An Experimental Investigation into Failure and Localization Phenomena in the Extension to Shear Fracture Transition in Rock

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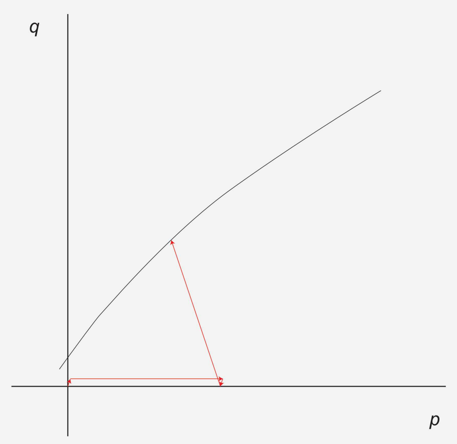
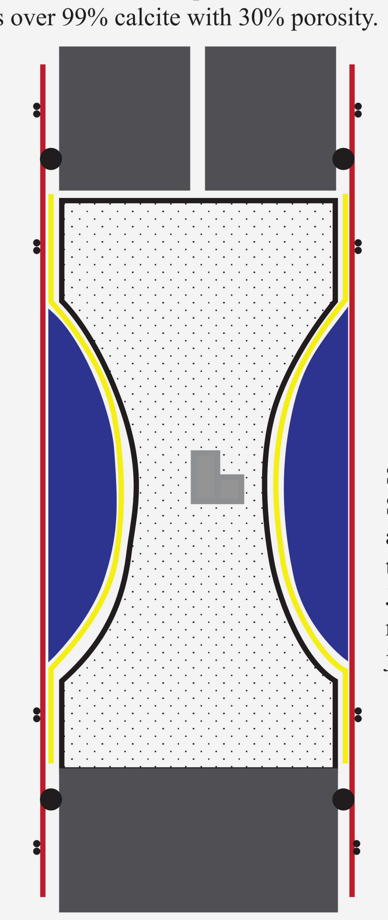
Introduction

Fluid-pressure assisted fracturing can produce mesh and other large, interconnected and complex networks consisting of both extension and shear fractures in various metamorphic, magmatic and tectonic systems. Presently, rock failure criteria for tensile and low-mean compressive stress conditions is poorly defined, although there is accumulating evidence that the transition from extension to shear fracture with increasing mean stress is continuous. We report on the results of experiments designed to document failure criteria, fracture mode, and localization phenomena for several rock types (sandstone, limestone, chalk and marble). Experiments were conducted in tri-axial extension using a necked (dogbone) geometry to achieve mixed tension and compression stress states with local component-strain measurements in the failure region.

Methods

Rock Types:
Berea Sandstone - Samples taken from a single block from Cleveland Rock Quarry in Ohio. The sandstone consists of subangular, well-sorted grains, 75-80% quartz, 20-25% feldspar, with minor amounts of clays and dolomite as grains and cement. 16-19% porosity, 185 micron mean grain diameter. Samples taken parrallel to bedding laminae of mafic minerals spaced 0.5 mm apart.
Carrara Marble - Samples taken from a single block from Lorano Bianco quarry in Italy. Carrara is nearly pure calcite with less than 1% porosity. The grain diameter is 250-355 microns. Undeformed marble has occational mechanical twins, sporadic intragranular microfractures.
Indiana Limestone - Samples taken from a single block. Indiana limestone is a calcite cemented grainstone that is over 97% calcite. Grain size is over 300 microns.
Kansas Chalk - Samples taken from a single block from the Upper Cretaceous Niobrara Formation. Kansas chalk is over 99% calcite with 30% porosity. Grains are 0.2 - 0.55 microns in diameter.





Load Path:
All experiments presented here are triaxial extension experiments. A small axial load is placed on the sample. The confining pressure is increased to the desired condition, and the axial load is increased to maintain a 1 MPa differential stress. Once the desired confining pressure is reached, the axial piston is reversed at a constant rate while the confining pressure is held constant. The confining pressure is the greatest principle stress, Sigma 1,2, and the axial stress is the least principle stress, Sigma 3. The axial strain rate is 10E-5/sec.

