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Simulation of granular materials with the discrete element method to investigate their suitability as crash-absorber in ship collisions

Sonja Kraus[1,*], **Christian Woitzik**[1], **Maksym Dosta**[2], and **Alexander Düster**[1]

[1] Numerical Structural Analysis with Application in Ship Technology (M-10), Hamburg University of Technology
[2] Institute of Solids Process Engineering and Particle Technology (V-3), Hamburg University of Technology

In recent years, the idea of increasing the crash-worthiness of ships by filling their double hull structure with granules has been studied. To this end, different granular materials have been investigated in [1, 2] with the result, that expanded glass materials are best suited for this purpose. Based on this work, it is important to gain deeper insights into the breakage behavior of expanded glass particles performing numerical investigations. The corresponding simulation procedure as well as the computational results are presented in this contribution.

1 Introduction

Every year, the BSU counts several ship collisions. Some of these collisions have a major impact on the environment due to the leakage of oil or other pollutants. To increase collision safety, the already existing double hull of ships can be filled with a granular material. A series of experiments was conducted in [3] to investigate the crushing behavior of the granular material. These experiments are used to validate numerical computations based on the discrete element method (DEM). The granular material applied in this work is Poraver® expanded glass, which presents some challenges due to its porosity (Fig. 1a) and shape diversity (Fig. 1b). This leads to a large scatter in the stress-strain curves when individual grains are crushed, see Fig. 2.

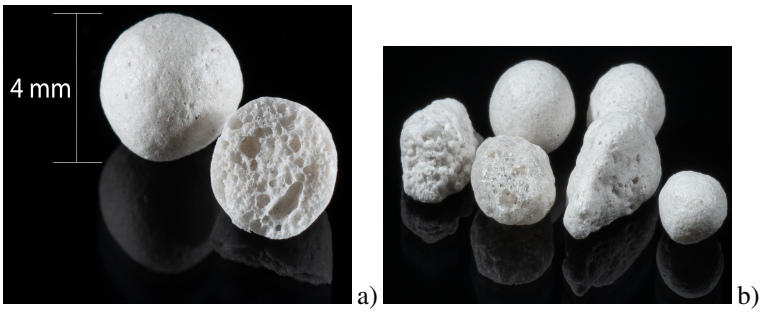

Fig. 1: Porosity and shape of Poraver ® particles

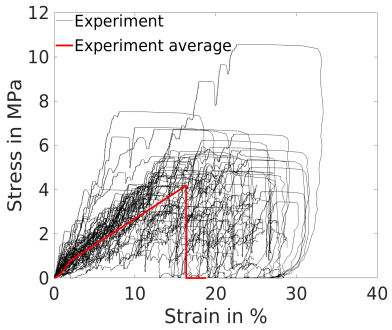

Fig. 2: Uniaxial pressure test results

2 Numerical approach

For the investigation of the granular material the DEM simulation tool MUSEN [4] is used. MUSEN simulates the dynamic behavior of discrete rigid bodies as follows. First, for each particle all relevant neighbors are ascertained. After that the resulting contact forces between neighbors are computed with a Hertz-Mindlin contact model. Using these forces the Newtonian equations of motion in translation and rotation are solved with an explicit time integration scheme. The particles are computed with a bonded-particle model i.e. they are simulated as agglomerates consisting of primary particles connected through solid bridges – also called bonds – which can be seen in Fig. 3. This allows the simulation of particle breakage. Two different bond models are used in this work. The first, introduced by Potyondy [5], is based on the beam theory and schematically depicted in Fig. 4. The second bond model is extended to account for partial failure due to micro cracks in the grains, see Fig. 5.

3 Simulation setup and results

First, a uniaxial pressure test in which single particles are crushed between two metal plates is simulated and compared with the experimental results. Thus, the correct material parameters corresponding to the crushing behavior are found. These simulations are performed with both bond models, leading to the resulting stress strain curves shown in Fig. 6. The second bond model, which takes into account micro cracks, leads to the green curve, matching the gradient (dashed red curve) of the average experiment results in red quite well. Also shown next to the stress-strain curve is the number of remaining bonds, illustrated with dashed curves, that disappear over the course of the simulation. The first model has a large number of bonds

