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Fractal behavior and shape characteristics of fragments produced by the impact of quasi-brittle spheres

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ABSTRACT

Impact induced fragmentation has been extensively studied in mechanical, geotechnical, aerospace and mining communities due to its direct relevance to a variety of engineering applications. In the present work, we investigated the fragmentation of quasi-brittle spheres subjected to a range of impact velocities using the combined finite and discrete element method (FDEM) coupled with a rate-dependent cohesive zone fracture model. The statistics of fragment mass distribution and shape characteristics are collected and interpreted using fractal analysis. The fragment mass distribution can be described by a power law with the exponential coefficient depending on the impact velocity. Whereas some previous experimental and numerical studies have revealed a high degree of robustness of the exponent against the impact velocity. At higher velocities, the concentrated local stress at the contact point initiates an increased number of microcracks which evolve into finer fragments as the kinetic energy converts to surface energy during the comminution. Such mechanism results in finer post-impact fragment size distributions that correspond to higher power law coefficients. The variation of fragment shape with respect to impact velocity is characterized by the Domokos shape descriptor and aspect ratio. It is found that all the fragment shapes will cease their variation and reach stable distributions as the impact velocities elevate. The variations of fracture patterns, the two largest fragments, and the average fragment mass with impact velocity are in good qualitative agreement with the existing experimental and numerical results. The present study demonstrates that the combined FDEM coupled with the cohesive zone model is a promising tool in fragmentation studies for its physical soundness and its convenience in conducting detailed post-impact fragment size and shape analyses.

1. Introduction

Impact induced fragmentation of solid particles has been intensively studied by various research communities due to its direct relevance to aerospace engineering [1], pharmaceutical production [2] and rock comminution [3]. For example, spacecraft and satellites are constantly exposed to possible impacts by space debris during service. Thus, understanding the impact process and the subsequent fragmentation becomes critical to improving the safety and the longevity of space activities [4]. In the case of rock engineering, there is also abundant literature concerning rock fragmentation subjected to blast loading or continuous milling [5,6]. These studies mainly focus on predicting fragment sizes and establishing energy input and fragment size relations via experimental observation and numerical simulation, which have important implications in defense evaluation, milling efficiency, and explosive mining. Particularly, the efficiency of the rock disintegration process can be improved, the energy necessary to achieve a given size distribution can be reduced, or the number of fragments resulting from the fragmentation process can be minimized. Many of these studies, however, have focused on the macroscopic behavior of granular assemblies with the microscale attributes of single breakage events smeared in a statistical sense. The present study aims at improving the fundamental understanding of the fragmentation of a single solid particle subjected to impact loading, the result of which can be potentially integrated with recent micromechanically based continuum models [7].

Experimental studies of either the single or double impact of individual spheres have been largely employed to understand the complex fracture mechanisms that govern the fragmentation process [8–14]. It has been widely observed that during impact, plastic deformation develops first around the contact point and forms a fracture cone with ring cracks. Such ring cracks soon propagate through the particle through the meridian plane and eventually split the particle [8,9]. Meanwhile, there are many semi-empirical models on the dynamic comminution or fragmentation of rocks, concrete, metals, and ceramics,

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where the fragmentation has been explained by the branching of dynamically propagating cracks. However, the application of these models for dynamic finite element analysis is not straightforward due to their lack of a continuum basis [15]. Bažant and his co-workers [7,16] proposed a continuum damage model to capture concrete comminution subjected to missile impacts. The essential idea of this model is that the grain-to-grain interface can be fractured when subjected to a high shear strain rate, leading to the release of local kinetic energy and comminution of the bulk material. The continuum-based approach is advantageous in that the energetics and physics of fracture propagation can be directly taken into account.

In parallel with continuum modeling, discrete element modeling (DEM) has been used to explore the detailed fracture process during an impact event. The application of DEM in impact fragmentation dates back to Potapov and Campbell [17] and Thornton et al. [18–20], followed by a large number of researchers [21–30]. Among these studies, a critical velocity that separates the particle response from damage to fragmentation (often referred to as a phase transition) was first identified by Thornton et al. [18] and later confirmed by Kun and Herrmann [22]. Timár et al. [31] have proposed scaling laws for impact fragmentation of spheres with different sizes and impact velocities. The effects of impact angle [23,24], impact velocity [25], material property (e.g., interface energy) [26,27], agglomerate packing density [28], dominant fracture mechanism [29], and material microstructure [30] on the fracture pattern and fragment mass distribution were also investigated. The impact breakage behavior of non-spherical agglomerates has also been studied by DEM approaches [32,33]. The advantages of discrete-based approaches are manifested in their ease in handling a massive number of fragments and their interactions (e.g., collisions, frictions). In both laboratory tests and numerical simulations, the impact angle [23,24,34,35] and impact velocity [17–25,34,35] have been considered to be two of the main controlling variables of fragment patterns and thus have been extensively investigated. The above numerical and experimental studies revealed that the fragment mass distribution follows a power law with the exponent insensitive to material properties and loading conditions [36]. However, there are few studies on the fragment shapes resulting from impacts [37,38].

