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Measurement of higher-order stress-strain effects in granular materials undergoing non-uniform deformation

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Highlights

- Discrete element (DEM) simulations were conducted on two-dimensional assemblies of three sizes and with particles of three shapes. After an initial stage of biaxial compression, the initial rectangular assemblies were deformed in two different ways: in a uniform, biaxial manner and in a non-uniform manner that produced a flexural bending of an assembly. The latter simulations produced a field of non-uniformstrain and a gradient of the particle rotations. The simulations demonstrate that granular materials are non-simple, meaning that the incremental stiffness of a granular assembly depends on the gradients of the strain increment as well as on the strain increment itself. In the quasi-static simulations, the two-dimensional granular assemblies were stiffer when the imposed deformation was nonuniformthan for uniformdeformation. The stiffer behavior is evidence of an internal lengthscale for granular materials. This result is also manifest in the effect of assembly size on the loading stiffness: larger assemblies exhibit softer behavior. The results are interpreted in the context of a higher-order micro-polar continuum, which admits the possibility of higherorder stress and couple-stress. Although the behavior was non-simple, no evidence was found for a couple-stress or an associated stiffness, as the contacts between particles were modeled as linear–frictional contacts with no contact moments. The measured absence of a Cosserat stiffness – a stiffness associated with the spatial gradient of micro-scale rotation–should discourage the use of micro-polar continuum models for granular materials. The experimental results apply consistently to three particle shapes (circles, ovals, and a nonconvex cluster shape), to assemblies of three sizes (ranging from 250 to 4000 particles), and at pre-peak and post-peak strains. This result suggests that a length-scale should be directly incorporated within the constitutive form: that granular materials should be modeled as non-simple materials, in which stress and stiffness depend upon both strain and the gradients of strain.