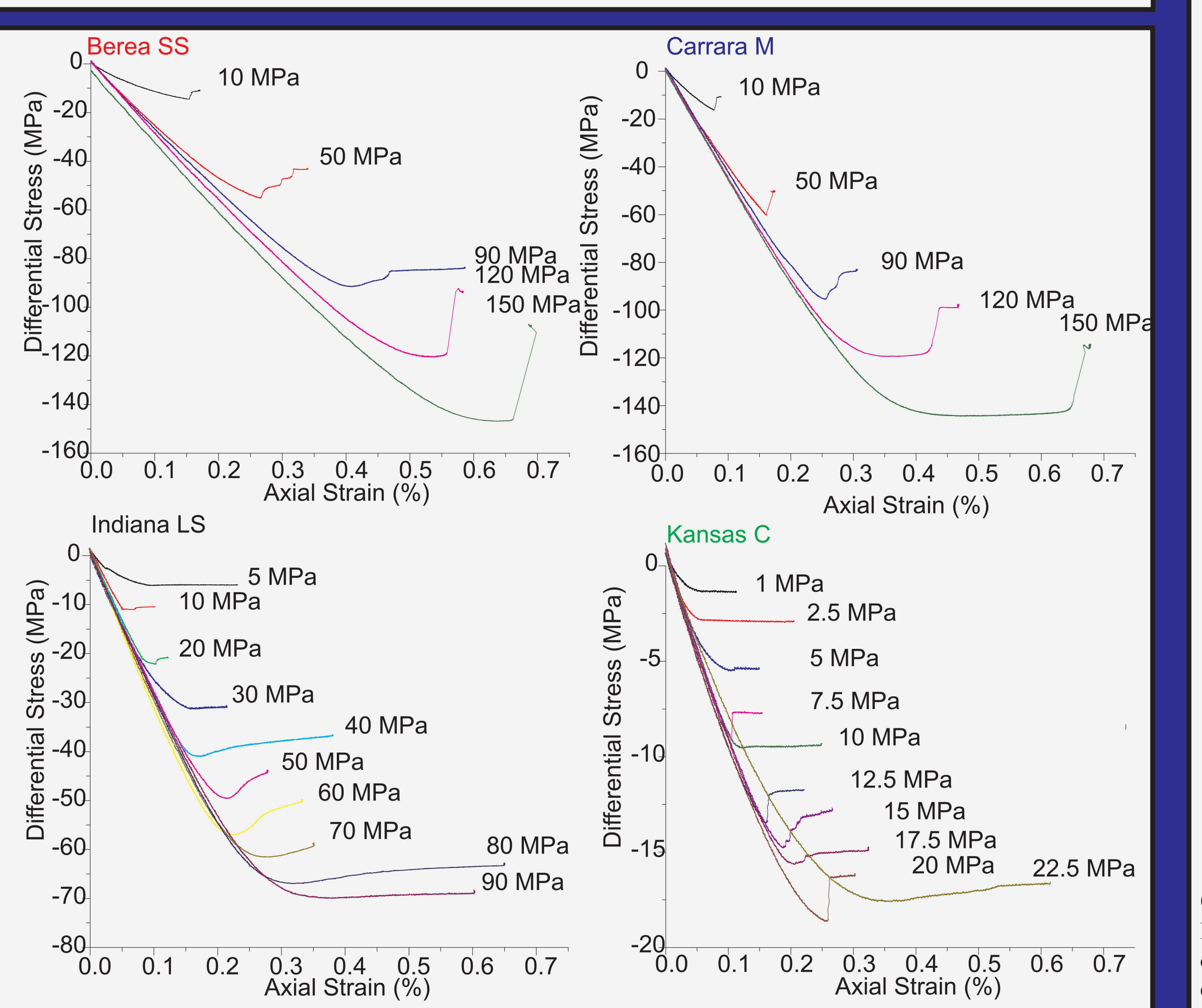
Sample Geometry:
The experiments presented here use a smooth notch cut, or dogbone, geometry. A precision surface grinder is used to create a constant radius of curvature for the neck. The sample is 102 mm long, 47 mm diameter at the shouler, 30 mm diameter at the neck, and a 88 mm radius of curvature.

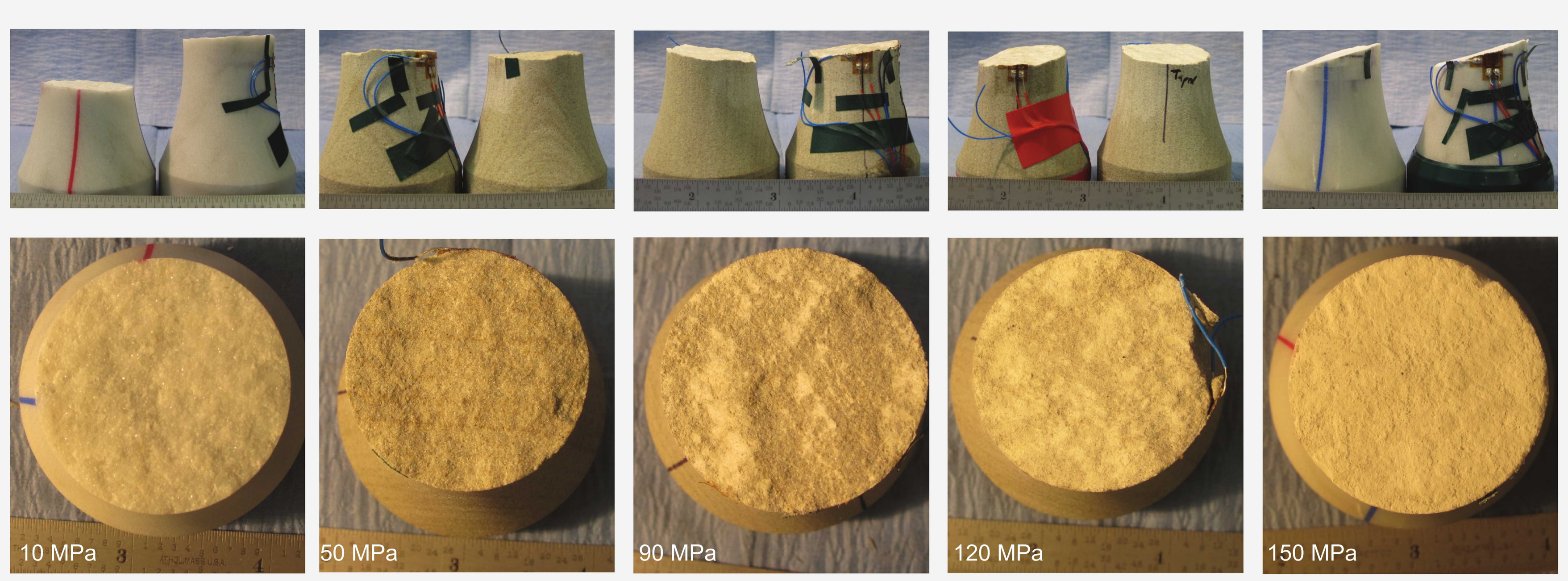
Sample Assembly:
Strain gage - Micro Measurement 350 ohm grids, stacked orthogonal rosette pattern measuring 10.7 mm square, was affixed to the neck of the sample. A groove was cut into the shoulder of the sample to run the strain gage wire under the jacketing and throught a pore pressure port in the piston.
Jacketing - The sample was wrapped in a single layer of latex sheeting. Plasticene modeling clay filled the void in the neck. A single layer of heat shrink polyolefin tubing enclosed the sample assembly from the confining medium. The jacketing was held in place by tie wire.

