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Fault zone strength and failure criteria

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Abstract. This paper discusses Coulomb failure criteria for brittle deformation of intact rock and fault gouge. Data are presented from laboratory experiments designed to identify the critical gouge layer thickness required to effect a transition from the standard Coulomb criterion to a modified failure law (referred to as Coulomb plasticity) appropriate for simple shear of a gouge layer. Experiments were carried out using tension fractures and quartz powder to simulate granular fault gouge. Fractures sheared without gouge obey the standard Coulomb law. A 0.6mm-thick gouge layer was required to effect the transition to Coulomb plasticity. I test and reject the hypothesis that fault zone strength and apparent coefficient of internal friction can be predicted from fracture of intact rock simply by accounting for differences in the failure laws and without considering variations in the Coulomb parameters. The data presented indicate that the stress state required for Coulomb plasticity is not developed within very thin gouge layers. This work implies that brittle fault zones have lower friction than predictions based on the strength of intact rock. However, the magnitude of this weakening effect is small (for example, a coefficient of sliding friction of 0.75 would be reduced to 0.6) and thus it is not an independent explanation of the apparent weakness of mature faults.

Introduction

A central goal in fault mechanics has been to understand why mature faults appear significantly weaker than estimates based on Byerlee's Law. Byerlee's Law predicts coefficients of sliding friction of 0.6 to 0.8 and fault strengths of ≥100MPa at seismogenic depths, whereas friction on mature faults is inferred to be 0.3 or less [e.g., *Rice*, 1992]. Immature faults (those with poorly-developed gouge zones and little recent slip) do not appear to be weak.

Explanations for the weakness of mature faults include the existence of weak material within the fault zone, high fluid pressure, and dynamic effects which reduce friction and heat production [*Rice*, 1992; *Chester et al.*, 1993]. Notwithstanding the importance of these mechanisms, an additional factor exists that has received relatively little attention: differences in the failure laws, and strength, for intact rock and fault zones deforming under simple shear. The purpose of this paper is to evaluate these differences and to present measurements showing the transition between failure laws with increasing gouge thickness.

Failure Criteria for Fault Zones and Intact Rock

For intact rock and granular material undergoing bulk deformation, shear strength τ is described by the Coulomb criterion (Figure 1)

$$\tau = C + \sigma_n \tan\phi, \tag{1}$$

where C is cohesion (or cohesive strength), σ_n is normal stress, and ϕ is the friction angle ($\tan\phi = \mu_i$, where μ_i is the coefficient of internal friction). However, laboratory data, theoretical studies, and field observations indicate that a layer of fault gouge deforming in simple shear obeys a different failure law [*Hobbs et al.,* 1990]

$$\tau = C\cos\phi + \sigma_n \sin\phi. \tag{2}$$

Criterion (2) represents a stress state in which the maximum principal stress is 45° to the gouge layer boundary, irrespective of the external stress state [*Hobbs et al.*, 1990; *Marone et al.*, 1992]. This implies coaxiality between the macroscopic stress and strain rate vectors and thus criterion (2) has been referred to as Coulomb plasticity [*Byerlee and Savage*, 1992; *Beeler and Tullis*, 1994; *Scott et al.*, 1994].

A consequence of (2) is that brittle fault zones are expected to have lower friction than predictions based on the standard Coulomb law (1). That is, (Figure 1a) the normal stress dependence of the shear strength of a gouge layer μ_a (the apparent coefficient of internal friction) and the apparent friction angle ϕ_a are related to the true friction angle and coefficient of internal friction by [*Hobbs et al.*, 1990]

$$\mu_a = \tan\phi_a = \sin\phi = \sin(\tan^{-1}\mu_i). \tag{3}$$

The gouge layer fails internally according to criteria (1) along Riedel shear surfaces [*Mandl et al.*, 1977] and thus the plane of the gouge layer appears to have lower friction than planes of other orientations.

