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Modelling brittle impact failure of disc particles using material point method

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ABSTRACT

Understanding the impact failure of particles made of brittle materials such as glasses, ceramics and rocks is an important issue for many engineering applications. During the impact, a solid particle is turned into a discrete assembly of many fragments through the development of multiple cracks. The finite element method is fundamentally ill-equipped to model this transition. Recently a so-called material point method (MPM) has been used to study a wide range of problems of material and structural failures. In this paper we propose a new material point model for the brittle failure which incorporates a statistical failure criterion. The capability of the method for modelling multiple cracks is demonstrated using disc particles. Three impact failure patterns observed experimentally are captured by the model: Hertzian ring cracks, meridian cracks, and multi-fragment cracks. Detailed stress analysis is carried out to interpret the experimental observations. In particular it is shown that the experimentally observed dependence of a threshold velocity for the initiation of meridian cracks on the particle size can be explained by the proposed model. The material point based scheme requires a relatively modest programming effort and avoids node splitting which makes it very attractive over the traditional finite element method.

1. Introduction

The brittle failure of particles during impact is an important issue in chemical and material engineering. Many experimental and modelling studies have been conducted during the past decades. Due to the high speed and violent nature of the brittle failure process, experimental observations are usually restricted to the final failure patterns of particles. In summary the failure patterns observed experimentally can be divided into three categories which are illustrated in Fig. 1. Pattern I shown in Fig. 1(a) represents a small damage concentrating on a ring of material surrounding the contact area, which is often referred to as Hertzian ring and observed typically at low velocity impact. Sometimes a secondary ring crack can be observed within the Hertzian ring as shown in Fig. 1(a). If the impact velocity increases, a cone crack linked with the meridian cracks is often observed which is referred to as Pattern II and shown in Fig. 1(b). At high velocity impact oblique cracks split the particle into small pieces with or without the help of the meridian cracks as shown in Fig. 1(c). The left hand side of Fig. 1(c) shows the oblique cracks observed by Salman and Gorham during medium velocity impact of large particles [1]. The right hand side of Fig. 1(c) shows the meridian cracks developed and then the oblique cracks followed turning the particles into small pieces at a high velocity impact [2]. Arbiter et al. [3] studied the fracture patterns of sand–cement spheres and observed Hertzian ring and cone cracks at low velocity impact and meridian cracks at high velocity impact. For particles made of different materials after high velocity impact, meridian cracks were observed by Shipway and Hutchings [4] and by Andrews and Kim [5]. Salman and Gorham [1] found that the meridian cracks occurred in soda-lime glass particles of very small sizes at very high velocities and that oblique cracks occurred in large particles. Wu et al. [2] categorized 12 failure patterns observed in their impact experiments on plaster spheres.

The brittle failure process of materials during impact has been modelled extensively in the past decades. Most of the previous studies used the finite element method. However, dealing with crack formation and fragmentation has been a major challenge. Tvergaard [6] proposed an element vanishing technique which removes elements that meet a failure criterion in the sense that these elements no longer contribute to the virtual work integral of the weak form. The element vanishing technique was used to model the failure process of both brittle materials [7] and porous ductile materials [8]. Xu and Needleman [9] developed a mesh splitting method to simulate crack branching. Once a failure criterion is reached at a finite element node, it is duplicated and the two nodes separate according to a cohesive constitutive law. Based on this approach an elaborate model was developed by Camacho and Ortiz [10] to simulate the fragmentation process including crack opening, growing and healing. Espinosa et al. [11] simplified the model by Camacho and Ortiz [10] to take into account of material