Noticing the abovementioned advantages of continuum-based finite element modeling (FEM) and discrete-based DEM numerical approaches, we use the combined finite element method and discrete element method (FDEM) to study the fracturing and comminution of granular materials. FDEM is a time-explicit numerical method initially developed by Munjiza et al. [39,40], which combines continuum mechanics with DEM algorithms to simulate multiple interacting deformable solids. FDEM has been successfully used in the modeling of impact fragmentation of different kinds of materials [41–45]. In this method, materials are first discretized into a number of finite element meshes that are in contact with each other by interfaces. Further, within each particle mesh, the finite elements are interbedded with cohesive interface elements that incorporate a fracture constitutive law. In such a way, finite element analysis is conducted within individual particles, resulting in a more accurate estimate of contact forces and local stress fields and further enabling the computation of crack initiation and propagation in a more accurate and rational manner. After fragmentation is generated, the contact algorithm is immediately assigned to the newly created surfaces to allow for complex interactions with other bodies, similar to a DEM simulation. In summary, the combined FDEM inherits the advantages of continuum-based method in capturing the plastic deformation around the contact point and the complex stress state inside the sphere as well as the capability of discrete-based algorithm in modeling a large number of particle assemblies. The combined FDEM can also provide more details of the fragmentation process, i.e., high-resolution fragment shapes, and the process of energy transformation and dissipation [46,47].

In the current study, we limit our attention to a single particle subjected to high-velocity impact. FDEM can be readily extended to study the comminution of a batch of particles. The primary goal is to validate the physical soundness and the numerical stability of the combined FDEM and cohesive element scheme. A spherical grain is simulated to facilitate a direct comparison with the previous experimental and numerical studies, while the influence of grain geometry on fragmentation is not considered [46]. The effects of impact velocity on the fractal behavior and shape characteristics of the fragments are the main focus of this study, as there are few studies on the fragment shapes resulting from impact. The constitutive law of the cohesive model and post-processing method are briefly introduced in Sections 2 and 3, respectively. A mesh convergence analysis is performed to determine the optimal finite element mesh size compromising both numerical accuracy and simulation efficiency. A series of impact tests of a quasi-brittle sphere is then simulated with varying impact velocities. The simulation results are analyzed in terms of the fragment size distribution and the statistical distribution of various shape descriptors in Section 4.

2. Single grain impact simulation using FDEM

2.1. Constitutive law of cohesive interface elements

Among many computational techniques for modeling fracture propagation, the cohesive zone model combined with FEM or FDEM has demonstrated advantages in convergence and convenience in implementation [48]. The cohesive zone model can also account for the effect of material bending, aggregate interlocking, and surface friction in the fracture process zone (FPZ) by adopting the proper constitutive laws. In this hybrid approach, fracture is explicitly represented by the cohesive interface elements (CIEs) along inter-element boundaries, which can be either updated stepwise (i.e., the extrinsic approach) [49] or remain unchanged throughout the computation (i.e., the intrinsic approach) [50]. Due to the vast number of fractures and fragmentations involved in the impact comminution problem, we employed the intrinsic approach combined with refined meshes to achieve the desired computational efficiency. The zero-thickness CIEs are embedded a priori between all volumetric elements, which are 10-node tetrahedral elements in this study [51]. The physical justification of this model is that solids such as rocks or concrete are essentially composed of individual grains or aggregates that are connected by interfacial bonds or cementations [52]. These microstructures can be numerically represented by unbreakable solid elements joined by zero-thickness cohesive elements, as in other more comprehensive numerical schemes such as the Lattice Discrete Particle Method (LDPM) [53].

The traction-separation behavior of fracture zone interfaces for different materials can be described by assigning various constitutive relationships. Several constitutive relationships of the cohesive zone model have been developed by experimental results from 3-point bending or 4-point bending tests [48]. For example, the traction-separation law with cubic polynomial, trapezoidal, smoothed trapezoidal, exponential, linear softening, and bilinear softening functions are proposed for different types of materials. The length of the FPZ is defined as the distance from the crack tip to the point where the maximum taxation is attained. The FPZ of brittle material is relatively small due to its brittleness; thus, a linear relation is a reasonable assumption [54]. In 3D analysis, the nominal traction stress vector **t** acting on the fracture surfaces consists of three components: t_n, t_{s1} and t_{s2}, which represent the normal and the two shear traction components, respectively. The corresponding relative displacements of fracture surfaces are denoted by δ_n, δ_{s1} and δ_{s2}. The traction-displacement relation before damage initiation is assumed to be linear and is written in terms of a constitutive matrix as

$$\mathbf{t} = \begin{Bmatrix} t_n \\ t_{s1} \\ t_{s2} \end{Bmatrix} = \begin{bmatrix} k_n & & \\ & k_{s1} & \\ & & k_{s2} \end{bmatrix} \begin{Bmatrix} \delta_n \\ \delta_{s1} \\ \delta_{s2} \end{Bmatrix} = \mathbf{Kd} \tag{1}$$