Results

External Axial Stress vs Strain:
- Smooth increase in fracture strength with increasing confining pressure
- Increasing Young's modulus with increasing confinig pressure
- Increasing inelastic strain with increasing confining pressure
- Previous experiments demonstrate twinning active for Carrara marble at 120, 150 MPa confining pressure
- Sharp stress drop for shear failure
- Indiana limestone, Kansas chalk ductile at highest confining pressures tested

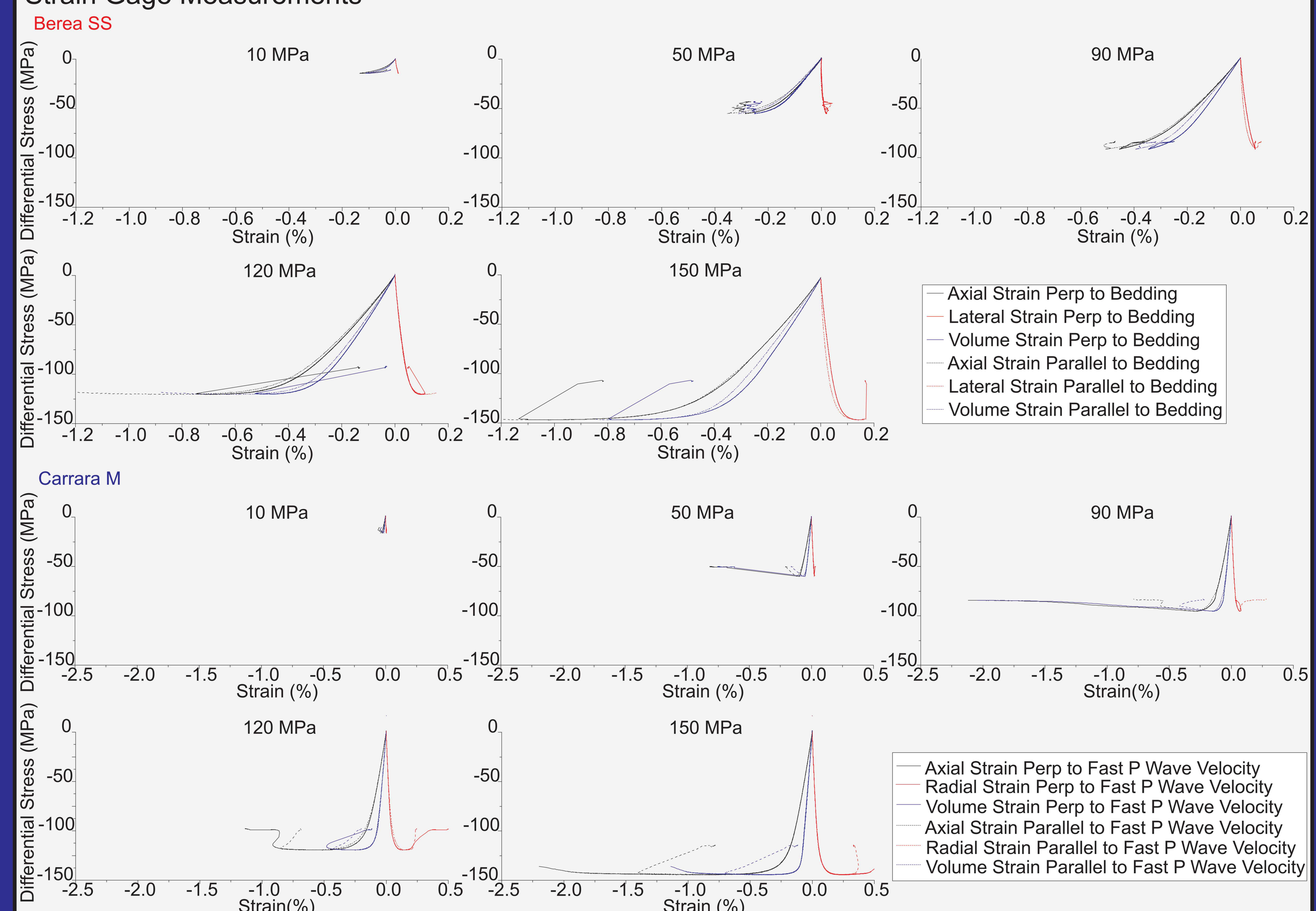
Fracture Morphology:
Tensile Fracture - Rough fracture face, no shear indicators. Frature propagated along crystallographic faces and cleavage planes
Max Tensile Fracture - Rough fracture face, no shear indicators. Face of fracture appears to have semblance of topography.
Tensile Hybrid Fracture - Rough fracture face with interspersed patches of gouge. Tensile and shear mechanisms active concurrently.
Shear Hybrid Fracture - Gouge covered fracture face with interspersed rough patches. Tensile and shear mechanisms active, but dominated by shear
Shear Fracture - Smooth fracture face covered by gouge.





