Characteristics of shear localization in brittle-ductile deformation of rocks: An experimental study

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Abstract

Most of the crustal rocks are mechanically heterogeneous due to various types of inherent micro- to macro-scale heterogeneities, e.g., compositional or physical flaws in the form of hard objects, weak zones, voids or pre-existing fractures. Such heterogeneities can greatly influence the modes of brittle as well as ductile deformations under geological conditions. Using laboratory experiments a part of this thesis aims to explore their role in controlling the mechanism of shear localization in elasto-plastic rocks. Commercially available polymers: polymethylmethacrylate (PMMA) and polystyrene (PS) were used as rock analogues (elasto-plastic rheology) in the experiments. Both PMMA and PS show a characteristic property of plastic strain induced permanent optical birefringence, which has been utilized to delineate continuum scale high-strain zones in models. Compression tests were performed on models with desired heterogeneities under plane strain conditions to systematically investigate the problem of heterogeneity-controlled shear band formation. It is demonstrated from PS model experiments that a transition in the plastic creep mechanism gives rise to a spectrum of shear band structures: homogenous to narrow sharp high-strain zones. This study identifies weak mechanical flaws as a crucial parameter to govern the transition in the mode of deformation localization. Homogenous models, without any pre-existing flaws produced uniformly distributed narrow shear bands (NB), symmetrically oriented at ~41°-44° to the compression axis. On the other hand, heterogeneous models produce a completely different band pattern, forming localized composite bands (CBs), with a core of densely packed NBs (at ~46°-49° with compression axis), flanked by transition zones on either side. In addition, decreasing the strain rate from $\acute{\varepsilon}$ (3 x 10^{-5} sec^{-1} to 2 x 10^{-5} sec^{-1}) is found to transform the CBs to well-defined HBs, with a homogenously sheared core bounded by a narrow gradational zone shear localisation. The experimental results are substantiated by numerical simulations to propose the possible mechanism of the shear band growth. PMMA model experiments also showed similar influence of mechanical flaws (incipient cracks) in deformation localization. Their initial geometry (orientation and crack length) critically controls the brittle – ductile transition of deformation localization around them.

Another major direction of this thesis deals with an in-depth topological study of irregular slip surfaces produced by shear localization in brittle-ductile rocks. Field observations in the Singhbhum Shear Zone revealed a type of slickensides in deformed quartzites, characterized by the absence of any hard asperity, which rules out the possibility of mechanical wearing as a possible mechanism of their formation. This thesis reports this unique type of slickensides through extensive field, and analogue experimental study (by sand-talc / talc models) and explores the factors controlling the shear fracture roughness. Shear fractures, in pure talc models, produced by plastic yielding display strong linear roughness, which become more prominent with increasing

fracture orientation (θ) to the compression direction (θ = 30° - 60°). A new computational technique, based on optical image analysis, has been developed to map the surface geometry from field casts and experimental models. From 1D fractal dimension calculations, it is demonstrated ΔD (difference in 1D fractal dimension across and along the slip direction) can be used as an effective mathematical parameter to quantify shear/fault surface roughness. Estimated ΔD from slickensides in naturally deformed quartzites and equivalent laboratory models is found to range from 0.38 to 0.95. Based on field observations, analogue experiments and numerical model simulations, mechanical wave instabilities at the soft interface between two walls is proposed as a potential mechanism for roughness generation in the form of linear irregularities.

Geodetic and seismological evidences suggest that, during shear failure the slip is not quite homogenous, rather it is quite complex, spatially as well as temporally. Such heterogeneous slip distributions have a serious implication in earthquake seismology as well as heterogeneous movements in a single event of faulting, as widely reported in the recent literature. This doctoral work provides a geometrical analysis of slip heterogeneity on fault surfaces. Two distinct roughness domains were identified on sheared quartzites from Singhbhum Shear Zone, marked by strong and weak or no roughness anisotropy. Using analogue laboratory experiments on brittle-ductile models under pure shear condition, the present study shows that shear localization on fault surfaces is partitioned into two domains: i) *slip zones*, defined by slip-parallel lineations and, ii) discrete domains showing little or no slip (called *stuck zones*). The two zones occur with varying geometrical patterns on shear surfaces. A series of analogue laboratory experiments was performed to find the factors governing slip versus stuck zone growth during a fault movement. The experiments indicate the initial fault inclination (θ) to the principal compression direction as one of the crucial factors in dictating their competitive growth. In general, increasing θ facilities the slip zones to dominate over the stuck zones. A fractal analysis is presented to show the use of ΔD in delineating these two roughness domains with contrasting anisotropy, slip zones with slip-parallel linear irregularities (strongly anisotropic), whereas stuck zones devoid of such linearity in their roughness (isotropic). Consequently, ΔD yields the lowest value (0.0036) in stuck zones, and the highest value (0.1735) in the slip zones. The field analysis is supported by experimental data (ΔD = 0.0024 and 0.2118 in stuck and slip zones, respectively).

The thesis finally draws conclusions on the following studies: i) effects of inherent mechanical heterogeneities on the mechanism of shear band formation; ii) control of applied strain rates in the transition of shear band mechanisms; iii) topological characterization of shear fractures in naturally deformed massive quartzites in a ductile shear zone, providing new explanation for the origin of non-abrasive slickenlines; and iv) dependence of shear surface roughness heterogeneities, controlled by slip versus stuck zone growth as a function of the initial shear surface orientation; and v) effectiveness of ΔD as a measure of the degree of anisotropy in surface roughness.

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