Although the distinction between (1) and (2) is well defined in the extreme, the transition between them is not. The Coulomb criterion applies to intact rock and bulk deformation of granular material, whereas Coulomb plasticity applies to thick gouge zones. Does the transition require a critical gouge thickness or a critical contrast in material properties between the gouge and surrounding rock? How is the transition accomplished with fault development? In this paper I address these issues by first considering the effect of variations in C and ϕ on a transition from criterion (1) to (2). I then present laboratory measurements of the frictional strength of gouge layers to examine directly the transition in failure laws.

If the Coulomb parameters are independent of the change in failure law from (1) to (2) differences in the shear strength of intact rock and fault gouge are due solely to differences in the stress state and boundary conditions *vis a vis* criteria (1) and (2). Existing data may be used to evaluate this hypothesis [*Lockner and Byerlee*, 1993]. Figure 1 shows fracture data for Westerly granite and the failure envelope they define. It is convenient to write the Coulomb criteria as $\mu_i = \tan\phi = \tau_p / (\sigma_p + \sigma_c)$ where τ_p and σ_p are the resolved shear and normal stresses on the fracture plane and $\sigma_c = C / \tan\phi$.

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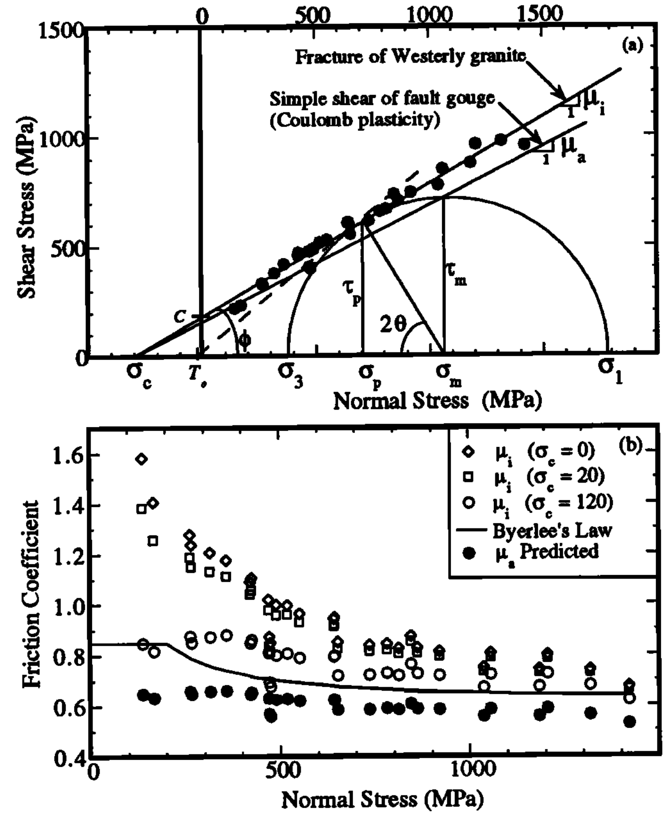

Figure 1. (a) Fracture data of *Brace et al.* [1966] and *Byerlee* [1966] for Westerly granite along with the Coulomb failure envelope they define (upper line of slope μ_i). Data are shear and normal stress resolved on the fracture plane at failure. The line of slope μ_a represents the Coulomb plasticity failure law. Dashed line indicates failure criteria used by *Lockner and Byerlee* [1993] who mistakenly took C equal to T_o. (b) Coefficient of internal friction derived from the fracture data for three values of σ_c. The data require σ_c = 120MPa and thus the predicted μ_a values are significantly below laboratory measurements of gouge strength which follow Byerlee's law. (Modified from *Lockner and Byerlee*, [1993])

Under these assumptions, *Lockner and Byerlee* [1993] suggested that the fracture strength for intact rock could be used to predict the strength and μ_a for fault gouge, via equation (3). They reported agreement between μ_a so derived and laboratory measurements of gouge strength (Figure 1). However, *Lockner and Byerlee* mistakenly identified σ_c as the tensile strength T_o and equated this with cohesion (their equation 1). From Figure 1, $\sigma_c = C$ if $\phi = 45°$, a rare case for brittle rocks. However, there is no theoretical basis for equating C with tensile strength, which is generally a factor of 5 to 10 less than C.

