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DEM-FEM coupled numerical investigation of granular materials to increase crashworthiness of double-hull vessels

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In this contribution, a novel design strategy is investigated for improving the crashworthiness of double-hull vessels, which involves usage of granular materials. For numerical simulation, a framework based on coupling of the Discrete Element and the Finite Element Method is used to study load bearing capacity of granular materials during uniaxial compression. In addition, the effect of Young's modulus of particles is also investigated with respect to the load transferability.

1 Introduction

Improving crashworthiness of double hull vessels is an important subject as damage to ships can have significant economical and ecological consequences. Several strategies exist to improve crashworthiness, for instance, Schöttelndreyer et al. [1] investigated a modified design of the bulbous bow to effectively absorb impact energy without causing significant damage to the ship. Another design approach, which is investigated here, involves usage of granular material inside the hull of a ship. This strategy provides a granular material between the outer and the inner hull. The granulate serves to transfer the load of the outer hull to the inner hull and absorbs kinetic energy. Therefore, impact energy is shared between the two hulls, in contrast to localized impact on the outer hull only. However, usage of such materials requires better understanding of their mechanical properties under different loading conditions. Therefore, mechanical response of granular materials is investigated during confined compression. For numerical simulation, the Discrete Element Method is used for modeling of granular materials as it can effectively capture discontinuous deformation behaviour along with finite rotation.

2 Discrete element method

The Discrete Element Method (DEM) is based on the assumption that material, referred here to as particles, is rigid but soft at a given region of contact. These particles have translational and rotational degrees of freedom assigned to their center of mass. Interaction of particles takes place via contact forces computed from their overlapped distances. Contact forces are used to update the velocity and displacement of particles using the equation of motion integrated with a explicit time integration scheme. Here, the DEM framework based on the work of Wellmann and Wriggers [2] is used, which incorporates coupling between the DEM and Finite Element Method (FEM). The normal contact force is calculated using Hertzian contact theory,

$$\mathbf{F_N} = F_N \boldsymbol{n} = \gamma E^* \delta^{3/2} \boldsymbol{n} \quad \text{with} \quad \frac{1}{E^*} = \frac{1-{\nu_1}^2}{E_1} + \frac{1-{\nu_2}^2}{E_2} \tag{1}$$

where γ is a function of principle radii of curvature of the interacting particles and δ is their overlapping distance in direction of the common normal $\boldsymbol{n}$. For tangential contact, the Mindlin theory is used where the contact force is integrated over time and bounded by Coloumb's criteria. Interaction of particles with the finite elements is implemented via contact forces between the mesh surface and particles.

3 Uniaxial compression

Uniaxial compression tests provide ample insight into the mechanical behaviour of granular materials. It is an ideal setup to replicate the configuration of particles confined in the hull during collision and predict the load bearing capacity of particles. One indispensable phenomenon in confined compression is fragmentation/crushing of particles. Particles loaded beyond their critical strength are susceptible to fragmentation. Several strategies exist for inclusion of fragmentation. To account for computational efficiency, new particles are introduced during run time rather than predefining an agglomerate of particles in

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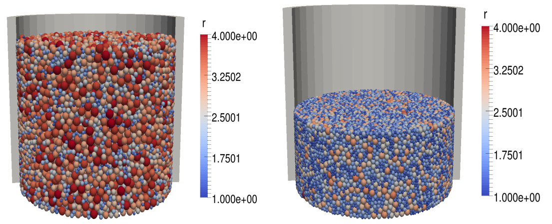

Fig. 1: Configuration of particles. Initial configuration (left), final configuration (right)

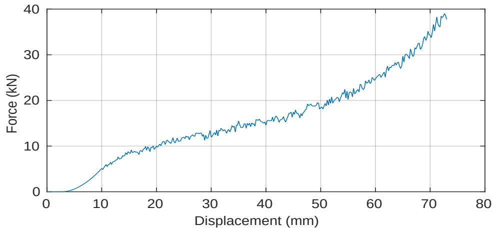

Fig. 2: Load displacement curve for uniaxial compression.

the numerical model. A bi-parametric strength criterion [3] is used for the crushing of particles, taking into account a modified form of the Hertzian contact theory [4],

$$F_N \leq \left[\sigma_{lim,0} \frac{d}{d_0}^{-3/m} \pi \left(\frac{3r^{'}}{4E^{'}}\right)^{2/3}\right]^3 \quad \text{with} \quad \frac{1}{E^{'}} = \frac{1-{\nu_1}^2}{E_1} + \frac{1-{\nu_2}^2}{E_2}, \quad \frac{1}{r^{'}} = \frac{1}{r_1} + \frac{1}{r_2}. \tag{2}$$

where $\sigma_{lim,0}$ is the limit strength of particles with size d_0 and m is a shape fitting parameter. In equation (2), the size effect on the strength of particles is taken into account using a Weibull-like statistical model. Figure 2 shows the load-displacement curve obtained from uniaxial compression of granular materials. It can be observed that the load required to compress particles increases exponentially in the beginning but initiation of crushing results in a change of the slope of the curve (also observed in experimental results [1]). Some parameters used for the DEM and FEM part are $E^{DE} = 200MPa$, $\nu^{DE} = 0.23$, $\sigma_{lim,0}^{DE} = 68MPa$, $E^{FE} = 69GPa$, $\nu^{FE} = 0.32$, $\mu^{DE-FE} = 0.1$. It should be noted that the results are of qualitative nature while experimental determination of material parameters is part of future work.

In addition, a parametric study is also carried out to investigate the effect of the stiffness of the particles on the load transferability. A distributed load is applied to one end of a FE based hollow box (with elastic material) shown in figure 3 and the resultant displacement of the opposite wall is calculated. Here the displacement of nodal points along the center line of opposite wall is plotted (figure 4), which is normalized with the length (L) of the box. It can be interpreted that the stiffness of the particles plays an important role concerning the load transferability.

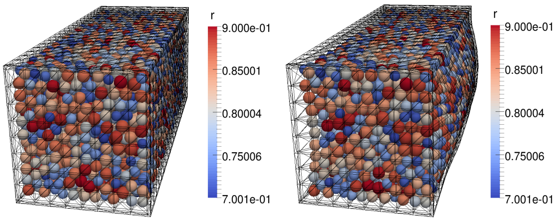

Fig. 3: Particles confined in a hollow box discritised with finite elements. Initial configuration (left), final configuration (right)

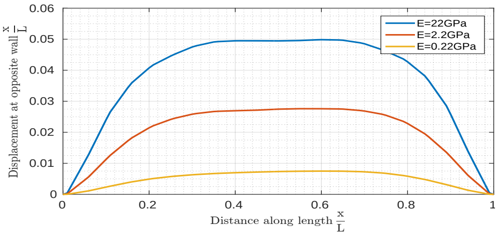

Fig. 4: Effect of the Young's modulus of the particles on the load transferability.

In conclusion, the behaviour of granular materials is simulated during confined compression. It is observed that the inclusion of fragmentation of particles captures the behaviour observed in the experiment. In addition, the effect of Young's modulus of the particles on the load transferability is also investigated. In future, a detailed analysis of the above shown impact problem will be carried out, where damage and plastic behaviour of the material will also be considered for the finite element simulation.

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