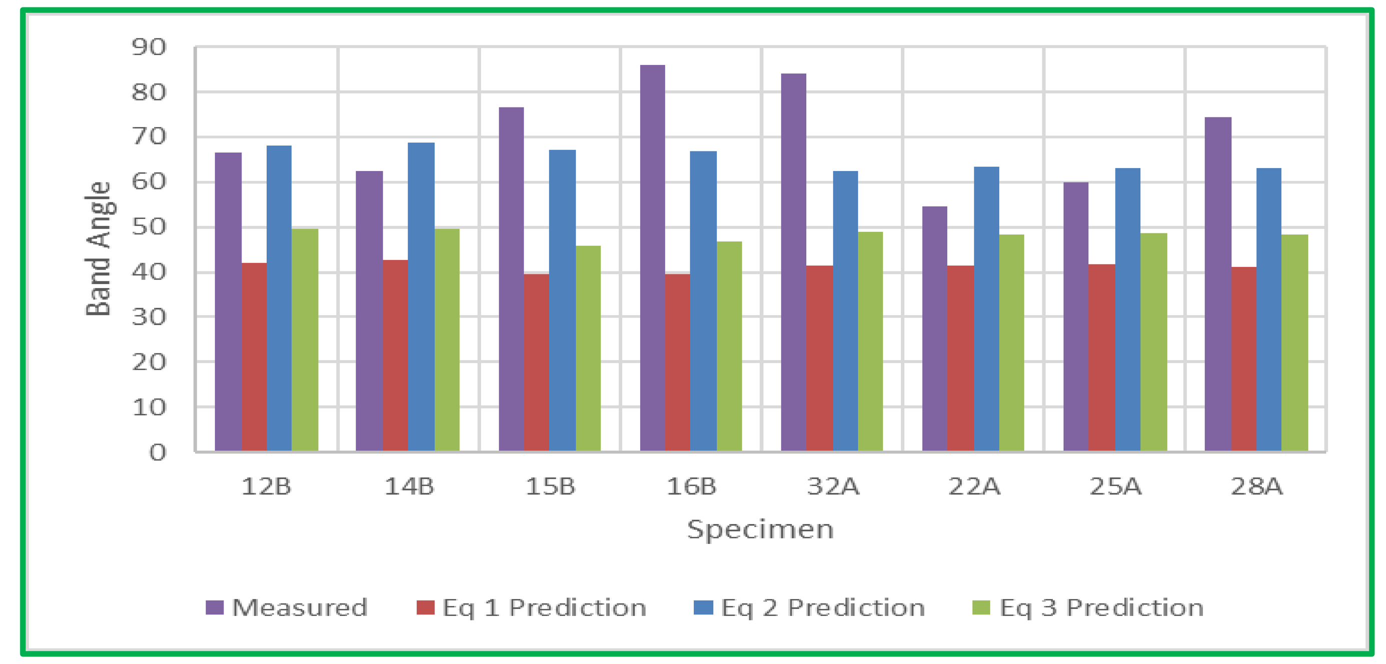
$$(1)\ \tan^2(\theta_{crit}) = \frac{\left[\sqrt{(G_l + 9K\,r/4)(G_l + 9K\,\nu/4)} - G_l\right]^2}{(G_t + 9\,K/4)}$$

