EFFECT OF GRAIN SHAPE ON MICROMECHANICAL BEHAVIOR OF SHEARED GRANULAR LAYERS

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Summary Digital Image Correlation (DIC) has been used to experimentally evaluate the evolution of vortex structures in shear bands in sands and glass beads undergoing plane strain compression. We have defined a temporally recurring micromechanical pattern of vortex formation and dissolution that defines the macroscopic critical state and physically relates to observed fluctuations in macroscopic shear stress. Here, we highlight differences in the microstructural responses observed between sand and glass beads.

INTRODUCTION

Densely packed granular solids manifest nonaffine deformation during shear. Various forms of coherent structures, such as force chains, vortices and microbands, arise from mesoscale particles interactions. These structures yield pronounced, local kinematic signatures in the deformation field and are responsible for macroscopic response evolution. Further understanding of these coherent structures and their inter-relation is crucial toward developing advanced physics-based models for granular materials. Most of our understanding about these structures has been derived from numerical research using the discrete element method (DEM). While some experiments have been performed, these, as well as the simulation work, have focused mainly on behavior of circular or rounded particles. Observations in granular materials comprising irregular shaped particles are lacking.

Using Digital Image Correlation (DIC), we capture and characterize microstructural evolution in shear bands in dense granular specimens undergoing plane strain compression. In previous work on sands [1, 2], we observed a temporally recurring, spatially varying kinematical pattern along the shear band. Vortices form during softening, induced by buckling of force chains that initially comprise the shear band. Opposing displacements between adjacent, co-rotating vortices arrest vortex rotation and macroscopic softening and induce the transition into critical state. During critical state, the local grain jamming between co-rotating vortices leads to local volumetric contraction, providing an avenue for formation of new force chains along the shear band. These force chains eventually buckle, inducing new vortices, and the process continues. This microstructural pattern directly correlates with fluctuations in macroscopic shear stress [2].

Here, we show evidence of similar microstructural evolution in a bi-disperse mixture of glass beads. We contrast the character of observed vortices with those seen in sands. We additionally contrast the nature of the macroscopic, critical state shear stress fluctuations as they correlate with microstructural behavior. The results suggest that different modes of frictional dissipation underlie granular shear in dense assemblies comprised of angular versus rounded grains.

EXPERIMENTAL AND ANALYTICAL METHODS

Specimens are subjected to drained, plane strain compression. The zero strain conditions are enforced by glass-lined acrylic walls, permitting image-based tracking of in-plane, grain-scale movements. The specimen rests on a translatable base, and all interfacing surfaces are lubricated, producing minimal boundary effects on the impending shear band. Throughout shear, digital images of in plane deformations are collected at frequent intervals. Two materials were tested. The first was a bi-disperse mixture of glass beads, consisting of 50% by mass each of 1.5 mm and 2.0 mm beads (D_{50} about 1.75 mm). Second was a pre-sieved, mixture of Masonry and Concrete sands (MC sand), resulting in a uniform sand with D_{50} = 0.84 mm.

Digital Image Correlation (DIC) uses mathematical correlation to track patterns of pixel gray level variations contained within small pixel subsets in digital images of a material surface undergoing deformation. A more detailed description of the technique and parameters used is given in [1]. VIC-2D by Correlated Solutions, Inc. was used to conduct the DIC analyses. Due to the discrete nature of unbonded granular materials, DIC analyses had to be performed incrementally. To track the behavior of coherent structures over longer increments, an accumulation algorithm was developed [3].

To pursue detection and characterization of vortex structures and their evolution, we examine fluctuations from the mean shear displacement field. To assess these “residual displacements”, first, the shear band boundaries are delineated by thresholding the displacement norm gradient. Then, a mean shear field is fit across the shear band boundaries and subtracted from the DIC-measured displacements.

