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The relationship between strain rate and fracture density under 2D isotropic tension

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Background: *Brittle fracture in fault damage zones alters permeability and storage properties of faulted reservoir rocks; therefore, our ability to predict damage zone size and fracture density based on observable fault properties is highly desirable. Field observations typically show that damage zone width and fracture density scale with fault displacement, but the mechanisms behind this scaling are still enigmatic. Recent work linking simulations of earthquake rupture with borehole observations in petroleum fields has suggested that damage zone formation may be closely related to impulsive stress fields associated with shear rupture. In the numerical simulations, brittle damage is quantified in terms of continuum plasticity, yet the constitutive behavior of brittle rock failure at rapid strain rates is poorly understood. Thus far, experimental constraints on rock failure at near tip strain rates (10^0-10^3 s^{-1}) are largely limited to compressive loading configurations, whereas coseismic damage should be substantially more pervasive in tension.*

To rectify this gap in understanding, I proposed to simulate rock failure under impulsive isotropic tensile stress conditions using a recently developed experimental design, which is a modification of traditional Split Hopkinson Pressure Bar experiments, where a uniaxial compressive pulse is converted to isotropic radial and circumferential tension in a rock disk bonded between two cylinders made of more compliant materials. In particular proposed to study the relationship between volumetric strain rate (under tension) and fracture density by combining different materials in the bonded sandwich structure and comparing most-mortem fragmented rocks to predictions from theoretical fragmentation models.

Progress During Year 1:

During Spring 2018 while the proposal was being considered, I submitted a manuscript on the method and initial results, and it was published in the Journal of Geophysical research in Autumn 2018, soon after the beginning of the first reporting period [Griffith, W. A., St. Julien, R. C., Ghaffari, H. O., & Barber, T. J. (2018). A tensile origin for fault rock pulverization. *Journal of Geophysical Research: Solid Earth*, *123*(8), 7055-7073.]. Key findings in this paper gave us a head start on our research objectives, including:

(i) The fragment size in Westerly Granite during fragmentation experiments is roughly independent of strain rate in the experiments we studied (covering extensional strain rates over half an order of magnitude) (Figure 1)

(ii) Strain energy likely exerts a stronger control on fragment size over these strain rates, so the dynamic tensile strength (which caps the elastic strain energy) is a key parameter in predicting fragment size (Figure 1)

(iii) The tensile strength varies from the static strength (~10^1MPa) up to the shock tensile strength (~10^2MPa) over strain rates ranging from 10^0-10^2 s^{-1} (Figure 2).

We fit our data and explained the relationship with strain energy using a fragmentation model developed by Glenn and Chudnovsky (1986). This theory predicts decreasing fragment size at much higher strain rates expected very close to the slipping zone (Figure 1a), as opposed to the strong strain rate dependence predicted by the Grady (1982) model (Figure 1b). As we continue our research over the next year, we will test the updated hypothesis regarding combined roles of strain rate and strain energy in determining fragment size (and by extension, fracture spacing) using the Glenn and Chudnovsky (1986) model in addition to the classic model of Grady (1982) discussed in the original proposal.

Activities during the first year of the proposal include further experiments with Westerly Granite using different end cap materials (i.e., polycarbonate in place of lead) as well as varying the relative thickness of the rock and end caps to (a) extend the range of strain rates we can consider, and (b) to test the sensitivity of the experimental method to changes in these parameters to determine best practices for further experiments. We have also begun conducting experiments with Berea Sandstone as the rock material. For Westerly Granite, we have been able to extend our dataset in lower strain rates between 10^0 and 10^1 s^{-1} (Figure 2). We have also been able to narrow in to an optimal ratio of lengths of the rock specimens and endcaps to achieve a homogeneous stress field in the rock sample. This has been done with the help of Digital Image Correlation using high speed imagery using a Shimadzu HPV-2 camera in my lab. We will supplement this data with data from lower strain rates (> 10^0 s^{-1}) using a newly installed GCTS servo-controlled load frame that will be installed in the lab in November. Furthermore, we have demonstrated using this method that at high strain rates localized fractures do not form in sandstones. Instead the sample fails by quasi-localized disaggregation and porosity increase. We will quantify this relationship during the next reporting period.