In Figure 1b, I show μ_i for the fracture data of Figure 1a using three values of σ_c. *Lockner and Byerlee* used values of $\sigma_c = 0$ [1992] and 20MPa [1993], however, these are incorrect. In his original study, *Byerlee* [1966] reported cohesion values of 70 to 170MPa, which would imply σ_c of 100 to 200MPa. A least squares fit of equation (1) to all the data of Figure 1a gives C = 191MPa and $\mu_i = 0.60$. Neglecting curvature in the failure envelope, the data require C of at least 100MPa and $\mu_i = 0.83$, which gives σ_c=120MPa. From equation (3) this yields μ_a values significantly below measurements of gouge strength and Byerlee's law (Figure 1b).

The observation that gouge strength is not predicted from the strength of intact rock indicates that σ_c is not the same for these materials (Figure 1). This is perhaps not surprising since cohesion differs greatly for intact and fractured rock. The derivation of equation (3) requires that σ_c be the same for both criteria [*Hobbs et al.*, 1990]. Hence, a better test of equation (3) and the relationship between criteria (1) and (2) would be to compare cases for which this were true. Shear of a pre-existing, natural fracture at moderate normal loads provides such a case. Failure is expected to obey (1) when the fracture is sheared from the mated (fully interlocking) position without gouge, whereas shear of a sufficiently thick gouge layer obeys (2). Cohesion for a pre-existing fracture at low normal loads can be taken as zero, hence σ_c is zero in both cases. Friction measurements made on increasingly thick gouge layers should show a transition from criteria (1) to (2).

Shear of Natural Fractures

Tension fractures were produced within samples of Westerly granite and sheared at 15MPa normal stress within the direct shear apparatus of J. Dieterich at the U.S.G.S., Menlo Park, Ca. Normal stress was held constant and a roller-bearing assembly was used to isolate shear on a single fracture surface in the double direct shear geometry (Figure 2). Fractures had nominal area of 5cm x 5cm and were made approximately flat at longer wavelengths by notching the perimeter of the block to guide tensile fracture. Maximum peak-to-trough roughnesses of the surfaces were 6-8mm [*Marone and Durham*, 1992].

Fractures were sheared from the mated position with ultra-fine quartz powder (median diameter < 10μm) used to simulated fault gouge. Twelve experiments were run with varying thicknesses of gouge. Stress-strain characteristics varied systematically with gouge thickness (Figure 2). For zero gouge, the stress-strain

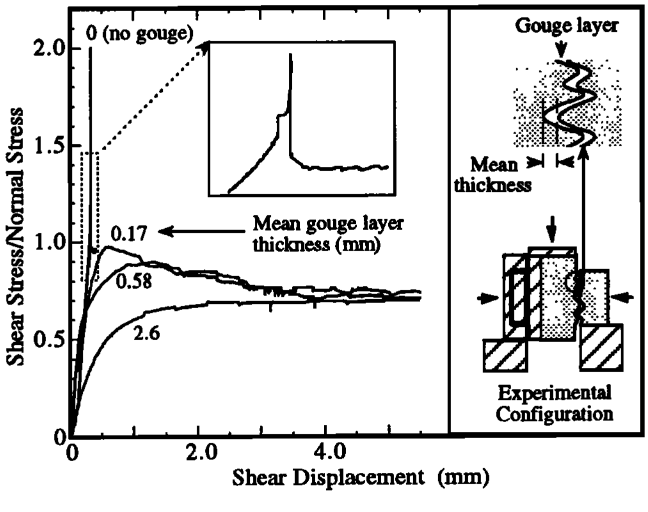

Figure 2. Main plot shows friction data from four experiments in which gouge layers of different thickness were sheared between tension fractures at 15MPa of normal stress. Right inset illustrates direct-shear experimental configuration with roller-bearing-way assembly, rock (stippled), and definition of mean gouge thickness. Peak-to-trough fracture roughness was 6-8mm. Upper inset is enlargement of data for shear without gouge, showing stable post-failure sliding with sliding friction=0.95. Shear displacement has been corrected for apparatus stiffness. Second order variations in friction are related to slip velocity changes used to interrogate detailed frictional characteristics [*Marone and Durham*, 1992].

