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Failure initiation and propagation of Li_4SiO_4 pebbles in fusion blankets

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ABSTRACT

Lithium orthosilicate (Li_4SiO_4) pebbles are considered to be a candidate as solid tritium breeder in the helium cooled pebble bed (HCPB) blanket. These ceramic pebbles might be crushed during thermomechanical loading in the blanket. In this work, the failure initiation and propagation of pebbles in pebble beds is investigated using the discrete element method (DEM). Pebbles are simplified as mono-sized elastic spheres. Every pebble has a contact strength in terms of critical strain energy, which is derived from a validated strength model and crush test data for pebbles from a specific batch of Li_4SiO_4 pebbles. Pebble beds are compressed uniaxially and triaxially in DEM simulations. When the strain energy absorbed by a pebble exceeds its critical energy it fails. The failure initiation is defined as a given small fraction of pebbles crushed. It is found that the load level for failure initiation can be very low. For example, if failure initiation is defined as soon as 0.02% of the pebbles have been crushed, the pressure required for uniaxial loading is about 2.5 MPa. Therefore, it is essential to study the influence of failure propagation on the macroscopic response of pebble beds. Thus a reduction ratio defined as the size ratio of a pebble before and after its failure is introduced. The macroscopic stress–strain relation is investigated with different reduction ratios. A typical stress plateau is found for a small reduction ratio.

1. Introduction

Pebble beds are integral parts of fusion reactors as solid breeder and neutron multiplier in the HCPB blanket [1,2]. The blanket contains two types of pebbles, ceramic breeder (lithium compound, such as Li_4SiO_4) and neutron multiplier (beryllium). During the operation of fusion reactors, pebbles will expand because of high temperatures in addition to thermal stresses introduced by the thermal mismatch between the pebble beds and container wall. This may lead to the failure of ceramic pebbles. It is foreseen that pebble failure will affect the overall thermomechanical response of pebble beds [3]. Therefore, the knowledge of pebble failure initiation and propagation in pebble beds is necessary for a safe and reliable design of the HCPB blanket.

The discrete element method (DEM) [4] is suitable to compute the motion of a large number of particles constituting a granular material, such as a pebble bed. This method has been already used to investigate the mechanical or thermal response of pebble beds for non-crushable pebbles [5–9]. For example, An et al. [5] show that packing factor (PF) and bed geometry have an impact on the mechanical stiffness of pebble beds. The packing factor is the ratio of the volume of all pebbles to the volume of the particle assembly, i.e., pebble bed. The significant influence of the PF can also be seen using periodic boundary conditions [7]. Thermomechanical properties of pebble beds, such as thermal stress or creep due to thermal expansion or external pressure, have been investigated by DEM as well [6,8,9]. On the other hand, particle failure can be taken into account into the DEM method as long as the particle strength can be quantitatively described and imported into DEM. For example, Marketos and Bolton [10] assume that particles will fail if the maximum contact force exerted on them exceeds a critical value. In their DEM simulations, pebbles are removed once they are crushed. In the research activities related to fusion engineering, although there are some papers concerning the strength of single pebbles [11–13], no work has been reported on the influence of pebble failure on the overall response of pebble beds.

In this work, we will include the pebble–pebble contact strength into DEM to study pebble failure initiation and propagation. For this purpose, we employ the pebble strength formulated in terms of strain energy, as it has been derived from a verified strength model [13]. This approach relies on experimental data. We will first focus on the load levels for the initiation of pebble failure under different loading conditions. For the identification of this load level, two different methods are used. In order to simulate the propagation of pebble failure, a reduction ratio of pebble size is introduced to characterize the presence of crushed pebbles. We discuss in detail

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the influence of pebble failure on the overall response of pebble beds.

This paper is organized as follows. The DEM code and pebble contact strength used in this work will be introduced in Section 2. Two methods identifying the load level for failure initiation are shown in Section 3. The influence of pebble failure propagation on the overall response of pebble beds will be presented in Section 4. Finally, conclusions are made in Section 5.

2. Simulation methods

2.1. Discrete element method

The DEM code developed at Karlsruhe Institute of Technology (KIT) will be used here [7]. The normal and tangential contact forces are calculated from Hertz contact theory and a linear friction model, respectively. A separate code provides a random initial configuration, namely the positions of the centers of the mono-sized spherical particles, at a prescribed packing factor, such that there is no overlapping of any particles in the assembly [7]. Periodic boundary conditions are employed, by which only a comparably small number of particles in a representative volume element (RVE) is needed to obtain statistical information on the bulk behavior of a pebble bed. In this way, this boundary condition leads to a limitation of the computational efforts for simulations.

In this work, a periodic assembly of 5000 spheres in a cubic box is considered which is subject to periodic boundary conditions. The edge length of the box is about 8 mm. In view of Li_4SiO_4 pebbles for fusion breeding blanket applications, Young's modulus and Poisson's ratio of the spheres are chosen as $E = 90$ GPa and $\nu = 0.25$ [12], respectively. The spheres have a size of 0.5 mm which is the mean size of Li_4SiO_4 pebbles from the batch OSi 07/1 produced for breeding blanket applications [13,14]. The friction coefficient is set to $\mu = 0.1$ unless otherwise specified. The shear stiffness in the friction model is $16G^*/3$ where $G^* = 55$ GPa is the equivalent shear modulus for Li_4SiO_4 pebbles [13]. Uniaxial and triaxial load, respectively, will be applied under displacement control on the pebble beds. As mentioned before, we focus on the load level for failure initiation and on the macroscopic stress–strain relation along with failure propagation.

