International Journal of Impact Engineering 113 (2018) 132–143

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

The effect of different fracture mechanisms on impact fragmentation of brittle heterogeneous solid

Ma Gang[a,*], Yida Zhang[b], Zhou Wei[a], Tang-Tat Ng[c], Wang Qiao[a], Chen Xing[a]

[a] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
[b] Department of Civil, Environmental, and Architectural Engineering, University of Colorado Boulder, Boulder CO 80309-0428, USA
[c] Civil Engineering Department, University of New Mexico, Albuquerque NM 87131, USA

ARTICLE INFO

Keywords:
Impact fragmentation
FDEM
Fracture mechanism
Fragment mass distribution
Shape characteristics

ABSTRACT

The fragmentation of brittle and heterogeneous spherical solids under impact loading is numerically studied using the combined finite and discrete element method (FDEM) and cohesive crack model. The effect of different fracture mechanisms on the dynamics and statistics of fragmentation is investigated by adjusting the failure criterion of the cohesive interface elements (CIEs). Specifically, three sets of FDEM simulates modeling, the collision of a single spherical specimen against a rigid wall are conducted, each governed by tension-dominated, shear-dominated, and mix-mode fracture mechanisms, respectively. The influence of fracture mode on the resultant fragment mass distribution and shape characteristics after the impact are analyzed through statistical methods. It is found that the final fragment mass distribution can be characterized by a power law function with a higher power-law coefficient for shear-dominated fracture mode than for the tension-dominated fracture mode. This coefficient increases dramatically with increasing impact velocity in the three considered situations. As the impact velocity increases beyond the critical velocity, such coefficient converges to a relatively constant value around 1.743 ± 0.003, regardless of the controlling of fracture mechanisms. This value is very close to the mean values reported in other experimental and numerical studies in existing literature. The fracture structure is characterized by the direction distributions of fragment velocity and crack surface norms, and the fracture network is visualized by the spatial distribution of broken CIEs viewed from different perspectives. These statistical inspectors allow quantitative discussion of the effect of fracture mechanisms on the fracture patterns developed during impact. It is also found that shear-dominated fracture mode favors the generation of isotropic, rounded, and convex fragments, while tension-dominated fracture mode encourages elongated, angular, and concave fragments.

1. Introduction

Grain fragmentation plays an important role in numerous engineering processes including mining, powder manufacturing, and pile driving. During these processes, breakage or attrition of particles is achieved through repeated interparticle or particle-tool collisions. Consequently, much research has been devoted to understand the fragmentation mechanisms of single particle during collisions or impacts. Early experimental and theoretical studies on fragmentation have focused on the fragment mass distribution of particulate systems [1–9]. These studies revealed that the fragment mass or size distribution can be universally described by a power law, independent of the type of energy input, the relevant material length scales, and the loading conditions. Several theories have been put forward to understand the emergence of the universal fractal behavior. For rapid fracture of heterogeneous solids with a high degree of brittleness, the self-similar branching-merging scenario of propagating unstable cracks governed by tensile stresses can explain the main features of the fractal distributions [6,7,10,11]. For shell systems, an additional sequential binary fracture mechanism has to be taken into account [12,13].

The results of impact fragmentation tests are often presented in terms of particle size distribution and other statistical descriptors of the fragments. Modeling efforts have been largely limited to correlating these statistical descriptors with the controlling variables such as impact velocity and energy input, with finer details such as the fracture pattern, crack direction distribution, and fragment shape omitted [6,7,9,11,14]. In recent years, research on impact fragmentation has been benefited from the rapid development of computational capacities and numerical techniques, such as discrete element method (DEM) [15–22], molecular dynamics (MD) [23–26], material point method

---

[*] Corresponding author.
E-mail address: magang630@whu.edu.cn (G. Ma).

https://doi.org/10.1016/j.ijimpeng.2017.11.016
Received 21 July 2017; Received in revised form 23 November 2017; Accepted 26 November 2017

(MPM) [27], smooth particle hydrodynamics method (SPH) [28], cracking particle method (CPM) [29–31], peridynamics (PD) [32] and its variants (e.g., dual-horizon peridynamics (DH-PD) [33] and hybrid PD-SPH [34]), lattice discrete element method (LDEM) [35], and combined finite discrete element method (FDEM) [36–39]. Among them, Weerasekara et al. [40] provided a general and thorough overview of the application of DEM for comminution simulations. The CPM, PD, and DH-PD are superior in handling complex fracture problems and have been successfully used in the simulation of dynamic fragmentation due to explosive loading [29–34]. FDEM is a time-explicit numerical method combining continuum mechanics with DEM algorithms to simulate multiple interacting deformable and breakable solids. The benefit of conducting numerical experiments is that the process of dynamic fragmentation at any instant can be inspected at any desired level of details, which enables the possibility of developing more sophisticated and accurate theoretical models for fragmentation processes.

