3rd International Conference on Tomography of Materials and Structures
Lund, Sweden, 26-30 June 2017, ICTMS2017-187

FORCE CHAIN EVOLUTION IN GRANULAR MATERIALS UNDER COMPRESSION DETECTED BY X-RAY TOMOGRAPHY AND 3DXRD

Stephen A. Hall[1], Ryan C. Hurley[2], Jonathan Wright[3] & Stefanos Athanasopoulos[1]

[1]Division of Solid Mechanics, Lund University, Sweden
[2]Physical and Life Sciences, Lawrence Livermore National Laboratory, USA
[3]European Synchrotron Radiation Facility, France

Keywords: granular mechanics, 3DXRD, x-ray tomography, in-situ

Summary: The mechanics of a granular material are investigated for a sample of >1000 grains using a combination of x-ray tomography and 3DXRD with image analysis and a force inference methodology. Grain displacements and contact forces plus continuum stresses and strains are followed through a cyclic compression test. The results reveal the evolution of force transfer, in the form of "force chains", including as grains fracture.

1. INTRODUCTION

In recent years, significant progress has been made in exploring the mechanics of granular materials using x-ray tomography to reveal local grain kinematics and how these combine as shear bands during localised failure (e.g., [1]). However, with such approaches, the internal stresses and force transfer mechanisms cannot be resolved. To this end, recent works have explored the use of grain-resolved x-ray diffraction by 3DXRD (e.g., [2][3]) to measure the internal strains of individual grains in granular samples undergoing deformation. Such work has yielded some intriguing results but has previously been limited to smaller numbers of grains. In the current work, the mechanics of granular materials are investigated with a more representative number of grains (> 1000) using a combination of x-ray tomography and 3DXRD with image analysis and a force inference methodology to follow displacements and forces as well as stresses and strains during in-situ oedeometric loading.

2. EXPERIMENTAL METHOD AND RESULTS

The experiment was performed at beamline ID11 at the ESRF. The sample was prepared by pouring 1099 near-spherical, single-crystal ruby grains into an aluminum cylinder of inner diameter 1.5 mm (grain diameters ranged from 124.6 μm to 133.0 μm and the mean diameter was 125.7 μm). The loading included an initial compaction stage, followed by two uniaxial compression cycles up to a force of about 120 N (as recorded on the load cell); see Fig. 1a. At each load step, loading was paused with the piston displacement held constant and 3DXRD and x-ray tomography scans were made using a monochromatic beam of 55 keV. During each scan, the sample was rotated 180° degrees twice; once during which 720 2D diffraction patterns were acquired, for the 3DXRD, and a second time to acquire 1800 transmission radiographs for the tomography. Force relaxation of 2-5 N occurred quickly after loading was stopped for each scan and was recovered upon reloading.

3D tomographic images were reconstructed with a resolution of $(1.54\ \mu m)^3$ per voxel (see Fig. 1b) and processed with binarisation and topological watershed algorithms in Matlab® to segment grains and determine grain volumes, centroids and grain-grain plus grain-boundary contact locations and orientations. The 3DXRD data, from each load step, were analysed using ImageD11 [4] tools to provide the unit cell parameters and centres of mass for the individual ruby grains by indexing, tracking, and fitting diffraction spots. The kinematics of the individual grains were determined by comparing the centres of mass of the grains between load steps (either from the tomography segmentation or the 3DXRD). From these data, the "continuum" 3D tensor strain fields were calculated for each load step over the whole sample using 3D Delaunay triangulations.

The crystal unit cell parameters from the 3DXRD analysis were used to determine the individual grain strain tensors based on the changes relative to a reference, unloaded unit cell for each grain. Subsequently, based on the assumption of an elastic-brittle behaviour, the grain stresses were determined using anisotropic elastic constants for ruby. From these data and the grain kinematics, it was also possible to determine the "macroscopic" sample stress-strain response to compare to the boundary measurements from the loading device. Furthermore, using the contact locations and orientations from the segmented tomography images and the grain stresses from the 3DXRD, it was possible to obtain the contact forces for each load step, based on the developments of [5][6].

Figure 1(c) shows the calculated contact force network and grain stresses determined form the 3DXRD and the corresponding continuum strain field from the Delaunay tessellation of the grain centres and their displacements for one of the load steps. Clear preferential pathways of force transfer can be observed, i.e., "force chains", which evolve through the unload cycle and reorganise as individual grains are seen to break.