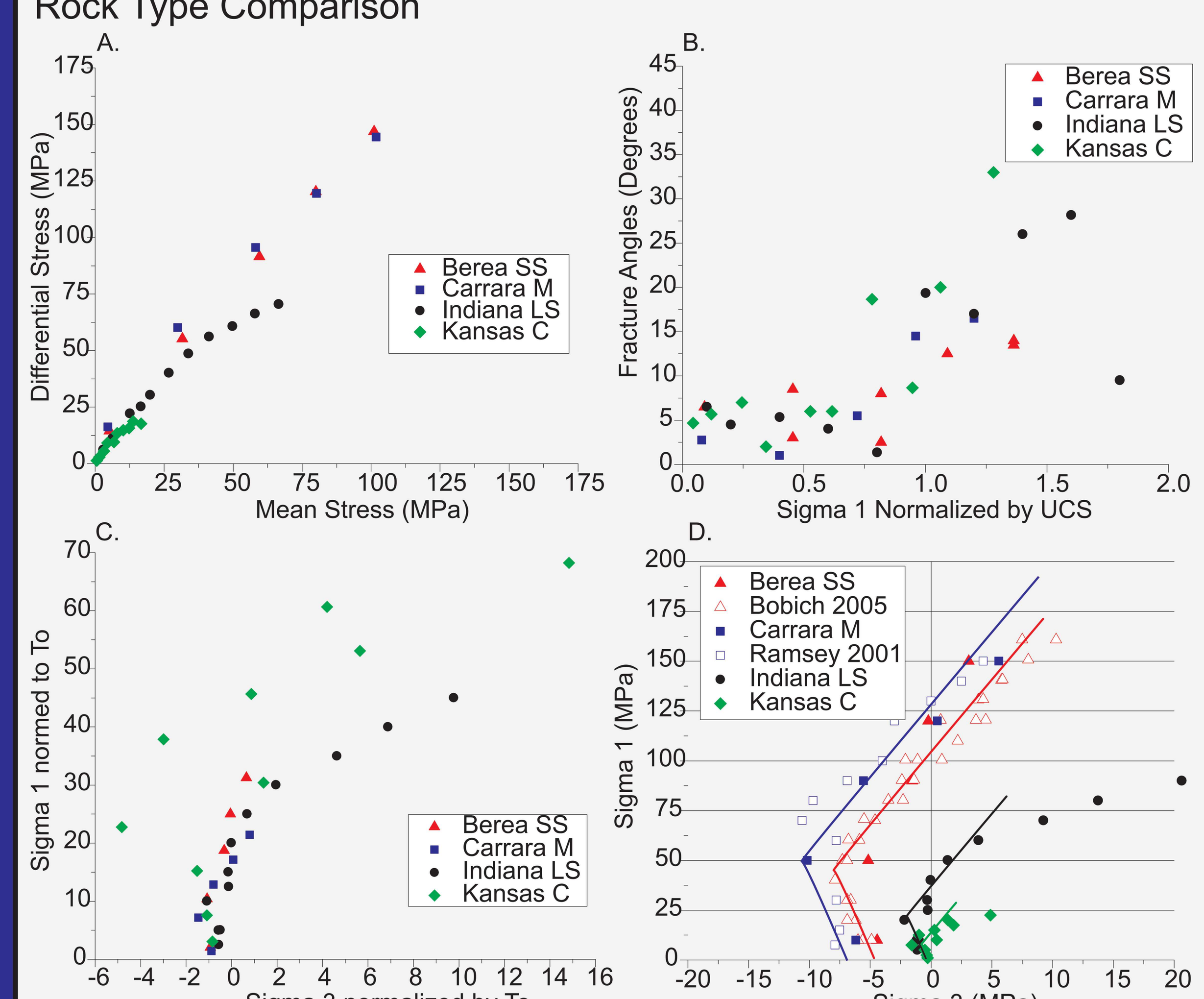
Tensile | Max Tensile | Tensile Hybrid | Shear Hybrid | Shear