Despite the above mentioned advances, the numerical simulation of fracture and fragmentation of brittle materials under impact loading is still a challenging problem and an open research topic. Difficulties exist in handling the transition from a continuum body to highly discretized system, the deformability of fragments, multibody contact, rate-dependent fracture kinetics, branching and coalescence of fracture network, and the strong coupling between these phenomena. In this study, we use FDEM to overcome these difficulties. Comparing to other modeling approaches, FDEM offers several unique advantages. The most attractive one is its ability to consider multiple physical processes acting at different length scales that are typically difficult to capture altogether within a single approach. Among the many numerical methods for multibody systems, FDEM is one of the few methods can handle the interaction between discrete bodies as well as resolving the strain and stress field within each discrete body. The second main benefit is that the combined FDEM and cohesive crack model does not require the specification of any predefined fracture paths and initial flaws, which are typically the prerequisites for crack growth in many fracture models (Guo et al. [37]). Cohesive crack model permits the initiation of new fractures based on user-defined failure criterion and allows the use of physical concepts such as critical energy release rate for modeling the growth and opening of fractures. Different fracture initiation criterion and evolution law can be easily implemented in the current framework. Thirdly, the discrete nature of the approach (i.e., the addition of contact detection and interaction algorithms) allows the simulation of a large number of fractures that are simultaneously propagating, branching, and interacting with each other. Thus, the combined FDEM and cohesive crack model is particularly useful when a large number of fragments are generated after impact [37–39], and for modeling fracture and fragmentation in multibody systems, such as crushing of granular materials [41–43].

The authors have recently developed a combined FDEM and CIE platform [41] and implemented a rate-dependent fracture propagation model [44]. The full details of FDEM implementation including contact detection, contact interaction, and governing equations can be found in other references [45,46]. To allow for fracturing, zero-thickness cohesive interface elements (CIEs) are inserted between the edges of all adjacent bulk finite element pairs at the beginning of the simulation. The initiation and propagation of fractures are explicitly modeled using the cohesive crack model [41]. A series of pre- and post- processing Python scripts have been developed to facilitate the study of multi-body interaction problems [47]. These developments have enabled the full capacity for simulating dynamic complex fracturing problems using FDEM complementing to the existing research on impact fragmentations.

Fragmentation of brittle and ductile materials is controlled by various fracture mechanisms that depend on the material properties and loading methods. For example, Timár et al. [19] reported that the emergence of complicated stress state like shear has a significant effect on the fragmentation process, which give rise to the emergence of a novel class of fragmentation phenomena. However, the relative contribution of different fracture mechanisms, i.e., tensile cracking and shear-induced fracture, to the resultant fragment patterns and populations of brittle materials is still an open question. Understanding the relation between failure mechanisms and the fragment statistics is not only of great importance from a theoretical perspective, but is also of practical significance such as the quality control and energy optimization in powder manufacturing process. In the present paper, we extend the previous study [48] by conducting three sets of FDEM simulations of the impact of a brittle sphere with controlled fracture mechanism. By adjusting the strength threshold of the failure criterion of CIEs, the dominated fracture mechanism (i.e., tension-dominated, shear-dominated, and mix-mode fracture) during impact can be controlled. The influence of different fracture mechanisms on the process and the outcome of impact fragmentation are systematically analyzed in terms of the statistics of crack orientation, fragment size and shape.

2. FDEM and impact simulation

2.1. Outlines of FDEM and CIE framework

This section aims to provide a brief overview of FDEM. From the algorithmic point of view, FDEM employs FEM continuum formulations to assess the deformation and stress of each discrete body, while the contact and motion of discrete bodies are considered by DEM concepts. FDEM solves the contact mechanics using a distributed contact force approach and a penalty function method. Compared with DEM, this approach is more versatile when addressing deformable, irregularly shaped and breakable discrete bodies. Compared with FEM, this approach is more robust and efficient in addressing the interaction between multiple bodies.

The most important feature of the combined FDEM and CIE approach is its capacity in handling the transition of a material from continuum to discontinuum (i.e., comminution or fragmentation). Potential fracture planes are explicitly represented by the CIEs along inter-element boundaries which can be either stepwise updated with an initially coarse mesh (i.e., extrinsic approach) [49] or remain unchanged using a highly refined mesh throughout the computation (i.e., intrinsic approach) [50]. Due to the vast number of fractures and fragmentations involved in impact comminution problem, we employ the intrinsic approach combined with refined meshes to achieve the desired computational efficiency. To setup a model, a solid is initially discretized using a tetrahedral FEM mesh, followed by inserting zero-thickness CIEs between each pair of adjacent elements. Such CIE interbedded FE model has certain physical merits in representing the inner structure of brittle materials. For example, rocks such as sandstone can be regarded as “cemented granular materials”, where individual sand grains are fused together through interfacial bonds [51]; concretes are made of aggregates with different gradings and joined by cementitious materials [52,53]. By choosing the element size as the intrinsic length scale (e.g. grain size) of the material in the CIE interbedded FE models, the relatively strong grains and aggregates can be represented by the deformable solid elements, and the relatively weak cements and interfaces are modeled by breakable CIE elements.

During simulation, the CIEs and the solid elements experience linear elastic deformation together during the initial loading stage. The stress state on a CIE is characterized by a traction vector $\mathbf{t}$, which consists of three components t_n, t_{s1}, and t_{s2} representing the normal and the two shear stresses, respectively. The corresponding relative displacements 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 term of a constitutive matrix as: