CaliParticles: A Benchmark Standard for Experiments in Granular Materials

Caliper Consortium

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1 Introduction

Granular materials are discrete particulate media that can flow like a liquid but also be rigid like a solid±[1]. This complex mechanical behavior originates in part from the particles shape±[2, 3, 4, 5, 6, 7]. How particle shape affects mechanical behavior remains poorly understood. Understanding this micro-macro link would enable the rational design of potentially cheap, light weight or robust materials. To aid this development, we have produced a set of standard particle shapes that can be used as benchmarks for granular materials research. Here we describe the collection of benchmark shapes. Some part of the particles are modeled on superquadrics±[8, 9], others are custom designed. The particles used so far were made from polyoxymethylene (POM) whose specifications are also listed. The benchmark shapes are available as molds in a plastics manufacturing company, whose contact information is also included. The company is capable of making other molds as well, giving access to more particle shapes. The same particle shapes can thus also be made in different types of (colored) plastic, and in amounts of 50.000 particles or more, larger than conveniently be produced with a 3D printer. We also provide the associated .step and .stl files in the repository in which this document is included.

2 Convex particles

Most granular materials are composed of non-spherical particles. The first group of such particles deviate from the ideal spherical shape in one direction only: they are elongated or flattened. Ellipsoids are one of the simplest geometrical forms for such shapes. Recent numerical codes can already model the interaction of ellipsoidal grains. In a shear flow, such ellipsoids will rotate and perform complex dynamics due to their interactions. The goal of laboratory experiments with the custom made ellipsoids is twofold: (i) to quantitatively characterize this dynamics, focusing on individual particle motion during shear deformation of the granular material using CT or optical (high speed imaging) observations and

(ii) determine, how the bulk flow properties (e.g. effective friction or discharge rate and flow field in a silo) change with increasing aspect ratio of the grains.

2.1 Oblate particles

Oblate particles correspond to a special case of ellipsoids where the shape can be characterised by two large axis $a_1 = a_2$ and a small axis a_3. Although it correspond to a first level of complexity, it has been shown that the increase of aspect ratio for presents an effect on the shear strength and the volumetric response of a granular assembly. The latter can be explained due to the competition between particle sliding and rotation. Additionally, interparticle friction can be though as a key parameter that controls directly the interaction between dry particles. The relation between these two parameters and the deformability and strength for dry granular assemblies is one of open questions for granular mechanics. Given the difficulty of performing particle-based measurements on physical experiments, Discrete Element Method (DEM) simulations have been used as the traditional tool to explore the latter.

However, the use of x-ray computed tomography directly allows the quantitative observation of the evolution of granular assemblies under deviatoric loading. To understand the role of inter-particle friction and aspect ratio on 3D physical experiments, two different sets of particles are ordered under two different surface configuration. The first group correspond to oblate particles with an aspect ratio of 1.5 with a rough and smooth surface (0403 ellipsoid_lentil_2 and 0403s ellipsoid_lentil_2_R on Table 2). The second group of particles correspond to oblate particles with an aspect ratio of 1.1 with a rough and smooth surface (1206 ellipsoid_lentil_5_R and 1206 ellipsoid_lentil_5_R on Table 2). Using x-ray tomography, the assembly is scanned each 0.5 percent of axial shortening. Particles are identified at the initial image and followed through the test Additionally, inter-particle contacts are identified and their respective orientation is measured.

Preliminary results have shown that the particle shape presents a strong influence on the initial packing of the specimen, where the particle orientation distribution displays a stronger initial arrangement for higher aspect ratios, independent of the inter-particle friction. However, once the specimens are subjected to deviatoric loading the resulting kinematic field is directly a function of the particle shape and friction. On-going analysis is focused on the effects of the latter parameters on the morphology of strain localisation, and specifically, its relation with the particle-scale deformation modes (*i.e.*, sliding vs. rotation).

3 Non-convex particles

The second group of grains deviating from the spherical shape are particles with bumps on their surface in several directions. Geometrical forms as spherotera-hedrons, tetrapods, or hexapods are the simplest shapes, which can be modeled by DEM simulations. These grains present even more complex dynamics during shear flow, their shear resistance can be much larger than that of ellipsoids, involving clumping due to their non-convex nature.