SHEAR BAND MICROSTRUCTURES

Our assessment here focuses on the critical state of deformation. Fig 1 shows residual displacements along a shear band in a glass bead specimen over a roughly 12% shear strain increment during critical state. A coherent vortex structure is clearly seen near the centre of the shear band. Similar vortex structures in MC sand were shown in [1, 2]. In glass beads, the vortex is nearly symmetric and rounded. In contrast, in sands, more oblong and nonsymmetric vortices were observed. Just near the right edge of the vortex in Fig. 1, the downward-directed displacement vectors quickly spatially transition to nearly zero displacement (the dots are points below the displacement gradient threshold used to delineate the shear band boundaries). We believe this indicates the presence of a microband. In sands, little evidence of microbands was seen: displacement vectors were mostly seen to converge at the conflux between adjacent vortices [2]. Note also in Fig 1 the opposite-directed rotational “wakes” near the upper shear band boundary. These were similarly observed in sands, and are observed only in displacement increments where vortices are present.

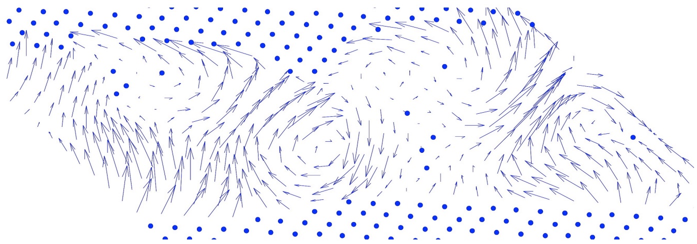

Figure 1. Residual displacements during critical state in glass beads. Sense of shear is top of band moving right relative to bottom.

IMPACT OF MICROSTRUCTURE ON MACROSCOPIC RESPONSE

Fig 2 zooms in on the critical state macroscopic shear stress versus axial strain responses of glass beads (Fig 2a) and MC sand (Fig 2b). Both x- and y-axes are plotted to the same relative scales. Considering the differences in thicknesses of the shear bands, for both, 1% axial strain corresponds to roughly 30% gross shear strain along the shear band. Note that the stress fluctuations in the sand are more pronounced than in glass beads. Noted on the figures are the corresponding microstructures observed in the residual displacement data: J/A = jamming (residual displacement convergence) and/or locally affine-like displacement (in [2], spatially constrained zones affine deformation are associated to semi-stable force chain locations), and V = vortices. In both cases, vortices are associated with local stress drops, and jamming and affine deformations (force chains) are associated with stress levelling or stress rise. The stress drops and rises are consistently smaller in magnitude in glass beads than in sands. Further, in glass beads, the temporal durations over which jamming and force chain growth occur are characteristically shorter. The differences observed here highlight the likely different modes of frictional dissipation that occur between angular and rounded grains: rounded grains are more likely to succumb to frictional slip, whereas angular grains are more constrained by interlocking.

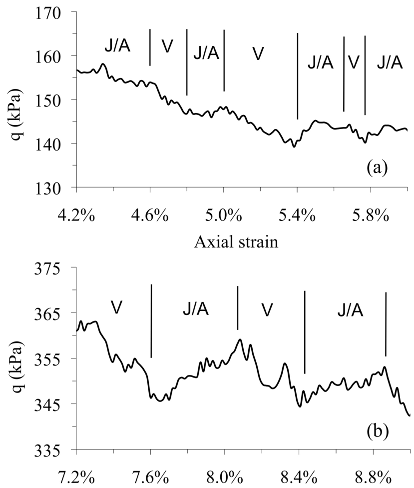

Figure 2. Critical state macroscopic shear stress vs. axial strain for a) glass beads and b) MC sand.

CONCLUSIONS

Displacement fluctuations along persistent shear bands in dense specimens of a uniform sand and a bi-disperse glass bead mixture were analyzed using Digital Image Correlation (DIC). A temporally recurring pattern of local grain jamming and force chain formation, followed by force chain collapse, followed by vortex formation and dissolution are observed in both materials. However, the character of observed vortex structures, the temporal lifetimes of the various coherent mesoscale structures, and the impact of these structures on macroscopic shear stress fluctuation differ between sand and glass beads. These observed differences suggest that interlocking among angular grains leads to different modes of dissipation in sands versus granular assemblies with rounded grains, which are more likely to exhibit inter-grain frictional slip.

References

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