International Journal of Rock Mechanics & Mining Sciences 64 (2013) 139–147

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Shear-enhanced compaction in dilating granular materials

Christian Klimczak [a,*], Richard A. Schultz [b]

[a] Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, N.W., Washington, DC 20015-1305, USA
[b] ConocoPhillips, PR2010, 600 North Dairy Ashford, Houston, TX 77079, USA

ARTICLE INFO

Article history:
Received 2 July 2012
Received in revised form
19 July 2013
Accepted 4 August 2013
Available online 21 September 2013

Keywords:
Volumetric deformation
Shear strain
Deformation bands
Dilation bands
Compactive shear bands

ABSTRACT

Compaction of loose, granular materials commonly results in the loss of porosity and, hence, a volumetric decrease of the material by the localization of deformation bands. Different types of deformation bands tend to form at a range of specific angles to maximum compression (σ_1), as documented in numerous field and laboratory studies. Usually, localization of bands occurs at low angles to σ_1 during deformation involving volumetric increase and at higher angles during compaction of the material. Generally in agreement with field and laboratory orientation measurements, several models have been used to obtain the optimum angle deformation band formation with respect to σ_1. However, some field and laboratory studies report deformation bands with substantial compaction across them that have orientations requiring material dilation to be in accord with those models. This discrepancy is explored by modeling the orientations of structures under progressive deformation for all combinations of simultaneous pure and simple shear. Our results allow for shear-enhanced compaction at the onset of dilational shear band formation, thus accounting for both the band orientation as well as the observed compaction within the bands. These findings indicate that compaction localized within a deformation band is not simply related to a total volumetric decrease of the material, since the transition between localization of compaction and dilation is found not to coincide with the transition of volume decrease to increase of the material, and hence to the material's mechanical response at a given stress state.

1. Introduction

Compactional shear bands [1] in the Entrada Sandstone in Arches National Park and near Goblin Valley, Utah, were found to have formed from micro-mechanisms involving substantial porosity reduction by grain crushing [2–4], indicative of a volumetric reduction within the band [e.g. [5]]. However, the orientations of these bands at low angles to maximum compression was related to a dilational material response instead [6]. Interestingly, angular relationships of compactional shear bands from several other localities, compiled in this study, are comparable to those reported from the Entrada Sandstone, indicating that despite the presence of micro-mechanisms indicative of volume decreases across the bands, the initial material response should also have been dilational.

At the scale of an incipient deformation band and with respect to the local stress tensor, volumetric increase within granular materials have been associated with the localization of dilation bands [5]; isochoric deformation, i.e., deformation with no volume change, has been related to the formation of shear bands, and compaction bands are believed to localize in materials undergoing volumetric decrease [1,5,7]. Simultaneous shear and volumetric changes produce dilational or compactional shear bands [1,7] and so-called shear-enhanced compaction bands [e.g. [8]]. Deformation mechanisms in dilation bands include pore growth by disaggregation of grains through grain rolling, grain boundary sliding, and breakage of grain bonding cement. Compaction bands typically display micro-mechanisms such as cataclasis and dissolution transfer [1] that involve physical and chemical porosity decrease by grain breakage and pressure solution, respectively.

Different types of deformation bands tend to develop at specific ranges of angles with respect to the axis of maximum compression, σ_1 (Fig. 1). Pure compaction bands (CB) are generally thought to form approximately perpendicular [9–11], while dilation bands (DB) are considered to form more or less parallel to maximum compression [e.g. [11,12]]. Depending on the stress state and constitutive relations, shearing mode and mixed mode structures can localize at orientations anywhere between 0° and 90° with respect to maximum compression, where compactional shear bands (CSB) [e.g. [6,13–19]] and sheared dilation bands tend to have smaller angles to σ_1 as compared to shear-enhanced compaction bands (SECB) [e.g. [14,16,20]]. For example, several field examples of deformation band orientations with respect to σ_1 are pictured in Fig. 2. Pure compaction bands at Buckskin Gulch, Utah, first described as crooked compaction bands at this field site [21] are localized at ~80°, while shear enhanced compaction bands are oriented at ~40° with respect to maximum compression (Fig. 2a). Sets of compactional

* Corresponding Author. Tel.: +1 202 478 8842; fax: +1 202 478 8821.
E-mail address: cklimczak@ciw.edu (C. Klimczak).

1365-1609/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijrmms.2013.08.012

shear bands in the Orange quarry, France, are oriented at 39° to σ_1 (Fig. 2b). A normal fault (F) oriented at 20° to σ_1 is associated with compactive shear bands of orientations of ~25° relative to σ_1 in the Entrada Sandstone near Goblin Valley (Fig. 2c).

Several empirical and theoretical models are used to predict the optimum angle, α, a fault or deformation band would make relative to σ_1 [22–24]. Theoretical predictions may vary by several degrees among those models [23–26], so that different field or laboratory measurements may be described adequately by different models, depending on rock properties and boundary conditions [23,24].

For a first order estimation and with general applicability to a great variety of materials for which volume change during deformation is not considered, the empirical Mohr–Coulomb failure criterion is widely accepted for inferring the orientations of faults or shear bands. Here, the optimum orientations, α_C, of two conjugate planes of shear failure are oriented at angles of $\alpha_C = \pm(\pi/4-\phi/2)$ relative to maximum compression [27], where ϕ represents the angle of internal friction.