4 Polyoxymethylene properties

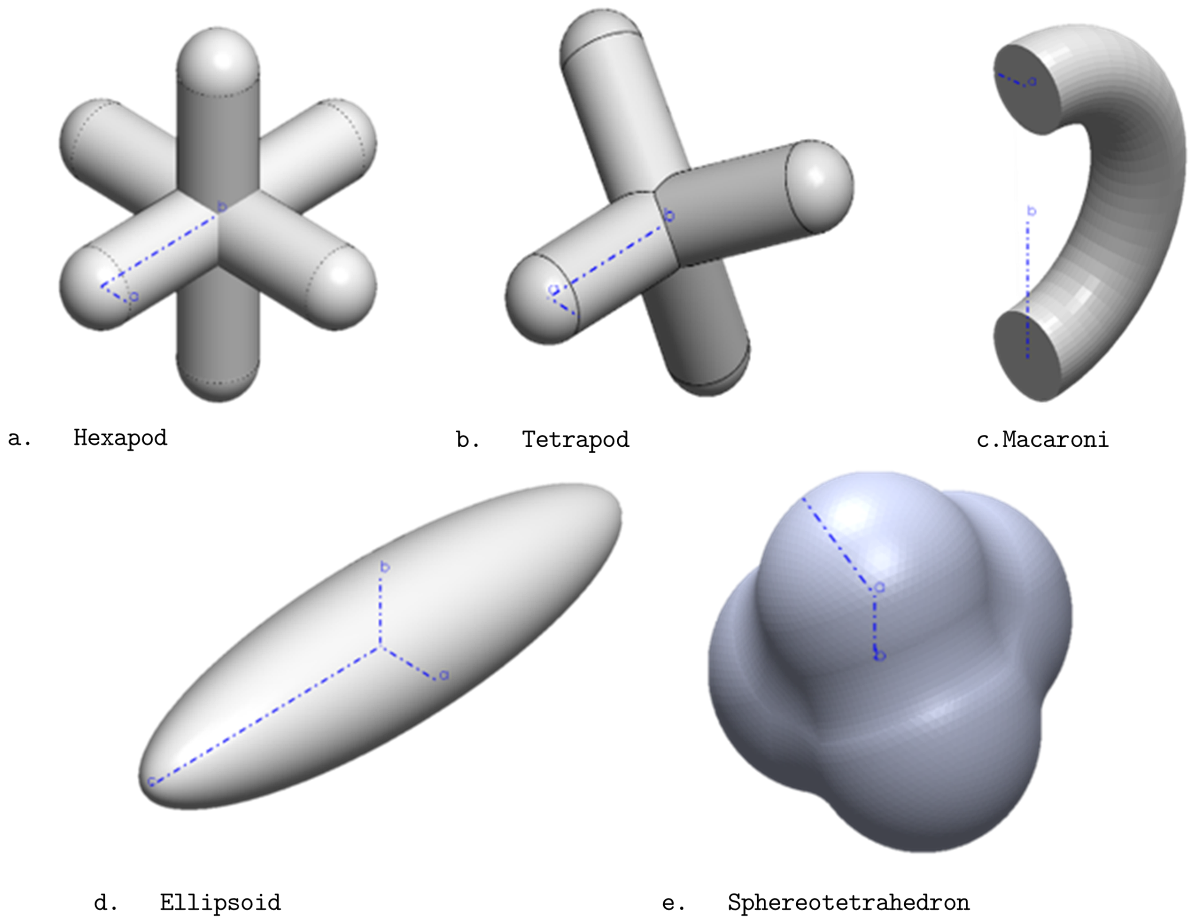
Table 1: Material properties of polyoxymethylene (POM).

