I. Experimental Fracturing in Rocks

A. Methodology

1. Experimental Work in Rock Mechanics
   a. Rock core samples placed in triaxial press
   b. Pressure applied until strength exceeded
   c. Fractures examined to provide insight into Mohr relations.

B. Basic Concepts and Variables

1. Rock failure

   a. critical stress relations at which sample is unable to support further stress increase without permanent deformation

2. Strength

   a. critical stress conditions at which failure of rock sample occurs

3. Brittle Failure: brittle cracking of sample

   a. Brittle Fracture: surface zone across which rock sample loses cohesion

      (1) atomic bonds broken at subatomic level

4. Ductile Failure: rock material becomes permanently deformed without losing cohesion

5. Confining Pressure: pressure applied to and surrounding the exterior of the sample

6. Pore Fluid Pressure: pressure of fluids contained in pore spaces of rock

7. Temperature: may be controlled in experimental aparatus

8. Axial Stress: stress applied parallel to core cylinder axis
9. Radial Stress: stress applied perpendicular to core cylinder axis
   a. i.e. confining pressure

C. Common experimental conditions

1. Axial compression experiments (positive stress)

   a. axial stress = sigma1
   b. radial stress = sigma2=sigma3

2. Axial tension experiments (negative stress)

   a. axial stress = negative = pull = sigma3

D. Concepts from Rock Fracture Experiments

1. Mode I, II and III Fractures Commonly Produced in Experiments

a. Review of Terminology
(1) Mode I: extension fractures, separation perpendicular to fracture surface
(2) Mode II: strike-slip shear fracture
(3) Mode III: dip-slip shear fracture

b. Extension Fractures (Mode I)

(1) From under positive, compressive stress

(2) fracture plane perpendicular to minimum principal stress sigma3
(3) fracture plane parallel to maximum principal stress sigma1
(4) displacement normal to fracture surface

c. Tension Fractures (Mode I)

(1) Form under negative, tensile stress
(2) fracture plane perpendicular to minimum principle stress sigma3

d. Shear Fractures (Mode III)

(1) Form under conditions of confined compression
(2) Commonly form at angles < 45 degrees to maximum compressive stress, sigma1
(3) Displacement, by shear, parallel to fracture surface

(4) If under triaxial conditions: sigma1 > sigma2 > sigma3...
(a) shear fractures form parallel to intermediate principal stress, sigma2

2. Conditions of Tension

a. Tensile strength of rock

(1) critical tensile stress (negative sigma3) at which rock undergoes brittle failure to form tension fractures

b. Fracture plane angle

(1) angle between maximum principal stress (sigma1) and the fracture plane

c. Fracture angle

(1) angle between maximum principal stress (sigma1) and a

normal to the fracture plane

d. For a tension fracture:

(1) tension fracture perpendicular to sigma3
(2) tension fracture parallel to sigma1
(3) fracture plane angle = 0
(4) fracture angle = 90

3. Conditions of Compression

a. General Relations under Compressive Conditions

(1) Initiation of fracturing dependent upon differential stress

(a) differential stress = sigma1-sigma3

(2) Critical differential stress: magnitude necessary to initiate brittle failure

(a) critical differential stress > with > confining pressure

(b) under greater confining pressure, greater differential stress required to initiate fracturing

(3) Conditions for formation of conjugate shear fractures

(a) common fracture plane angle = 30 degrees
(b) angle between conjugate set commonly = 60 degrees

b. Mohr Envelope

(1) Defines regions of stable and unstable stress states, relative to rock failure

(2) Tangent lines of Mohr envelope represents the critical states of stress that lead to brittle failure

(a) Mohr circle stress conditions that cross the mohr envelope lead to failure of rock

c. Coulomb Fracture Criterion

(1) Equation: mu = tan(phi);

where mu = coefficient of internal friction, phi = angle of internal friction.

(2) Cohesion: measure of resistance to shear fracture across a plane in which normal stress = 0, and shear stress is maximized.

(3) Angle of Internal Friction: defined by angle between tangent lines of Mohr envelope and horizontal of mohr circle

(4) Coulomb Coefficient

d. Other Fracture Relations

(1) Conjugate Shear Fractures

(a) a set of two shear fractures that commonly develop under shear failure

(b) angle between two conjugate shear fractures approximately 60 degrees

(c) each shear at 30 degree angle between sigma1 and conjugate each shear plane

(d) under triaxial conditions: sigma1>sigma2>sigma3, conjugate shears will form parallel to sigma2

i) most common stress condition in nature
ii) however, usually one dominant shear direction will prevail.

(e) under confining conditions of sigma1>sigma2=sigma3, conjugate shears may form in infinite number of orientations

(2) Reidel (Secondary) Shear Fractures

(a) determined from clay-shear experiments

(b) R shears = synthetic secondary shears that form within 15 degrees of primary conjugate set, same sense of shear motion

(c) R' shears = antithetic secondary shears that form at 75-80 degrees of primary conjugate set, with opposite sense of shear motion

E. Controlling Factors of Fracturing

1. Confining Pressure

a. As confining pressure increases, Mohr circle shifts to the right of the mohr diagram

(1) under very high confining pressure, rocks commonly undergo ductile deformation

b. Frictional Sliding

(1) At low confining pressures, Mode I fractures commonly develop

(2) Mode I fractures commonly reactivated as Mode II or III fractures at higher stress states

(a) At lower confining pressures: shear motion = continuous sliding
(b) At higher confining pressures: reactivated shear motion = stick-slip

i) "stick" interval = > internal shear stress
ii) "slip" interval = rapid sliding and release of internal shear stress

2. Pore Fluid Pressure

a. Effects of internal fluid pressure in rock

(1) internal fluid pressure effectively reduces confining pressure in straight arithmetic relationship

(2) Effect: internal fluid pressure shifts mohr cirlce to the left

(a) stress conditions that are stable at 0 pore pressure, may become unstable at > pore pressure

(3) Thought to be primary mechanism for creating extension fractures at great depths, under great confining pressures.