* Corresponding author: e-mail sonja.kraus@tuhh.de, phone +49 40 42878-4764

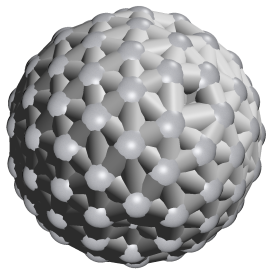

Fig. 3: Agglomerate

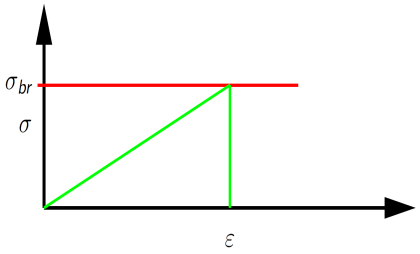

Fig. 4: Bond model 1

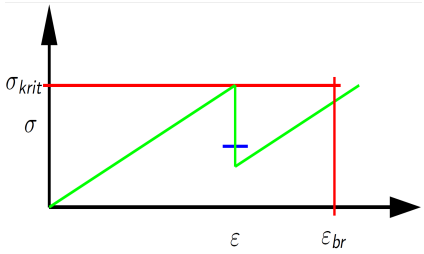

Fig. 5: Bond model 2

disappearing at once, in contrast to the second model, which leads to a more uniform disappearance of bonds. With respect to the non-spherical shape of the grains, Fig. 7 shows the result of a slightly flattened agglomerate in purple, computed with model two, compared to the green curve from Fig. 6 computed with a spherical agglomerate. The flattening of the agglomerate leads to an almost perfect match with the averaged experimental results.

Since the granules under investigation are to be used in a large number to fill the double hull of ships, the behavior of this larger number of granules interacting with each other has to be examined, too. Therefore, an Oedometer test is performed and simulated, in which the material is filled into a rigid cylinder and compressed by the upper plate. Only spherical agglomerates are used for the simulation. To obtain the best possible agreement between simulation and experiment, the number of grains used in the experiment was counted and the average particle diameter and sample weight were measured. In addition, the simulated particles do not all have the same diameter, but are divided into three diameter fractions as described in [3]. Fig. 8 shows the experimental setup for the Oedometer test with a 50 mm cylinder containing 7.1 g of Poraver ® particles. The simulation results compared to the experimental results are illustrated in Fig. 9. The Odometer test was also simulated with both bond models. Again, it can be seen that the result with model two agrees better with the experiment. For the first 30 % of strain, the blue curve slightly underestimates the stress and after 30 % strain the stress increases more than in the experiment. This may be due to the simplification caused by the use of spherical agglomerates, which leads to a less stiff material behavior. The stress increase in the second half of the simulation arises from disappearing bonds and remaining primary particles, which cannot be broken further and thus press against the upper plate.

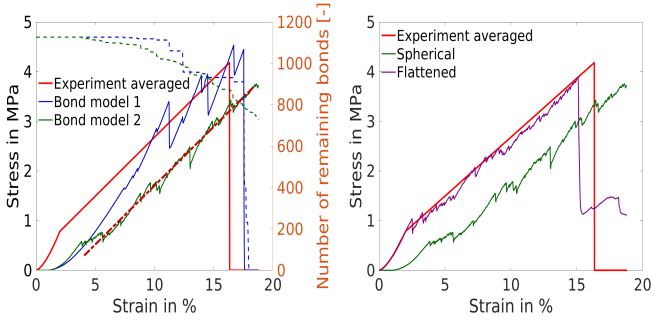

Fig. 6: Uniaxial pressure test with both bond models

Fig. 7: Unixial pressure test with different agglomerate shapes

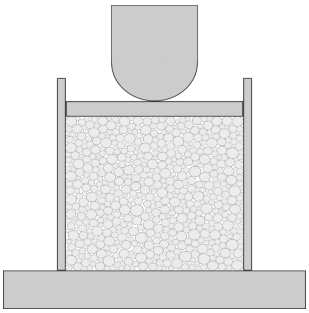

Fig. 8: Oedometer test setup

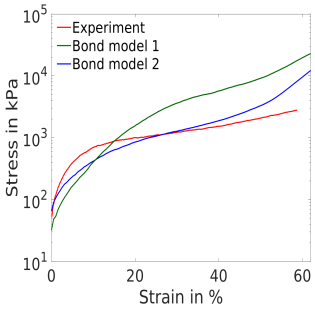

Fig. 9: Oedometer test results

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