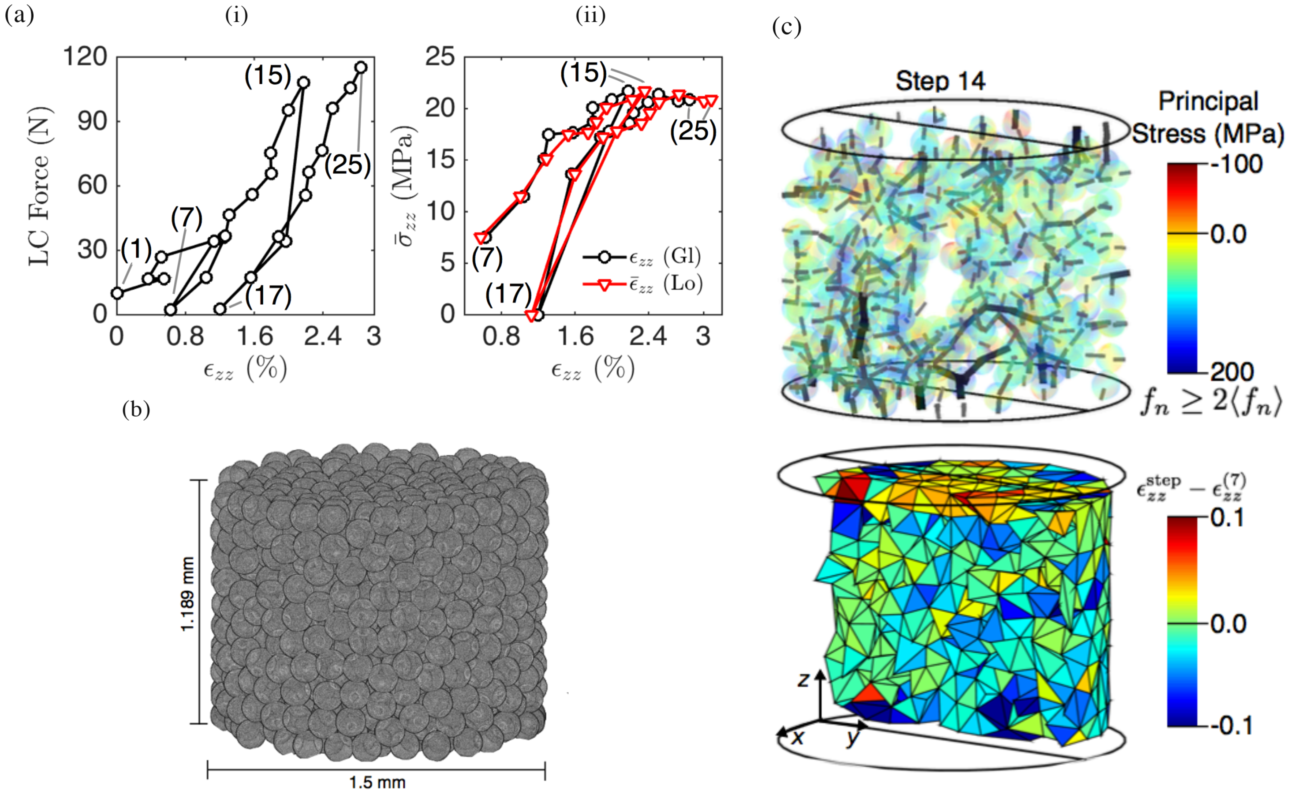

Figure 1: (a) Stress strain curves for the loading using stresses based on (i) the load cell of the device and (ii) the grain stresses derived from the 3DXRD data; the sample strain was determined by $\varepsilon_{zz} = (z_{top} - z_{bot})/h_0$, where z_{top} and z_{bot} are the z coordinates of the top and bottom piston surfaces in contact with the grains, respectively, and $h_0 = 1.189$ mm was the initial height of the sample. (b) 3D rendered image of the sample consisting of 1099 near-spherical, single crystal ruby grains. (c) (upper) Contact force network for load step 14 with only forces greater the twice the average shown with corresponding grains. Forces are shown as lines, centered at the corresponding contact points, scaled linearly in width and length with total magnitude. Grains are colored by principal stresses and given 70% transparency. (lower) Local vertical strains in each tetrahedron of the Delaunay triangulation (only nodes with coordinate $x \leq 0$ are plotted to reveal the interior of the field).

References

[1] Andò, E., Hall, S.A., Viggiani, G., Desrues, J. and Bésuelle, P., 2012, Experimental micromechanics: grain-scale observation of sand Deformation, Géotech. Lett., 2, 107–112

[2] Hall, S.A., Wright J., 2015, Three-dimensional experimental granular mechanics. *Géotech. Lett.* 5, 236–242.

[3] Hurley, R.C., Hall, S.A., Andrade J.E. and Wright J., 2016, Quantifying interparticle forces and heterogeneity in 3D granular materials. *Phys. Rev. Lett.,* 117, 098005.

[4] Wright, J., ImageD11 software, https://sourceforge.net/p/fable/wiki/imaged11/

[5] Hurley, R.C., Lim, K., Ravichandran, G. and Andrade J.E., 2016, Dynamic inter-particle force inference in granular materials: Method and application. *Exper. Mech.* 56, 217–229.

[6] Hurley R.C., Marteau, E., Ravichandran, G. and Andrade J.E., 2014, Extracting inter-particle forces in opaque granular materials: beyond photoelasticity. *J. Mech. and Phys. of Solids*, 63, 154–166.