Strain Gage Measurements



The strain gages on the sample neck were able to capture the mechanical behavior as failure localized. The measurements from the strain gages for Berea sandstone and Carrara marble reflect the same trends as the external measurements: Increasing strength, stiffness, and inelastic strain with increasing confining pressure. The strain gages recorded higher values compared to the external values. The radial and volume strains show the same trends as the axial strain component. The radial strain is much stiffer than axial strain, and displays less inelastic strain. Volume strain is calculated from the axial and radial strain components. The othogonal stain values are very similar, indicataing the homogeneous nature of these rocks.

Rock Type Comparison



A. - Failure strengths for Berea sandstone, Carrara marble, Indiana limestone, and Kansas chalk plotted in differential stress versus mean stress space. The four different rock types have similar slopes for the tensile and transitional behavior. For Indiana limestone and Kansas chalk, at the highest confining pressures tested the failure strengths deviate from the initial trend. This is indicative of a switch to a different deformation regime, likely shear enhanced compaction, also supported by the axial stres strain responses.

B - Fracture angle for Berea sandstone, Carrara marble, Indiana limestone, and Kansas chalk. To compare between the different strength materials, the confining pressure for each experiment was divided by the material's unconfined compressive strength. The fracture angles for the different materials are in excellent agreement. At low sigms 1 values, the fracture angles are very low, less than 10 degrees. At a sigma 1 value around 0.75*UCS, there is a linear increase in fracture angle.

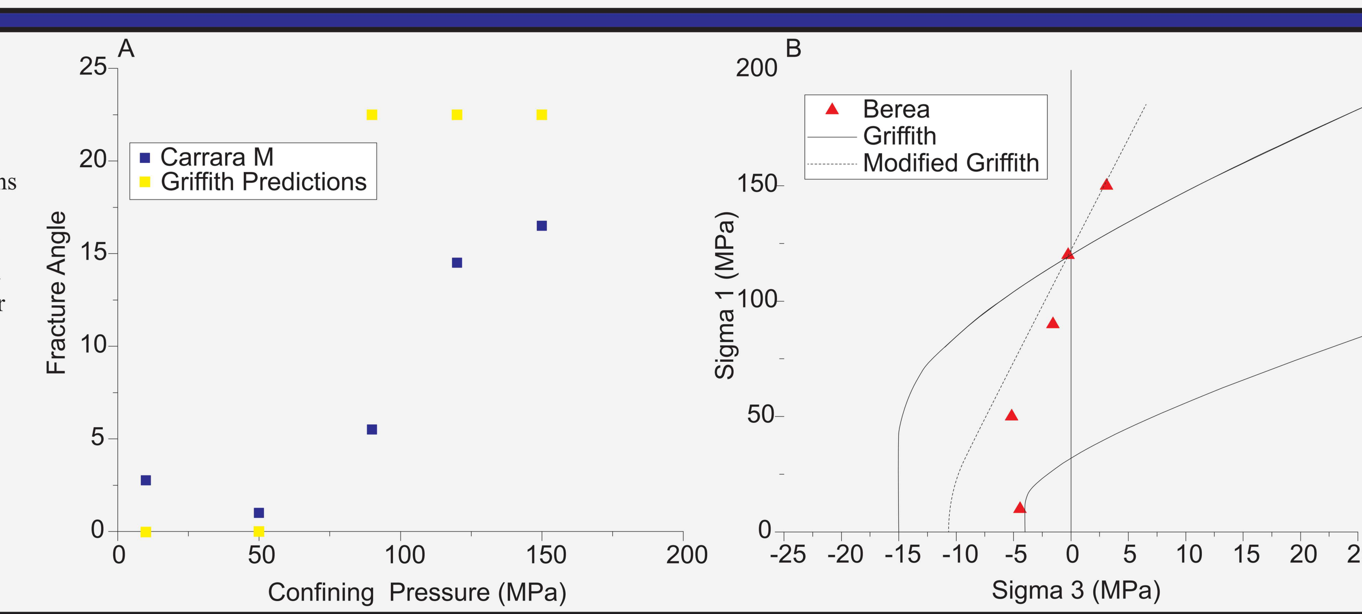
C - Failure strengths for Berea sandstone, Carrara marble, Indiana limestone, and Kansas chalk. To compare the different strength materials, the failure strengths for each experiment was normalized by the materials tensile strength. All of the materials tested here show a similar shape to the failure envelope, suggesting a characteristic shape.

