NUMERICAL SIMULATIONS OF LOW-SPEED IMPACT DISRUPTION OF COHESIVE AGGREGATES USING THE SOFT-SPHERE DISCRETE ELEMENT METHOD AND COMPARISON WITH EXPERIMENTS ON SINTERED-GLASS-BEAD AGGLOMERATES.

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Introduction: Thanks to the increasing performance of ground-based observations and to the images obtained by space missions, we have an expanding data set regarding the physical properties of the small bodies of our Solar System, showing a great diversity in terms of sizes, shapes and morphologies. Moreover, we also know that these bodies undergo various kinds of processes, such as impacts, shaking, and spin ups/downs during their lifetime. Therefore, it is important to understand how the physical properties of small bodies influence their response to those processes, and how in turn those processes may modify their physical properties. We have adapted the *N*-body code *pkdgrav* [1] to model the behavior of cohesive aggregates under various kinds of stresses. More precisely, we implemented both the Hard-Sphere Discrete Element Method (HSDEM) and the Soft-Sphere Discrete Element Method (SSDEM) into the code, as well as the ability to bind particles together using spring-like restoring forces characterized by a Young's modulus and a strain limit to failure. As a validation test, we compare impact experiments on sintered-glass-bead agglomerates to simulations under the same conditions. In general, numerical codes of fragmentation are required to simulate the catastrophic disruption of a small body at high impact speed by computing the crack propagation throughout the body, eventually leading to fragment production (see e.g. [2]). However, in the considered impact experiments, the impact speeds are small enough that the fragmentation is driven by the breakage of bonds between individual beads and not by the fragmentation of individual beads themselves, which makes our adaptation of *pkdgrav* appropriate in principle. The aims of this study are (1) to establish the validity of simulating the salient physics involved in impact experiments adapted to the modeling using our numerical code; (2) to quantify how both laboratory and computational parameters affect outcomes; and (3) to justify using this computational method to explore low-speed impact outcomes involving gravitational aggregates with weak cohesion, and then to apply it to other processes, such as rotational fragmentation resulting from YORP spin-up.

Numerical Model: In the HSDEM version of the code *pkdgrav*, the gravitational interaction between up to millions of hard spherical particles is computed and collisions between them are detected in advance. Collisions are then treated as instantaneous bounces with dissipation parameterized by normal and tangential coefficients of restitution [3]. In the version adapted to model cohesive aggregates, spring forces between particles, following Hooke's law plus an inelastic damping component, are used to mimic cohesion [4,5]. The SSDEM has recently been implemented to account in a more realistic way for contact forces between particles and the different kinds of friction that can occur during contact, such as static, dynamic, rolling and twisting friction [6].

Numerical Simulations: Impact experiments on sintered glass bead agglomerates consisting of 90 5-mm-diameter beads have been performed [7]. Our numerical model is in principle perfectly adapted to simulate these experiments, as the targets can be modeled using spheres with similar sizes as the real glass beads, connected by springs whose forces mimic the measured strength between glass beads. Note that the neck between beads developed by the sintering process is solid and different from the neck due to van der Waals force expected for fine particles. We started performing numerical simulations aimed at reproducing the impact experiments with speeds from 40 to 280 m/s that were performed on agglomerates with 40% porosity and two different bulk tensile strengths [7].

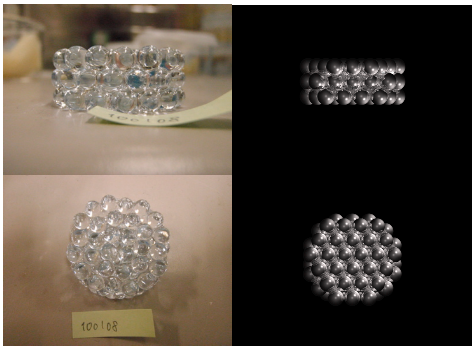

Figure 1: left: experimental target consisting of a sintered glass bead agglomerate; right: modeled target consisting of soft spheres bound together by spring forces. Side and top views are shown.

Figure 1 shows pictures of a real target and images of a computationally modeled one. For the latter, the parameters of the spring forces that bind the particles to one another (Young modulus, damping) were adjusted to be consistent with measured strengths between the real beads.

A first numerical test was performed consisting of simulating the Brazilian disk test on the modeled target, which allows for the determination of the tensile strength (see Fig. 2). The same test was applied to real targets. The breaking of the targets in simulation imply similar tensile strengths as the real ones. We could thus verify that the mechanical properties of our modeled targets are similar to the real ones, as well as the ability of our numerical code to simulate such experimental tests. We then simulated an impact of a small projectile with a speed of 78 m/s. The result shows that the simulation reproduces remarkably well the experiment in terms of the resulting fragment size distribution (see Fig. 3), noting that two experiments on the same target will exhibit scatter. Fragments consist either of individual beads whose links with other beads were fully broken, or of cohesive agglomerates of different sizes depending on the number of particles that comprise them. Results will also be presented for an experiment performed at a different impact speed, showing that our code allows us to simulate well experiments performed at different impact energies. We will also show simulations over some range of the parameter space, allowing us to analyze the sensitivity of the outcome to various kinds of parameters that represent different physical properties.

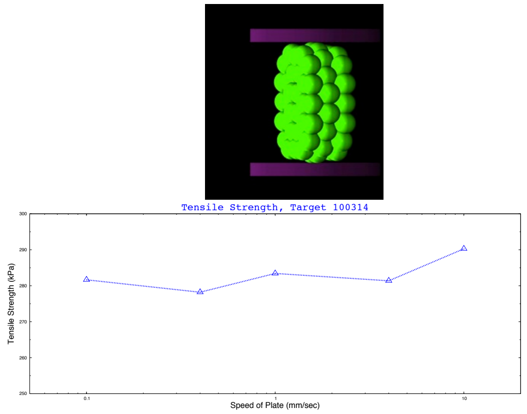

Figure 2: Top: image of a simulation of the Brazilian Disk Test on a modeled target. The purple horizontal bars are placed on the top and bottom of the target (in green), and a vertical velocity is applied to them in the direction of the target. The magnitude of the velocity imposes a given strain rate. Bottom: tensile strength at which the modeled targets break as a function of the applied strain rate.

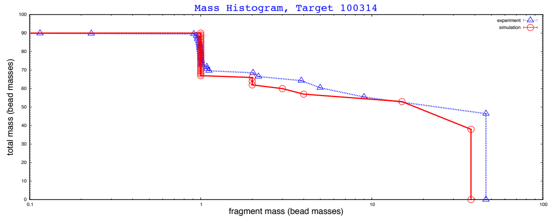

Figure 3: Fragment size distribution obtained in the simulation (red) and in the experiment (blue) for the impact of a projectile at 78 m/s.

Conclusions and perspectives: We adapted the *N*-body code *pkdgrav* to model cohesive aggregates, which can be used to represent small Solar System bodies that contain some degree of cohesion. We have begun performing a validation test consisting of a comparison with low-speed impact experiments on sintered-glass-bead agglomerates. Following this validation, we have covered some range of the parameter space and determined the sensitivity of each parameter [5]. We plan to explore the behavior of such cohesive aggregates under other conditions, e.g. the rotational excess due to YORP spin-up that can lead to their disruption and has shed light on the formation of binaries starting from purely gravitational aggregates [8].

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