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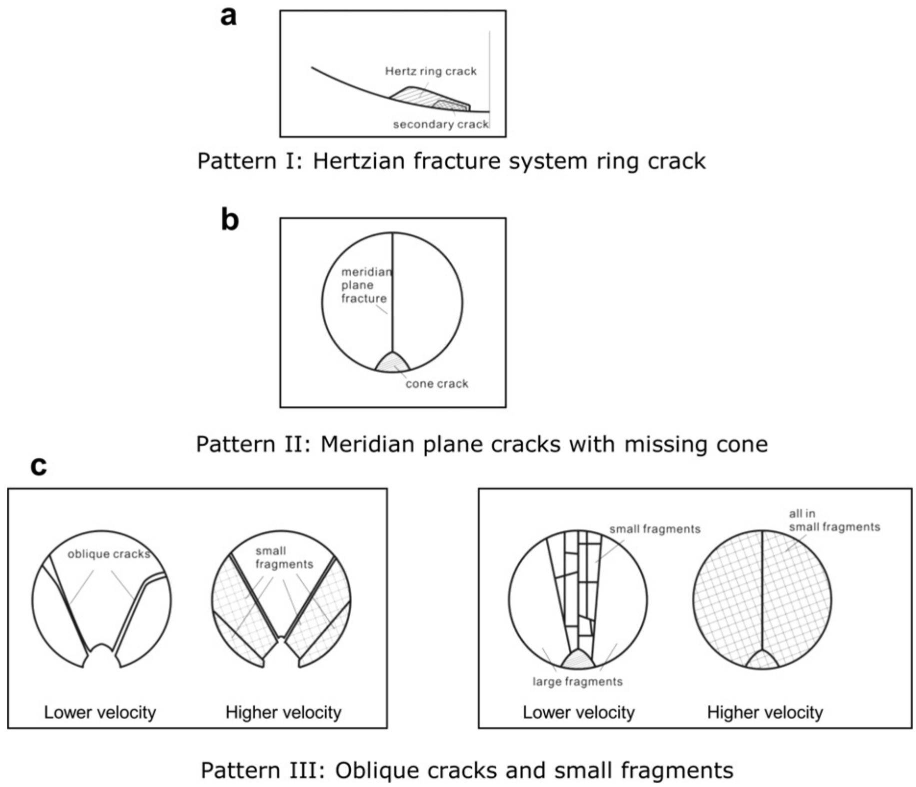

Fig. 1. Three types of experimentally observed failure patterns of brittle particles upon impact.

microstructures. The node-duplicating technique is widely used to solve different problems [12]. However, as multiple cracks appear, the node separation can be excessive and require adaptive mesh refinement. The complexity in the numerical procedure has severely limited the applications of the finite element based approach. Molecular Dynamics (MDs) is an alternative approach to model the failure of materials [13]. However, it is limited to nano-sized particles at extremely high impact velocities. Recently peri-dynamics has been developed to simulate cracking [14]. By scaling-up MD, the peri-dynamics approach is able to obtain some satisfying results. To characterise a specific material, the peri-dynamic (PD) simulation uses force between “particles” while the FE method uses a constitutive law. Although the inter-atomic potentials have been established for a wide range of materials, the real impact behaviour of a material can be controlled by factors such as microstructure, defect, alloying details and impurity. The continuum theory based on the constitutive law and the FE methods cannot be readily replaced by the peri-dynamic model. Another approach is to use the discrete element method [15–23]. However, the results of this approach heavily rely on the contact law and particle separation criteria which may not reflect the properties of a continuum solid.

The purpose of this paper is to demonstrate that the impact failure of brittle particles can be conveniently modelled using the material point method (MPM), which was initially proposed by Sulsky et al. [24] for large deformation plasticity. The MPM has been used to simulate impact problems [25,26] and the behaviour of granular materials [27,28]. It has also been used to simulate crack propagation by Sulsky and Shreyer [29]. This is accomplished by incorporating a de-cohesive constitutive law into MPM formulation. This approach, however, requires the pre-knowledge of the crack surface and hence cannot be used to simulate multi-cracking during particle impact. In the present paper, the material point method is combined with the Weibull’s failure theory to simulate the brittle impact failure. Details of the numerical scheme are described in the next section. Simulation results are presented in Section 3 where the proposed model is used to explain the experimental observations. The summary of the present work and the conclusion is in Section 4. The work presented here is limited to plane stress models of disc particles for simplicity. Full three-dimensional modelling of the impact failure requires extensive computer programming effort which is undergoing and will be reported in future publications.

2. Description of the model

2.1. Outline of the material point method

The basic idea of the material point method is to discretise a solid body into a collection of material points by density concentration. Fig. 2 illustrates a typical problem of particle impact to be solved using the MPM. All state variables are traced at these material points during the entire deformation and failure history. A separate computational mesh is employed to determine the velocities of the material points by mapping these state variables forward to the computational mesh and backward after the velocities are determined. At each time step only the positions of the material points are updated. Therefore mesh tangling or distortion is not an issue which causes a major problem in the traditional finite element method. Another attracting feature of the MPM is that no special treatment of the contact conditions is required. The material point velocity is determined using the computational mesh which automatically ensures no inter-penetration between the contacting bodies. The formulation of the material point method is described in details by Sulsky and Schreyer [25] and Wieckowski [28]. Here a brief outline of the method is presented in order to provide a context for our model for brittle failure. As shown in Fig. 2, in the MPM, a solid body is discretized into a collection of material points using a density concentration function