D - Failure strengths for Berea sandstone, Carrara marble, Indiana limestone, and Kansas chalk plotted in sigma 1 versus sigma 3 space. Earlier extension experiments on Berea sandstone and Carrara marable by Bobich 2005 and Ramsey 2001, respectively, are also included. The failure envelopes for the different materials are similar, suggesting this is a charcteristic shape applicable to all rock types. The increase in tensile strength with increasing sigma 1 is a repeatable phenomena that is seen in all rock types tested here. The shapes of the envelopes are similar, but the UCS to To ratio is not. The ratio increases with decreasing confining pressure.

Griffith Criterion

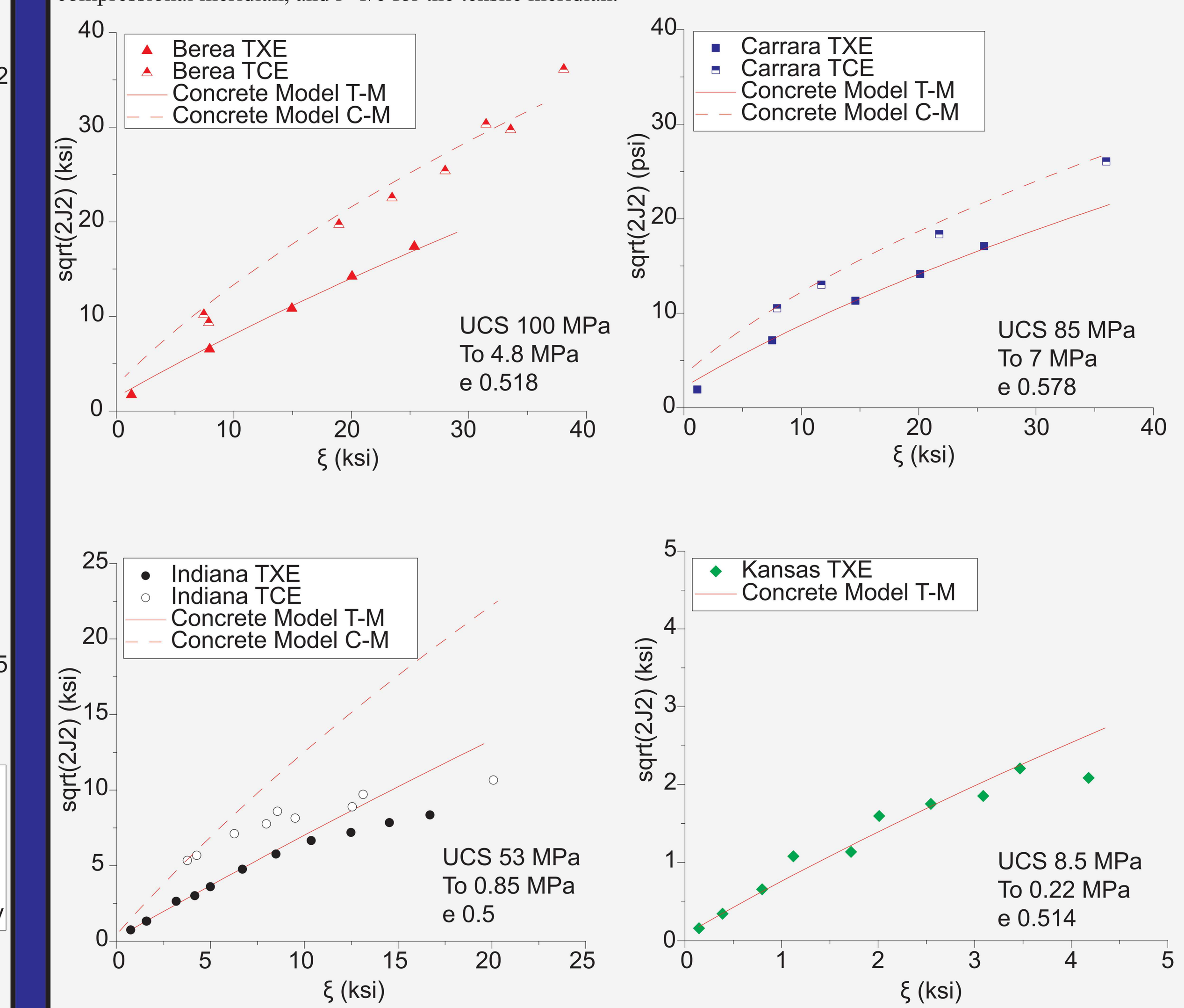
A - Fracture angles from Carrara marble plotted against confining pressure, compared against predictions from the Griffith criterion. The Griffith criterion predicts either 0° or 22.5°, Carrara marble demonstrates a smooth increase in fracture angles for the tenile to shear transition.

B - Failure strengths for Berea sandstone plotted in Sigma 1 versus Sigma 3 space, compared against predictions from the Griffith, and modified Griffith criterions. Neither criterion is able to accurately predict the observed failure strengths.