behavior resembled that for fracture of an intact sample: a steep loading curve was terminated by a sudden, audible stress drop at failure. The post-failure coefficient of sliding friction was 0.95. Thicker gouge layers showed a more gradual onset of sliding and lower peak frictional strength (Figure 2).

I take the values of peak strength as the point of macroscopic failure. Mated bare surfaces failed at a shear stress of 32MPa. Assuming standard Coulomb failure this corresponds to a coefficient of internal friction of 2.1, which from equation (3) predicts an apparent coefficient of internal friction of 0.9 for failure via Coulomb plasticity (Figure 3).

For the friction measurements involving gouge, I make no *a priori* assumption about the governing failure law. Values of μ_i and μ_a are calculated for both criteria (Figure 3). Measured friction for the 0.17mm-thick layer is close to μ_a predicted from the experiment without gouge, however, the reverse is not true. μ_i predicted from the measured value is significantly above the 2.1 value appropriate for Coulomb failure. For a slightly thicker gouge layer (0.58mm thickness), the measured friction matches that predicted for Coulomb plasticity and this value predicts μ_i of about 2.1, in agreement with the measured value for criterion (1).

Although the preceding analysis has focused primarily on the coefficient of internal friction, the weakening effect associated with failure via Coulomb plasticity also applies to sliding friction. An estimate of this effect can be made using the steady-state friction value for shear without gouge (see inset to Figure 2), which is roughly 0.95. Applying equation (3) indicates a coefficient of friction of 0.69 for a gouge layer of sufficient thickness to deform by Coulomb plasticity. This is about equal to the sliding friction values for the 0.58 and 2.6mm-thick layers (Figure 2) and thus in agreement with the results for internal friction.

Discussion and Conclusions

The data indicate that a gouge layer approximately 0.6mm thick is required to effect the transition from failure via the Coulomb criteria (1) to failure by Coulomb plasticity (Figure 3). A thinner layer shows transitional behavior. These observations rely on two assumptions: 1) that cohesion is approximately zero and 2) that the coefficient of internal friction is independent of gouge thickness over the range considered. The first is justified for pre-existing fractures sheared at low normal loads. The second is justified because the surface roughness is large in comparison to the layer thickness. Peak frictional strength decreased significantly when mean layer thickness, 2.6mm, was comparable to surface roughness (Figure 2).

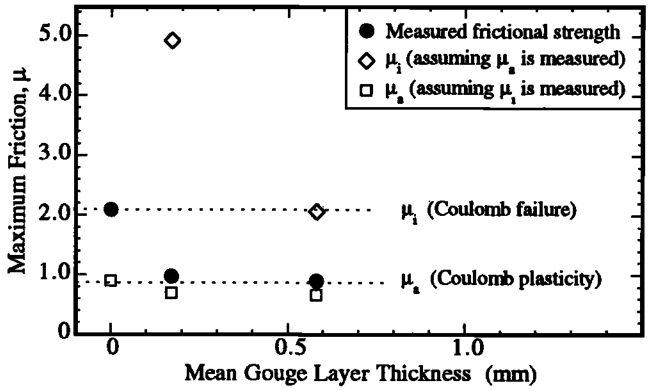

Figure 3. Maximum (peak) friction values for the data of Figure 2. The experiment with a 2.6mm-thick layer is not included because it did not show a peak stress. For shear without gouge, failure obeys criterion (1) and thus the measured friction value is the coefficient of internal friction μ_i. From equation (3), this value predicts that failure via Coulomb plasticity will show an apparent coefficient of internal friction μ_a of 0.9. μ_i and μ_a are calculated assuming that the measured friction value is μ_a and μ_i, respectively. The data show that Coulomb plasticity is met for a mean gouge thickness of 0.58mm.