Description			
Catalog	Improved general polyformaldehyde		
Properties	Acid resistant	High wear resistant	High hardness
	Antisepsis	Good chemical stability	high strength
	Alkali resistant	Good dimensional stability	Low coefficient of friction
	Solvent resistant	Good electric property	Low contraction ratio
	Fatigue resistant	Good fluidity	Copolymer
Application	Electric and electronic device	Various kinds of parts	Thin-wall part
	Automotive exterior part	Gear	Valve part
	Automotive interior part/bearing	In-line pump part	Roller
Color	White particle		
Molding method	Injection molding	Extrusion molding	

Physical properties	value	unit	Testing standard
density	1.41	g/cm^3	ISO 1183
Melt flow rate (190°C/2.16Kg)	9.0	g/10min.	ISO 113
Water absorption (24h, 23°C)	0.12	%	ISO 62
Mechanical property	value	unit	Testing standard
Tensile strength	63	MPa	ISO 527-2
Tensile modulus	2650	MPa	ISO 527-2
Elongation at break	40	%	ISO 527-2
Bending strength	89	MPa	ISO 178
Flexural modulus	2550	MPa	ISO 178
Charpy notched impact strength	6.5	KJ/m^2	ISO 179/1eA
Thermal property	value	unit	Testing standard
deflection temperature underload	90	°C	ISO 75
Combustion performance	value	unit	Testing standard
Combustibility	HB	class	UL94

5 Digital drawings

The digital drawings are available in .step (ISO 10303) en .stl format. In the attached "Custom particles overview.xlsx" file and in Table 2 are the specifications of the custom particles. The filenames are formed from the order date, type of particle, increment numbering and optional surface finish. The dimensions are different for each type of particle and the reference images of these dimensions can be found in Figure 1. Section 6 lists all the relevant files and their location. The digital drawings may not include the location of the defects induced by the injection molding, process. The choice for the location of the $< mm$ sized defect depends in the use of the particles.



a. Hexapod b. Tetrapod c.Macaroni

d. Ellipsoid e. Sphereotetrahedron

Figure 1: Custom particles with measurement lines

Table 2: Specifications of the custom particles.

Order date	Description/filename	a (mm)	b (mm)	c (mm)	Surface finish
3/4/21	0403_ellipsoid_lentil_1	1.75	2.75	2.75	smooth
3/4/21	0403_ellipsoid_rice_1	4.95	1.65	1.65	smooth
3/4/21	0403_ellipsoid_lentil_2	1.10	1.70	1.70	smooth
3/4/21	0403_ellipsoid_lentil_2_R	1.10	1.70	1.70	rough
3/4/21	0403_sphereotetrahedron_1	2.65	1.22		smooth
3/4/21	0403_sphereotetrahedron_2	2.43	1.62		smooth
3/4/21	0403_ellipsoid_sphere_1	2.37	2.37	2.37	smooth
6/12/21	1206_ellipsoid_sphere_1	3.50	3.50	3.50	smooth
6/12/21	1206_ellipsoid_rice_1	3.30	3.30	3.95	smooth
6/12/21	1206_ellipsoid_rice_2	3.06	3.06	4.59	smooth
6/12/21	1206_ellipsoid_rice_3	2.78	2.78	5.56	smooth
6/12/21	1206_ellipsoid_rice_4	2.21	2.21	8.81	smooth
6/12/21	1206_ellipsoid_lentil_1	3.72	3.72	3.10	smooth
6/12/21	1206_ellipsoid_lentil_2	4.00	4.00	2.67	smooth
6/12/21	1206_ellipsoid_lentil_3	4.41	4.41	2.21	smooth
6/12/21	1206_ellipsoid_lentil_4	5.56	5.56	1.39	smooth
6/12/21	1206_hexapod_1	2.08	2.02		smooth
6/12/21	1206_hexapod_2	1.66	3.34		smooth
6/12/21	1206_hexapod_3	1.46	4.38		smooth
6/12/21	1206_hexapod_4	1.33	5.31		smooth
6/12/21	1206_hexapod_5	1.23	6.18		smooth
6/12/21	1206_ellipsoid_lentil_5	1.70	1.50	1.70	smooth
6/12/21	1206_ellipsoid_lentil_5_R	1.70	1.50	1.70	rough
6/12/21	1206_ellipsoid_rice_5	1.14	1.14	7.00	smooth
6/12/21	1206_ellipsoid_lentil_6	3.60	3.60	1.00	smooth
6/12/21	1206_macaroni_1	5.1	2.5		smooth
1/17/22	1701_tetrapod_1	1.25	4.75		smooth
1/17/22	1701_ellipsoid_lentil_1	4.40	3.24	4.40	smooth
1/17/22	1701_ellipsoid_lentil_1_R	4.40	3.24	4.40	rough
1/17/22	1701_ellipsoid_rice_1	1.39	1.39	7.00	smooth