Comparison Against Biaxial Concrete Failure Criterion

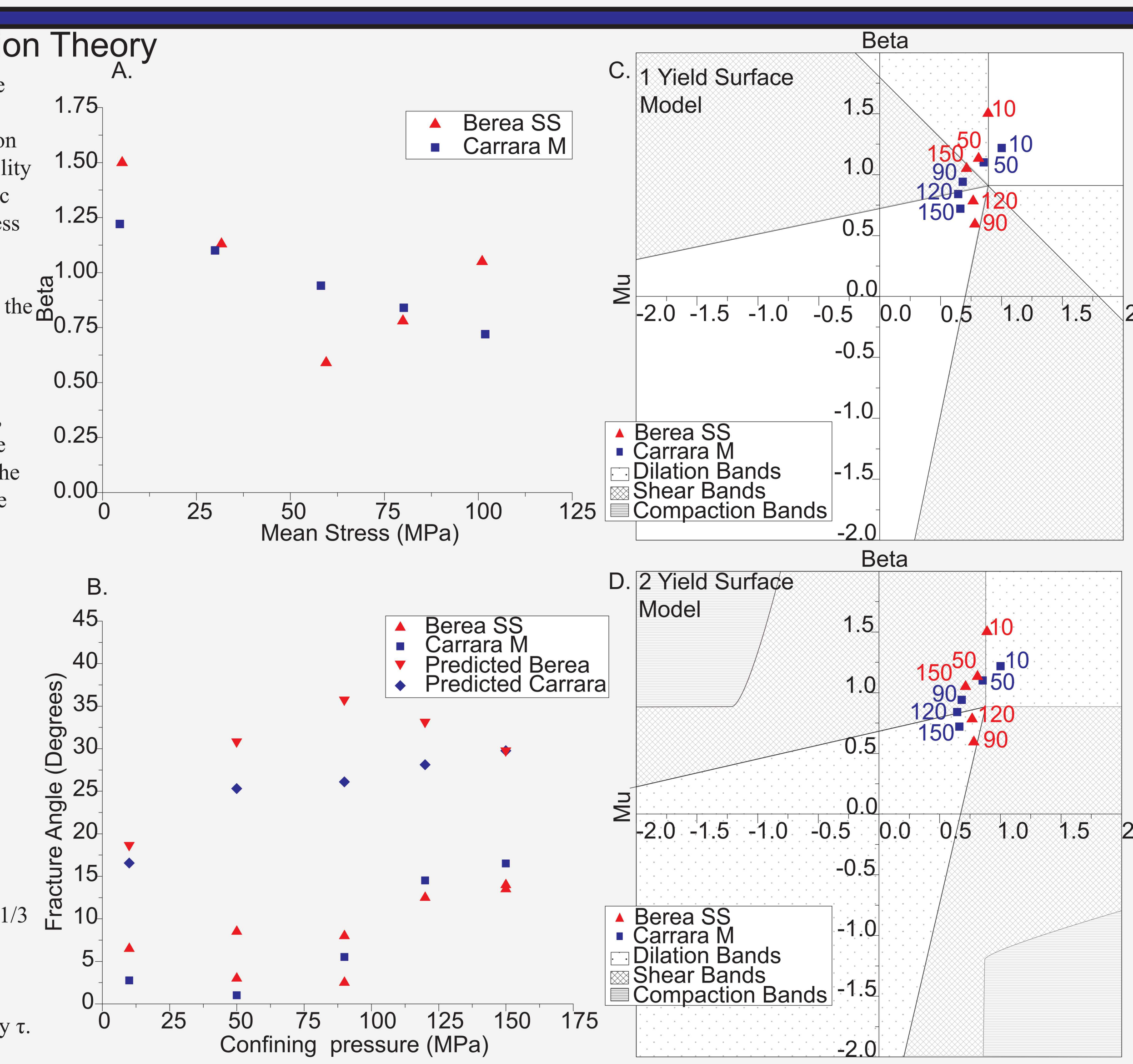
Data from the experiments presented here is combined with previous triaxial compression experiments to evaluate the applicability of a triaxial concrete model to natural material. A three variable geralized failure criterion was derived by Menetrey and Willam, 1995, to extend the Hoek and Brown criterion to predict the behaivor of concrete in triaxial compression and biaxial extension. The Hoek and Brown criterion was combined with the relationship between the principal stresses Haigh-Westergaard coordinates to account for the intermediate principal stress. The formula is scaled by the materials uniaxial compressive strength, tensile strenght, and e, a factor descrbing the eccectricity of the deviatoric trace, where lower values represent a higher J2 dependence. The generalized form of the equation:
$F(\xi, \rho, \theta) = [\sqrt{(1.5)}\rho/UCS)^2+m(\rho/(UCS\sqrt{(6)})r(\theta,e)+\xi/(UCS\sqrt{(3)})]-c=0$, where $m=(UCS^2-To^2)/(UCS*To)e/(e+1)$, $\xi=I1/\sqrt{(3)}$, $\rho=\sqrt{(2J2)}$, $c= 1$, $0.5<e\leq 1$, and $r = 1$ for the compressional meridian, and $r=1/e$ for the tensile meridian.