The results indicate that the stress state required for Coulomb plasticity is not developed within exceedingly thin gouge layers, presumably due to boundary friction with the contacting rough surface. Boundary friction is expected to scale with surface roughness, and thus the transition from criteria (1) to (2) may occur at a critical ratio of layer thickness to asperity height. This ratio is about 0.1 in the present experiments, which implies a critical layer thickness of about 10μm in experiments using ground surfaces, which typically have maximum roughness of 100μm or less. Thus in all previous experiments on gouge layers known to the author failure is governed by criterion (2).

Although equations (2) and (3) follow directly from the Coulomb criteria written in terms of the mean stress and maximum shear stress, only recently has the evidence and implications of these criteria for fault zones and friction been recognized [*Hobbs et al.*, 1990; *Marone et al.*, 1992; *Beeler and Tullis*, 1994]. A simple geometric relationship exists between the failure criteria for intact rock and fault gouge, however, fault zone strength cannot be derived from the strength of intact rock without accounting for differences in the Coulomb parameters.

The weakening effect implied by a transition from standard Coulomb failure to Coulomb plasticity within a fault zone is not of sufficient magnitude to explain the apparent weakness of mature fault zones. However, this effect could augment other weakening mechanisms such as increased pore pressure.

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References

Beeler, N. M. and T. E. Tullis, Implications of Coulomb plasticity for the velocity dependence of experimental faults, *Pure Appl. Geophys.*, in press, 1994.

Brace, W. F., B. W. Paulding, and C. H. Scholz, Dilatancy in the fracture of crystalline rocks, *J. Geophys. Res.*, *71*, 3939-3953, 1966.

Byerlee, J. D., The frictional characteristics of Westerly granite, Ph.D. thesis, MIT, Cambridge, MA, 1966.

Byerlee, J. D., and J. C. Savage, Coulomb plasticity within the fault zone, *Geophys. Res. Lett.*, *19*, 2341-2344, 1992.

Chester, F. M., J. P. Evans, and R. L. Biegel, Internal structure and weakening mechanisms of the San Andreas fault, *J. Geophys. Res.*, *98*, 771-786, 1993.

Hobbs, B. E., A. Ord, and C. Marone, Dynamic behaviour of rock joints, *Proc. Int. Symp. on Rock Joints*, eds. N. R. Barton and O. Stephansson, Loen, Norway, pp. 435-445, 1990.

Lockner, D. A., and J. D. Byerlee, Limits of fault strength due to the constraints imposed by fault geometry (abstract), *Eos Trans. AGU*, *73*, 511, 1992.

Lockner, D. A., and J. D. Byerlee, How geometrical constraints contribute to the weakness of mature faults, *Nature*, *363*, 250-252, 1993.

Mandl, G., L. N. J. de Jong, and A. Maltha, Shear zones in granular material, *Rock Mech.*, *9*, 95-144, 1977.

Marone, C., and W. Durham, Double-direct-shear friction experiments using tension fractures: scaling of constitutive parameters for rock friction to fractally-rough surfaces (abstract), *Eos, Trans. AGU, 73*, 565, 1992.

Marone, C., B. E. Hobbs, and A. Ord, Coulomb constitutive laws for friction: contrasts in frictional behavior for distributed and localized shear, *Pure and Appl. Geophys.*, *139*, 195-214, 1992.

Rice, J. R., Fault stress states, pore pressure distributions, and the weakness of the San Andreas fault, in *Fault Mechanics and Transport Properties of Rocks*, edited by B. Evans and T.-f. Wong, pp. 475-503, Academic Press, 1992.

Scott, D. R., C. Marone, and C. G. Sammis, The apparent friction of granular fault gouge in sheared layers, *J. Geophys. Res.*, *99*, 7231-7246, 1994.

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