Tying shear deformation band orientation to principal strain increments, the Roscoe orientation, α_R, gives shear band inclinations to σ_1 as a function of the dilatancy angle, ψ, with $\alpha_R = \pi/4-\psi/2$ [6,28]. For plane strain conditions, the dilatancy angle, as introduced by Hansen [29], represents the ratio of plastic volume change to plastic shear strain [30]. The Roscoe relationship is found to yield good orientation estimates in coarse-grained rock [31] and is consistent with typical orientations of shear-enhanced compaction bands [13].

In light of well-known mismatches between the Mohr–Coulomb and Roscoe relationships to experimental measurements for porous granular materials, a so-called hardening-softening model was developed [30], where both internal friction and dilatancy angles relate to the initial shear band orientation:

$$\sin(90^\circ - 2\alpha) = \sin\left(\frac{\phi+\psi}{2}\right)\cos\left(\frac{\phi-\psi}{2}\right) \tag{1}$$

This relationship reduces to:

$$\alpha = \frac{\pi}{4} - \frac{(\phi+\psi)}{4} \tag{2}$$

if the internal friction and dilatancy angles have comparable values [24,30]. Differences between the results of Eqs. (1) and (2) do not exceed 7° even if values for ψ and ϕ are at a large difference of 90° [24]. The relationship given in Eq. (2) also coincides with the empirically derived function of [32–33] and due to its simplicity and minor deviation from the Mohr–Coulomb model, it is widely used in field and laboratory studies [13,15,23,24,32–35].

From the Drucker–Prager yield surface, strain localization and shear band orientations can also be obtained by [36,37]:

$$\alpha = \frac{\pi}{4} - \frac{1}{2}\arcsin\left(\frac{2(1+\nu)(\mu+\beta) - 3N(1-2\nu)}{3\sqrt{4-3N^2}}\right) \tag{3}$$

where ν is Poisson's ratio, μ is the stress state dependent internal friction coefficient relating to the internal friction angle as $\mu = 2\sqrt{3}\sin\phi/(3\pm\sin\phi)$ [e.g., [37,38], and β, the dilatancy factor, relating to ψ in a similar manner than μ to ϕ [e.g., [23,39]. The variable N is a term related to the deviatoric stress state within the rock relating intermediate deviatoric stress to the von-Mises equivalent stress [e.g., [37]. The relation described by Eq. (3) is commonly used in numerical modeling applications [13,26,40–42] and for detailed laboratory experiments [11,15–17,43]. Comparison between the Drucker–Prager and the hardening-softening model derived by Vermeer and de Borst [30] shows that both models yield similar shear band orientations for small positive and negative dilatancy angles with reasonable differences even when ψ and ϕ values differ greatly [24].

In the following, we compile the orientations of several sets of deformation bands from field measurements and values reported in the literature. These orientation values are then used to infer dilatancy angles to further explore the relationship of deformation band orientations to volumetric changes of the material.

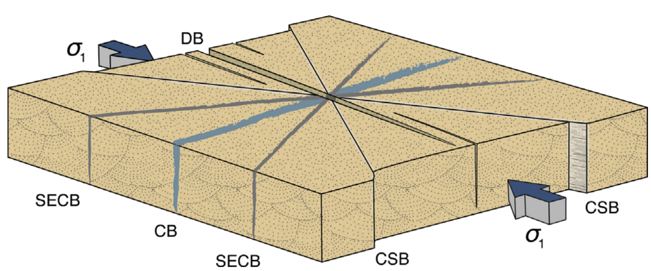

Fig. 1. Schematic of deformation band orientations relative to maximum compression (σ_1).

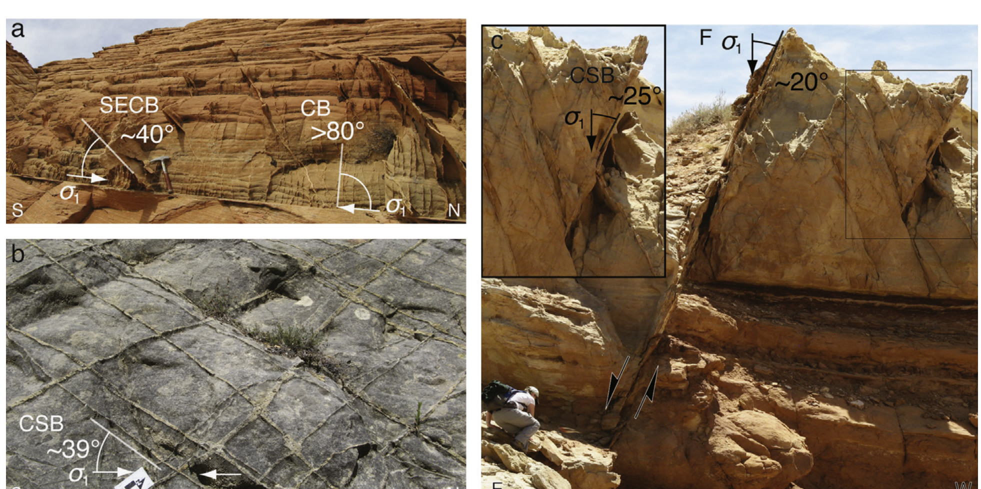

Fig. 2. Fractures and deformation bands relative to maximum compression. (a) Shear-enhanced and pure compaction bands in Navajo Sandstone, Buckskin Gulch, Utah. (b) Compactional shear band network in the Orange quarry, France. (c) Compactive shear bands accompanying a normal fault (F) in the Entrada and Navajo Sandstones, near Goblin Valley, Utah.