The concrete failure envelope accurately predicts the behavior for the four rock types tested, particularly for the tensile to shear transition in triaxial extension. The eccentricity values for the natural materials are consistent with reported values of 0.5-0.6 for concrete.
Berea Sandstone - The envelope accurately predicts both triaxial compression and extension behavior. The best fit e value for both meridians is 0.518.
Carrara Marble - The envelope accurately predicts the triaxial extension and compression behavior. The best fit e value is 0.578, the highest value for the rock types tested here. This indicates that Carrara is less dependent on the effects of the intermediate principal stress than the other types testd.
Indiana Limestone - The envelope is not able to accurately predict the behavior in triaxial compression and extension. The envelope predicts the behavior for the tensile to shear transition, but is not able to predict the failure strengths for the 3 highest confining pressures tested. The envelope is very inaccurate for triaxial compression. The e value is 0.5, the lower value allowed by the initial conditions.
Kansas Chalk - The envelope is accurate for the triaxial extension experiments presented here. The best fit e value for the data is 0.514. The envelope is not able to predict the behavior of the highest confining pressure experiment.

Comparison Against Localization Theory

Rudnicki and Rice, 1975, and other workers have developed a theoretical framework, bifurcation analysis, to predict strain localization, deformation band orientation, and strain type based on instability analysis in the constitutive description of inelastic behavior This analysis depends on the three stress invariants, τ and σoct, and the Lode angle, θ_L.
The classic formulation relies τ on and σoct; The yield condition and plastic potential are given by the equations:
$F(\tau,\sigma_{oct},\theta_L)=0$
$G(\tau,\sigma_{oct},\theta_L)=0$
The formulation is based on non-associated flow, where the normal to the yield surface is not in the same direction as the plastic potential, meaning the dilatancy factor, β, does not equal the slope of the yield surface, μ.
$-3\beta=(dG/(d\sigma_{oct}))/(dF/d\tau)$
$-3\mu=(dF/(d\sigma_{oct}))/(dF/d\tau)$
The fracture angle, θ, is given by
$\theta=(\pi/4)+(1/2)\arcsin(\alpha)$
where
$\alpha=(-(1+\upsilon)\cos\varphi((dF/(d\sigma_{oct})+dG/(d\sigma_{oct})))/(dF/d\tau)+(1-2\upsilon)\sin(\varphi+\theta_L)/\sqrt{3})/\cos(\varphi+\theta_L)$
where
$\tan\varphi=(dF/(\theta_L/\tau))/(dF/d\tau)$
Failure is predicted to occur when the plastic hardening modulus, h, reaches the critical value, hcr.
$h=d\tau/d\gamma^p$
$hcr/Gshear =((1-\upsilon))/(9(1-\upsilon))(\beta-\mu)^2-1/2(1-\upsilon)[N+1/3(\beta+\mu)]^2$
Where Gshear is the shear modulus, υ is the Poisson's ration, and N is the negative of the intermediate principal deviatoric stress divided by τ.



A. - β plotted against mean stress. For Berea sandstone and Carrara marble, β values are at maiximum values for the experiments at 10 MPa confining pressure, and decrease with increasing confining pressure. β decreases linearly for Carrara marble, but values are scattered for Berea sandstone.
B. - Measured and predicted fracture angles plotted against confining pressures. Predicted values are higher than measured values for all confining pressures tested. The predicted angles for Carrara roughly mirror the behavior of the measured values. The predicted values for Berea sandstone do not follow the same trend.
C. - β and μ values for Berea sandstone and Carrara marble plotted against predictions for a single yield surface model from Issen and Challa, 2008. Experiments agree with the band type predicted by the single yield surface model, except for Carrara marble at 10 MPa, 150 MPa, and Berea sandstone at 90 MPa, and 120 MPa confining pressures, which are not predicted to occur.
D. - β and μ values for Berea sandstone and Carrara marble plotted against predictions for a two yield surface model from Issen and Challa, 2008. Predicted band type agree with experimental observations except for Berea sandstone at 90 MPa and 120 MPa, and Carrara marble at 150 MPa confining pressure. The model predicts dilation bands for these experiments, where as observations suggest that these experiments are shear bands.

Conclusions

- The shape of the failure envelope is a characteristic shape that scales to different strength materials. The increase in tensile strength with increasing confining pressure is seen for all rock types. The envelope can be isotropically expanded or contracted to different strength materials, leading to UCS:To ratio that depends on the rock strength.
- Fracture angles are consistent for the rock types tested. The fracture angles are low for tension, 0-5 degrees, then increase linearly with the transition to shear behavior.
- The Griffith criterion is unable to predict the behavior seen in experiments. The criterion cannot predict the fracture angles, failure strength, or UCS:To ratio.
- The three variable model derived for uniaxial and biaxial tests on concrete is applicable to natural materials. The failure criterion can accurately predict failure strengthes for triaxial compression and extension for tensile to shear experiments. The failure criterion is not accurate in describing compactional failure.
- Bifurcation analysis based on localization theory is able to predict the type of deformation bands seen in experiments. The two yield surface model is the most applicable to the data presented here. The analysis is not able to predict fracture orientation, but does capture the general fracture behavior.

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