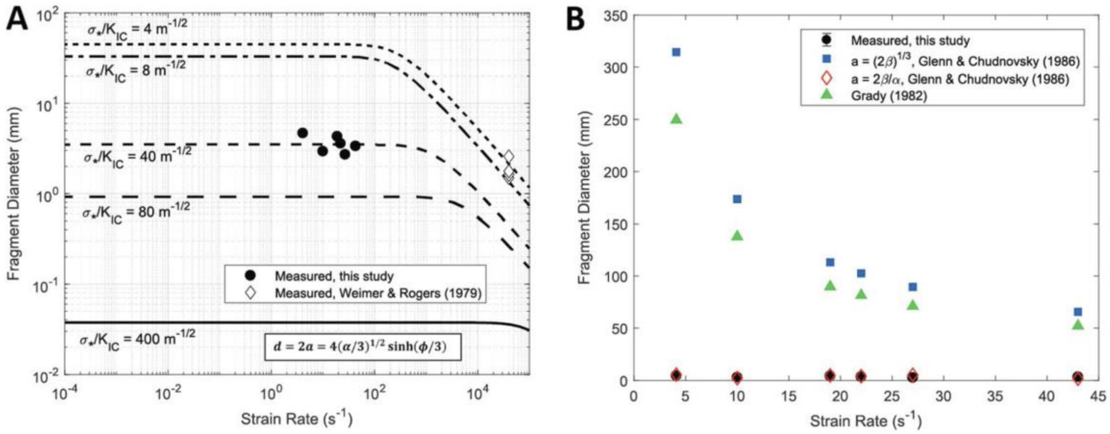

Figure 1 (a) Fragment size versus strain rate predictions for varying ratios of σ^*/KIC compared to data from this study (solid circles) and explosive fragmentation of brittle steel (Weimer & Rogers, 1979). (b) Predictions of fragment size from kinetic energy-dominant regime (solid squares, Glenn & Chudnovsky, 1986), strain-energy-dominant regime (open diamonds, Glenn & Chudnovsky, 1986), and kinetic energy-only (solid triangles, Grady, 1982) compared to six Westerly Granite isotropic tension experiments also shown in (a). (From Griffith et al., 2018).

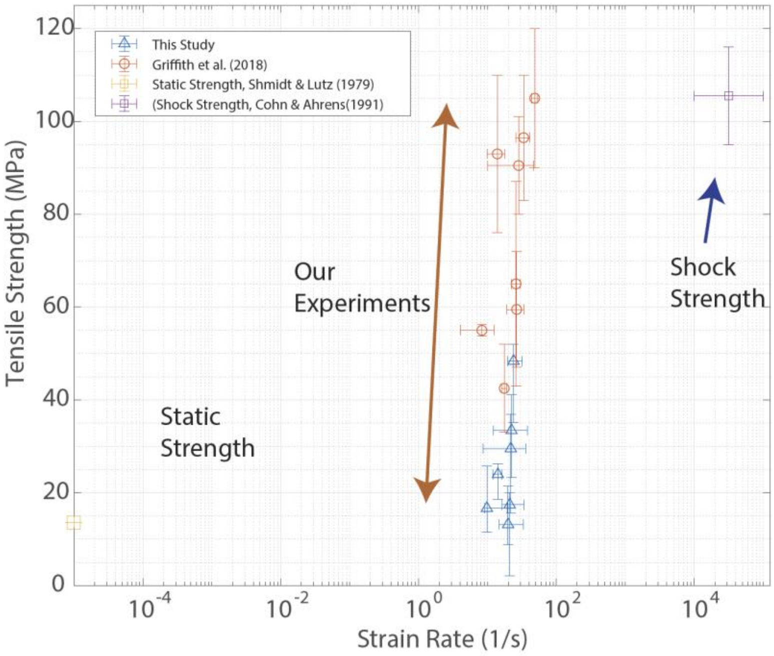

Figure 2. Tensile strength as a function of circumferential strain rate from research sponsored by this project (blue) and those from Griffith et al. (2018) (red) compared to the static strength (light orange) and the shock strength (purple) of Westerly Granite. The larger the strength the larger the strain energy stored in the sample at failure.

Impact on Project Personnel:

This project has supported one new graduate student during the past summer, and two undergraduate students during the first year of the project. Initial results were reported by the PI during the 2019 Southern California Earthquake Center (SCEC) annual meeting (Since the PI is on the Science Planning Committee, his travel was not paid by this grant), and graduate student Zach Smith will report more mature results, supported by this grant, at the 2019 AGU Annual Meeting in San Francisco.