2.2. Pebble strength

According to the strength model adopted in this work, a pebble fails if the strain energy absorbed by it reaches a critical level. For the case of the Li_4SiO_4 pebbles considered in this work, this criterion has been developed, verified and discussed in full detail in [13,15]. The probability density function (PDF) of the contact strength, i.e., critical strain energy of pebbles, is given by

$$p_s(W_c) = \frac{m}{W_{\text{Mat}}}\left(\frac{W_c}{W_{\text{Mat}}}\right)^{m-1} \exp\left(-\left(\frac{W_c}{W_{\text{Mat}}}\right)^m\right), \qquad (1)$$

where W_c is the critical strain energy, m and W_{Mat} are material parameters. For these material parameters, the values $m = 3.2$ and $W_{\text{Mat}} = 8.2 \times 10^{-6}$ J, have been identified for pebbles with a diameter of 0.5 mm from the mentioned batch OSi 07/1 under fusion relevant conditions, that is, the pebbles were subjected to high temperature and dry inert gas. In DEM simulations, a critical energy is distributed randomly among pebbles according to Eq. (1). The method to assign the critical energy to each pebble will be given later in Section 3.2.

We recall, that a pebble will fail if the strain energy it has actually absorbed exceeds its individual critical energy. Assuming that there is no interaction between different contact areas of a pebble, the strain energy for pebbles in pebble beds can be calculated by

$$W_a = \sum_{i=1}^{N_c} cF_i^{5/3}, \qquad (2)$$

where N_c is the coordination number, i.e., the number of contacts, of the pebble, F_i is the contact force of ith contact($i = 1, 2, \ldots, N_c$), and c is a constant derived from Hertz theory given by

$$c = \frac{1}{5}\left(\frac{9}{16R^*}\right)^{1/3}\frac{1}{E^{*(2/3)}}. \qquad (3)$$

Here, R^* is the relative radius of curvature, and E^* is the equivalent Young's modulus. For a contact between mono-sized spherical pebbles, $R^* = R/2$ and $E^* = E/(2(1-\nu^2))$, where R, E and ν are the radius, Young's modulus and Poisson's ratio of pebbles, respectively.

3. Prediction of failure initiation in a pebble bed

In this section we will introduce two approaches for the prediction of the initiation of pebble failure in a pebble bed. The first method relies not only on numerical simulations based on DEM but also analytical analysis, while the second one is completely numerical. Furthermore, both methods will be discussed and compared.

3.1. Numerical-analytical method

The basic assumption of the first method is that the distribution of the actual strain energy absorbed by pebbles and the distribution of the strength of single pebbles in terms of critical strain energy are two independent events. Furthermore, we assume that both events are not affected by the failure of pebbles, which seems to be acceptable as long as only a small number of pebbles have failed in the pebble bed.

For the case that the failure of spheres would be dominated by the maximum contact force, the failure probability of all spheres, i.e., the number of crushed spheres divided by the number of all spheres, has been derived by [10]

$$P_f = \int_{F_{\min}}^{F_{\max}} p_s(F = \Phi)\tilde{P}(F > \Phi)\,d\Phi, \qquad (4)$$

where the integration variable Φ represents the critical contact force, while $F_{\min}$ and $F_{\max}$ are the minimum and maximum contact strength (critical contact force) for the spheres which are given arbitrarily in their DEM simulations. $p_s(\Phi)$ or $p_s(F = \Phi)$ is the PDF of the contact strength. The notation $\tilde{P}(F > \Phi)$ means the probability of the maximum contact force exerted on a sphere being larger than Φ. For continuous distributions, $\tilde{P}(F > \Phi) = \int_{\Phi}^{\infty} p(\Phi)d\Phi$ where $p(\Phi)$ is the PDF of the maximum contact force on every sphere obtained in DEM simulations.

Eq. (4) can be adopted for other strength models, such as the critical energy distribution in our case, giving

$$\begin{aligned} P_f &= \int_{W_{\text{cmin}}}^{W_{\text{cmax}}} p_s(W_c = \Phi)\tilde{P}_e(W_a > \Phi)\,d\Phi \\ &= \int_{W_{\text{cmin}}}^{W_{\text{cmax}}} p_s(\Phi)(1 - P_e(\Phi))\,d\Phi, \end{aligned} \qquad (5)$$

where the integration variable Φ now represents the critical energy of pebbles, W_{cmin} and W_{cmax} are the minimum and maximum critical energy for pebbles, $p_e(\Phi)$ and $P_e(\Phi)$ are the PDF and the cumulative density function (CDF), respectively, with respect to the absorbed strain energy W_a in pebble beds. Similar to $\tilde{P}(F > \Phi)$, $\tilde{P}_e(W_a > \Phi)$ means the probability of the strain energy absorbed by