6 Folder tree

```
/
├── Overview.xlsx
├── 202134
│   ├── Ellipsoid
│   │   ├── 0403 ellipsoid lentil 1.STEP
│   │   ├── 0403 ellipsoid lentil 1.stl
│   │   ├── 0403 ellipsoid lentil 2.STEP
│   │   ├── 0403 ellipsoid lentil 2.stl
│   │   ├── 0403 ellipsoid lentil 2 R.STEP
│   │   ├── 0403 ellipsoid lentil 2 R.stl
│   │   ├── 0403 ellipsoid rice 1.STEP
│   │   └── 0403 ellipsoid rice 1.stl
│   ├── Sphere
│   │   ├── 0403 ellipsoid sphere 1.STEP
│   │   └── 0403 ellipsoid sphere 1.stl
│   └── Sphereotetrahedron
│       ├── 0403 sphereotetrahedron 1.STEP
│       ├── 0403 sphereotetrahedron 1.stl
│       ├── 0403 sphereotetrahedron 2.STEP
│       └── 0403 sphereotetrahedron 2.stl
├── 2021612
│   ├── Ellipsoid
│   │   ├── 1206 ellipsoid lentil 1.step
│   │   ├── 1206 ellipsoid lentil 1.stl
│   │   ├── 1206 ellipsoid lentil 2.step
│   │   ├── 1206 ellipsoid lentil 2.stl
│   │   ├── 1206 ellipsoid lentil 3.step
│   │   ├── 1206 ellipsoid lentil 3.stl
│   │   ├── 1206 ellipsoid lentil 4.step
│   │   ├── 1206 ellipsoid lentil 4.stl
│   │   ├── 1206 ellipsoid lentil 5.step
│   │   ├── 1206 ellipsoid lentil 5.stl
│   │   ├── 1206 ellipsoid lentil 5 R.step
│   │   ├── 1206 ellipsoid lentil 5 R.stl
│   │   ├── 1206 ellipsoid lentil 6.step
│   │   ├── 1206 ellipsoid lentil 6.STL
│   │   ├── 1206 ellipsoid rice 1.step
│   │   ├── 1206 ellipsoid rice 1.stl
│   │   ├── 1206 ellipsoid rice 2.step
│   │   ├── 1206 ellipsoid rice 2.stl
│   │   ├── 1206 ellipsoid rice 3.step
│   │   ├── 1206 ellipsoid rice 3.stl
│   │   ├── 1206 ellipsoid rice 4.step
│   │   ├── 1206 ellipsoid rice 4.stl
│   │   ├── 1206 ellipsoid rice 5.step
│   │   └── 1206 ellipsoid rice 5.stl
│   ├── Hexapod
│   │   ├── 1206 hexapod 1.step
│   │   ├── 1206 hexapod 1.stl
│   │   ├── 1206 hexapod 2.step
│   │   ├── 1206 hexapod 2.stl
│   │   ├── 1206 hexapod 3.step
│   │   ├── 1206 hexapod 3.stl
│   │   ├── 1206 hexapod 4.step
│   │   ├── 1206 hexapod 4.stl
│   │   ├── 1206 hexapod 5.step
│   │   └── 1206 hexapod 5.stl
│   ├── Macaroni
│   │   ├── 1206 macaroni 1.step
│   │   └── 1206 macaroni 1.stl
│   └── Sphere
│       ├── 1206 ellipsoid sphere 1.step
│       └── 1206 ellipsoid sphere 1.stl
└── 2022117
    ├── Ellipsoid
    │   ├── 1701 ellipsoid lentil 1.STEP
    │   ├── 1701 ellipsoid lentil 1.stl
    │   ├── 1701 ellipsoid lentil 1 R.STEP
    │   ├── 1701 ellipsoid lentil 1 R.stl
    │   ├── 1701 ellipsoid rice 1.STEP
    │   └── 1701 ellipsoid rice 1.stl
    └── Tetrapod
        ├── 1701 tetrapod 1.STEP
        └── 1701 tetrapod 1.stl
```

7 Supplier

YUYAO STRONG COMPANY
No. 1, East Yongxing Road
East Suburbs Industrial Zone
Yuyao Zhejiang
China
Tel: +86-574-22689655
Fax: +86-574-62630201
E-mail: strongthirteen@vip.163.com

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