(4) Pore pressure along fault planes, reduces effective normal stress, < friction, triggers fault motion

(a) "hydroplaning" along fracture plane
(b) proposed as a mechanism to artificially relieve stress along known fault zones
i) e.g. San Andreas

3. Mechanical Anisotropy

a. Terms

(1) mechanical isotropy: rocks have same rheology and fracture mechanics in all directions

(a) fracture criterion same in all directions, irregardless of orientation of principal stress fields

(2) Mechanical anisotropy: rocks have different mechanical strengths in different directions

(a) preferred directions of structural weakness

i) e.g. cleavage planes, pre-existing joint sets, bedding planes

ii) Will strongly influence orientation of fracture planes, as a function of orientation of principal stress regimes.

4. Temperature

a. Depending on rock type, at temps > 200-500 C, rocks commonly undergo ductile deformation

b. Experimental data
(1) > temp, may also decrease brittle shear strength of rock
(2) although difficult to substantiate

5. Mechanical Flaws

a. flaws = localized zones of weakness, that may serve at fracture initiation points

(1) e.g. fractures, microfractures, compositional heterogeneities, fossils, etc.

II. Natural Fractures (in rocks)

A. General

1. Structural features in rocks provide record of stress histories

2. Complicating factors

a. complex deformational histories
b. timing difficult to establish to any great degree
c. old structures may be reactivated during renewed (later) deformation

B. Techniques for Determining Stress in Earth

1. Importance of stress studies

a. geological engineering studies
b. slope stability studies
c. plate tectonic analysis

d. earth quake prediction

2. Borehole Analysis (Strain Gauging)

a. drill hole in rock, set up strain gages in hole
b. measure strain of bore hole in response to rock removal

3. Hydrofracturing

a. use of hydrofrac studies to delineate stress conditions

4. Earthquake First Motion Studies

a. using seismic analysis of earthquakes to determine sense of shear on faults
b. helps delineate stress field

C. Stress in the Earth

1. Types of Stress

a. Vertical Normal Stress

(1) downward compressive stress, perpendicular to horizontal
(2) generally equal to overburden stress, related to weight of rock parallel to vector of gravitational force

b. Nontectonic Horizontal Stress

(1) burial of sediments in sedimentary basin

(a) vertical stress = overburden compression
(b) horizontal stress: horizontal component related to overburden confining pressure and basin subsidence

c. Tectonic Horizontal Stress

(1) rift tectonics = tensile horizontal stress
(2) convergent zones = compressive horizontal stress

(a) brittle rheology in upper 15-20 km of crust
(b) ductile deformation at depths > 15-20 km due to temp. and pressure increase

2. Driving Mechanisms of Stress

a. Overburden Pressure

(1) stress due to weight of overlying column of rock

(a) common average density of rocks: 2.7 g/cu. cm.

(2) Thickening of overburden pressure

(a) sediment loading
(b) tectonic / thrust sheet loading
(c) ice loading during glacialtion

b. Tectonics

(1) stress associated with plate motion

(a) subduction pull
(b) spreading center push
(c) mantle convection

c. Vertical Motions

(1) Isostacy
(a) volcanic loading
(b) ice loading
(c) erosion and isostatic uplift

(2) igneous intrusion
(a) e.g. laccoliths

d. Effects of Temperature and Pressure

(1) stresses due to thermal expansion and contraction of rocks
(2) magmatic heating and cooling

e. Pore Fluid Pressure

(1) connate pore fluids create internal pressure
(a) sediment compaction of impermeable seds., > pore pressure
(b) prograde metamorphism
i) dewatering and release of carbon dioxide, > pore pressures

(c) magmatic melts exerting pore pressure, vein formation

3. Joint Formation and Timing of Stress

a. General

(1) Joints: essentially mode I fractures, extension in nature

(2) Problem: all stresses that have been measured in the earth are compressive in nature, tensile stresses are rare

(a) how to get extension in a highly compressive environment??

(b) internal pore fluid pressures must be high enough to reduce compressive confining stress to create tensile conditions

i) i.e. shift mohr circle to left of origin.

b. Joint formation During Sedimentary Burial

(1) sed. burial, compaction, dewatering, > pore fluid pressures ----- fracturing, clastic dikes, etc.

c. Joint formation During Erosion

(1) uplift and erosion process

(a) vertical overburden stress decreases with time
(b) temperature of rocks decreases

(2) horizontal stress regime will determine whether jointing will occur at this phase.

d. Joint formation in Response to Tectonic Deformation

(1) tectonic stresses, > pore pressure, fracturing

e. Unloading and Sheet Joints

(1) sheet joints: extension fractures parallel to surface topography of earth

(2) process: uplift, erosion, < in overburden stress through time
(a) sheet joints form in response to expansion via removal of overburden

f. Thermal Fracturing (Columnar Jointing)

(1) columnar joints: result from contraction of rock mass during thermal cooling

(a) commonly forms mutually intersecting, hexagonal-shaped fractures
(b) similar to mudcrack shrinkage and formation

III.