International Journal of Impact Engineering 87 (2016) 146–155

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Modelling the dynamic failure of brittle rocks using a hybrid continuum-discrete element method with a mixed-mode cohesive fracture model

Yi-Lin Gui [a], Ha H. Bui [a,*], Jayantha Kodikara [a], Qian-Bing Zhang [a], Jian Zhao [a], Timon Rabczuk [b]

[a] *Department of Civil Engineering, Monash University, Clayton, Vic 3800, Australia*
[b] *Institute of Structural Mechanics, Bauhaus-University Weimar, Marienstraße 15, D-99423 Weimar, Germany*

ARTICLE INFO

Article history:
Available online 9 May 2015

Keywords:
Cohesive fracture model
Mixed-mode
Dynamic failure
Notched semi-circular bending
Brazilian disc test

ABSTRACT

A cohesive fracture model that combines tension, compression and shear material behaviour is implemented into the hybrid continuum-discrete element method, i.e. Universal Distinct Element Code (UDEC), to simulate fracturing process in rock dynamic tests. The fracture model considers both elastic and inelastic (decomposed to fracture and plastic) displacements, with the norm of the effective inelastic displacement used to control the fracture behaviour. Two numerical examples, including notched semi-circular bending and Brazilian disc tests, are conducted to verify the applicability of the model in simulating the dynamic failure of rocks. Results show that the proposed approach is capable of realistically simulating the load rate effects on the mechanical behaviour of rock materials subjected to dynamic loads.

1. Introduction

Dynamic loads are usually associated with high amplitude, short duration stress pulses and are most commonly encountered in the form of explosion, impact and seismic load events [1]. Rock fracturing and the strength of rock under dynamic loads is usually loading rate-dependent; this rate-dependent has been proved to be significantly different under static loads [2]. Under dynamic loads, the strength of a material is normally enhanced due to the inertial effect which occurs within the extremely short-time loading period. The research on rock material strength and failure under dynamic loads has practical engineering applications such as blast and fragmentation in mining and military operation [1]. Thus, a better understanding of rock strength and fragmentation under dynamic loads is of importance in mining, earthquake and civil engineering.

In the past few decades, the study of rock failure under dynamic loads has received significant attention from different disciplines of science and engineering [2–33]. Research in this area can be classified into experimental work [5–8,11–13,15,18–20,22,23,25,26], numerical modelling [10,16,17,19,21,24,27–29] and theoretical modelling [5,9,14]. In terms of experimental work, a split-Hopkinson bar, which originated from the work of [32], has been extensively used to investigate the time-dependent behaviour of rock fracture under dynamic loading conditions. The principle of the split-Hopkinson bar is shown in Fig. 1a. An impact load is applied on the left end of the incident bar by a high velocity striker. The induced stress wave propagates along the incident bar and is partly transmitted through the sample, causing deformation of the transmission bar. Hence, the transmission bar reversely applies a load P_2 on the specimen (Fig. 1b).

Numerous researchers have studied dynamic rock failure using the split-Hopkinson bar. Goldsmith et al. [4] carried out compression, direct tension and torsion tests using split-Hopkinson pressure bar (SHPB) under various strain rates. An improved experimental approach was proposed in Li et al. [13] to eliminate oscillation existing in the stress-strain response of brittle materials from SHPB by virtue of using half-sine rather than a rectangular loading waveform. Li et al. [18] developed a large diameter SHPB with redesigned striker to obtain the complete stress-strain relationship of Bukit Timah granite at medium strain rate using a half-sine wave. In addition, a further modification to SHPB was carried out [22] to test the coupling effect of static and dynamic loadings on rock. Though experimental tests give insight to many phenomena, the failure mechanism of the material itself under dynamic loads is still unclear. Mechanisms such as the micro-crack initiation and propagation and failure mechanisms of rock mineral structures are not fully understood.

Many numerical techniques have been applied to model the dynamic failure of rocks and other brittle materials. Common techniques for dynamic fracture are finite difference methods (FDMs), finite element methods (FEMs) [10,19,21,28,29], mesh-free methods

---

* Corresponding author. Tel.: +61 03 9905 2599; fax: +61 03 9905 4944.
E-mail address: ha.bui@monash.edu (H.H. Bui).

http://dx.doi.org/10.1016/j.ijimpeng.2015.04.010

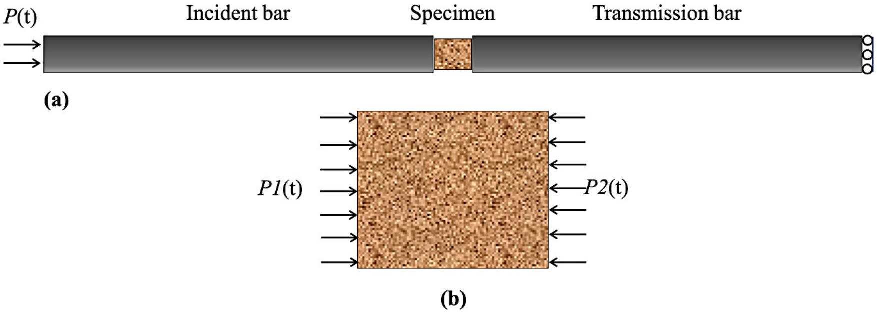

Fig. 1. Schematic illustration of split Hopkinson bar principle.