$$(2)\ \tan^2(\theta_{crit}) = \frac{r^2}{(1 + 4G_t/9K)}$$

$$(3)\ \tan^2(\theta_{crit}) = \sqrt{2r\nu}$$

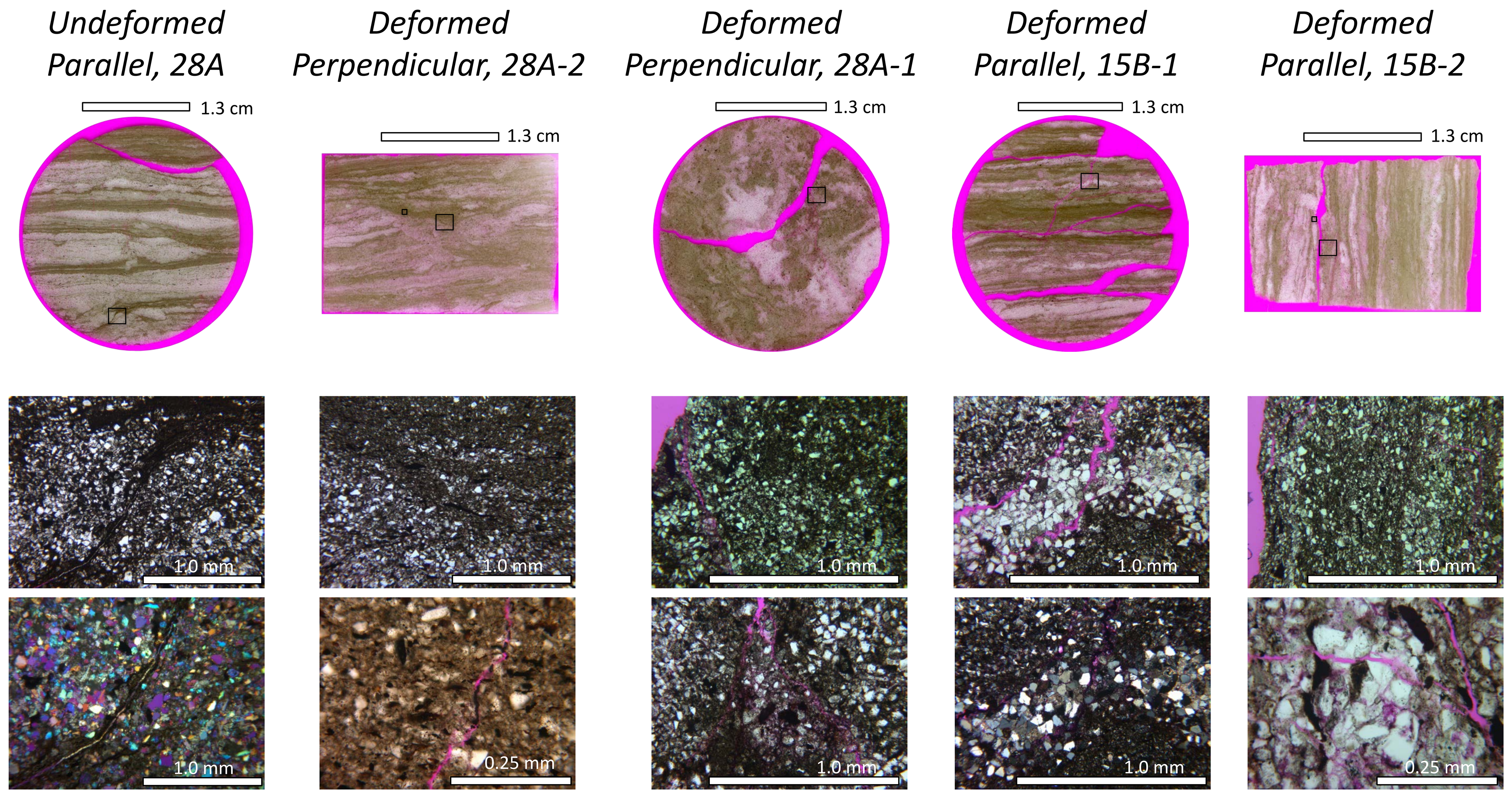
$$K = \frac{4(K_e+G/3)}{9}$$

Specimen	Eq 1 Prediction	Eq 2 Prediction	Eq 3 Prediction	Measured
12B	42.1	68.0	49.7	66.5
14B	42.7	68.7	49.6	62.5
15B	39.6	67.1	45.9	76.5
16B	39.7	66.7	46.9	86.0
32A	41.3	62.6	48.9	84.0
22A	41.5	63.3	48.4	54.5
25A	41.7	63.2	48.6	60.0
28A	41.2	63.0	48.2	74.5

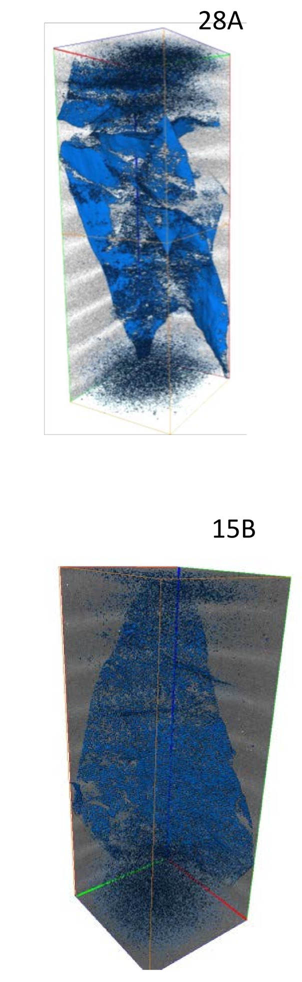


Pre and post shale texture and microstructual-to-macro deformation

Thin section images are referenced as bedding being perpendicular or parallel to core



XRCT reconstruction



Constitutive Results:

The local slope of the failure surface (μ) was determined by fitting a straight line to the failure data shown in the blue figure. The band angle results are shown in the orange figure and table. It is apparent from this plot that the best agreement with experimental results arose from assuming normality of the yield surface. Although the yield surface assumption should be appropriate especially at low mean stresses because the shale in question shows little plasticity until high mean stress is applied.

Thin Section and CT Results

"Undeformed " sample exhibits paleo-deformation including probable soft-sediment deformation and fracturing (mineralized). Perpendicular bedding to load: shear band as opposed to discrete fracture planes; orientation of organics suggest rotation. Parallel bedding to load: fracturing occurs predominantly in clay-rich laminae; stress focus on bends in calcite/quartz laminae may localize fractures across laminae. It is interesting to note that specimen 15B (lower CT reconstruction) shows a drastically different failure mechanism, essentially a single thoroughgoing fracture, while 28A (top CT reconstruction) shows a number of conjugate fractures. These specimens were tested under similar conditions, the only difference being the bedding orientation, parallel and perpendicular to loading for 15B and 28A respectively. Specimens cored parallel to bedding failed at a higher angle with respect to the axial direction when compared with specimens cored perpendicular to bedding.

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