(MMs) [42–44,97–99] or hybrid methods such as coupled FEM-MMs [45]. Those methods either model the crack as strong discontinuity or 'smear' the crack over a certain width. The first category can be categorized into 'enriched' and 'non-enriched' methods. Enriched methods are based on partition of unity [46,47] and introduce additional degrees of freedom in the variational formulation and commonly allow for crack propagation without re-meshing. Such approaches include the embedded finite element method [48], generalized or extended finite element method [51,52], extended meshfree method [53,54], phantom node method [59,60], numerical manifold method [61,62], cracking particles method (CPM) [55], or extended IGA [56–58], among others. They are commonly applied to dynamic problems with a moderate number of cracks [63–66] unless crack path continuity is not required such as in the CPM. Element deletion techniques [67–69], cohesive elements [70–72], certain meshless methods based on the visibility/diffraction/transparency method [73–78] or FEM based on re-meshing [79–81] are representatives for 'non-enriched' discrete crack methods. An overview of discrete crack methods is given for example in Ref. [82]. Methods that smear the crack over a certain width introduce a characteristic length into the discretization. Such approaches include for example gradient enhanced models, non-local models or viscous models [83–85], to name a few. They are implemented into FEM-software or codes based on other discretization techniques such as MMs, FDM, etc. Note that those methods can theoretically be combined with discrete crack approaches, see e.g. the approach in Ref. [86], which combines a viscous damage model with the CPM. Besides classical continuum mechanics approaches, discontinuous methods such as the DEM [16,17] or DDA [27,95,96] are a powerful alternative.

Camacho and Ortiz [10] simulated the impact damage of brittle materials through spall tests and the dynamic crack propagation in a double cantilever beam using a Lagrangian FEM. Wu et al. [19] investigated the dynamic tensile strength of concrete through both experimental and numerical simulation (ANSYS) of the SHPB test. Zhu and Tang [21] simulated deformation and failure processes in Brazilian disc tests under both static and dynamic loads using an elastic-damage based constitutive law implemented in a FEM based code-Rock Failure Process Analysis (RFPA). In this simulation, the heterogeneity of rock sample was taken into account by invoking a Weibull distribution. The same method as that in Ref. [21] was used to simulate rock fragmentation processes induced by two drill bits in Ref. [28]. Camborde et al. [16] developed a two-dimensional DEM to simulate rock and concrete fracturing processes under both static and dynamic loading. Hentz et al. [17] modelled concrete under the dynamic loading of SHPB using three-dimensional DEM. Ning et al. [27] adopted DDA to simulate rock fracturing and blast-induced rock mass failure. Gong et al. [29] used the finite element software ANSYS/LS-DYNA to simulate rock-like material failure under three waveform-types, including rectangular, triangular and half sine in a SHPB set. Although there have been many numerical studies of the dynamic rock fracture, existing constitutive models have not properly considered the breakage of bonds under dynamic loads. In fact, the interaction of rock mineral structures under dynamic loads is of importance when investigating dynamic failure mechanisms. Conventionally, elastic-damage models are used for the simulation [21]. A condition of using elastic-damage models is that the size of the non-linear process zone in front of the crack is sufficiently small. However, for many geomaterials, such as soils, rocks, concrete, cement-stabilised rock/soil aggregates and soil, it may be unrealistic to consider the size of the non-linear zone to be negligible. To tackle the deficiency of elastic-damage models, the cohesive fracture model has been proposed and utilised. To our knowledge, only few models have considered Mixed-mode fracture and most are still focused on the Mode-I case, which has been demonstrated to be insufficient in simulating rock fragmentation [32]. In addition, most available Mixed-mode cohesive fracture models have not taken plasticity, under loading-unloading, into consideration. In fact, experiments on concrete [34], rock [35], and soil [36] have revealed the existence of plastic deformation during the loading-unloading through bending tests. Therefore, it is reasonable to utilise a mixed-mode cohesive fracture model considering plasticity in describing fracturing behaviour of rocks.

In this paper, a mixed-mode cohesive fracture model [87] accounting for tensile, shear and compressive behaviour with an evolutionary failure mode, that is applicable to general mixed-mode rock fractures, is implemented into the hybrid continuum-discrete element method (i.e. using UDEC embedded FISH language) to investigate the rock failure under dynamic loads. The cohesive fracture model presented does not directly include strain-rate effects. However, all the rate effects predicted by the model are a consequence of the interplay between inertial effects and fracture at the micro scale, which are captured by modelling the material with the discrete element approach. This is in contrast to most past cohesive fracture models [92–94] that directly model the tensile strength as an increase function of strain rate. The combination of the cohesive fracture model and the hybrid continuum-discrete numerical method has advantages over other methods, such as finite element method (FEM) and discrete element method (DEM), in its ability to realistically handle multiple fractures and deformation problems in materials. More specifically, it is quite difficult to use the FEM to simulate multiple fractures, while the conventional DEM does not consider the block deformation. In this mixed-mode cohesive fracture model, elastic-plastic-damage is coupled. Two types of dynamic tests including notched semi-circular bending (NSCB) and Brazilian disc (BD) tests are carefully simulated.