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A review of the state of the art in modelling progressive mechanical breakdown and associated fluid flow in intact heterogeneous rocks

S.C. Yuan, J.P. Harrison*

Department of Earth Science and Engineering, Imperial College, London SW7 2AZ, UK

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Abstract

The purpose of this review is to present techniques, advances, problems, and new developments in modelling the progressive mechanical breakdown of, and associated fluid flow in, intact heterogeneous rock. In general, the theoretical approach to this physical process can be classified into the three categories of discrete models based on fracture mechanics, the continuum damage mechanics approach, and statistical approaches. This categorisation forms the skeleton of this article.

Recognising that intact rock contains ubiquitous cracks and flaws between grains and particles of various shapes, fracture mechanics has been widely used to study the mechanical breakdown process in terms of the growth of these discrete defects. Two types of fracture mechanics models, namely open crack and sliding crack models, are used to simulate the progressive microfracturing of rock upon loading, and the application of these to modelling mechanical breakdown is discussed in Section 2.

As an alternative to the explicit treatment of cracking given by fracture mechanics, continuum damage mechanics (CDM) takes a phenomenological route that considers the averaged effect of microstructural changes, and has found widespread use in simulating macroscopic stress–strain responses. Through the introduction of damage variables as state operators that quantify change in mechanical properties such as stiffness and strength with respect to damage, CDM models are capable of reproducing realistic hydro-mechanical responses during rock disintegration. This method is discussed in Section 3.

Recognising that intact rock is never strictly an isotropic and homogeneous material, statistical approaches use, in general terms, statistical distributions as a means of describing the variation of material properties in natural rock. These approaches have enjoyed a great deal of attention in past decades. By employing different numerical schemes, three major statistical models have been developed: continuum-based damage mechanics models, particle models, and network/lattice models. The merits and drawbacks of these models are discussed in Section 4.

Coupled deformation and pore fluid diffusion can be important in the process of progressive breakdown. This poromechanical effect involves the interaction between the solid constituents of, and the interstitial fluids in, heterogeneous rocks under those circumstances when mechanical perturbation occurs sufficiently rapidly that induced pore pressure changes cannot fully dissipate. The mechanisms and analytical approaches, and their development relevant to progressive mechanical breakdown and fluid-flow modelling, are outlined in Section 5.

Finally, based on this review, remarks are made summarising the current progress of, and fundamental problems with, these developments. Ideas for further improvements towards more comprehensive and robust techniques are suggested.

Keywords: Modelling; Progressive damage; Fluid flow; Heterogeneous rocks

1. Introduction

Both in the laboratory and in situ, fracture of rock in compression is due to a number of complicated microscopic processes. These include the formation of microcracks at multiple grain or defect boundaries, and the growth and coalescence of microcracks. Associated with these processes are non-linear macroscopic behaviours and volumetric dilatancy. Additionally, all of these processes and behaviours are notably influenced by confining pressure.

*Corresponding author. Tel.: +44 20 7594 7348; fax: +44 20 7594 7444.
E-mail address: j.harrison@ic.ac.uk (J.P. Harrison).

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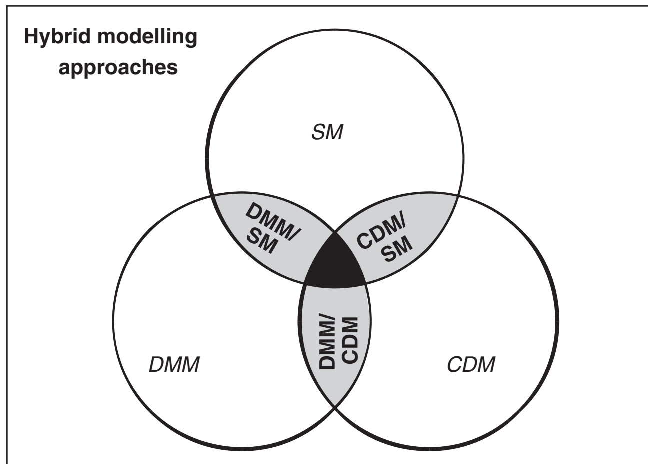
The microscopic processes associated with rock fracturing are manifested in the failure of many kinds of brittle materials, such as glasses, concrete, ceramics, and metals. In order to describe the progressive fracture process and the associated macroscopic behaviour, extensive studies have been conducted on different materials and have resulted in a number of failure hypotheses; those of Griffith [1], McClintock and Walsh [2], Kachanov [3], and Weibull [4] are notable. In the case of brittle fracture of rock, three such hypotheses—the discrete fracture mechanics theory, the continuum damage theory, and the statistical theory—appear to be most applicable, and have been used or referred to by various workers in the study of fracture of rock. This document reviews representative models developed from these three theories, and comments on their ability to capture the principal features of progressive breakdown of rock in compression.

An illustrative framework for the models is shown in Fig. 1, but it should be noted that, due to the multi-disciplinary nature of each method, they can often be identified as being based on more than one principle, thereby taking advantage of different concepts. Examples of these are listed in the table in Fig. 1, with four overlapping regimes. In order to focus on recent developments, the fundamental theories of discrete fracture mechanics, continuum damage mechanics, and statistical fracture mechanics are not covered here; this is left to other relevant texts [5–9].

Fundamental approaches to modelling microstructural breakdown of rock		
Discrete micromechanics models (DMM) based on fracture mechanics	Continuum damage mechanics (CDM) models	Statistical models (SM)
Examples of fundamental approaches		
Steif, 1982 Horii & Netmat-Nasser, 1986 Ashby & Hallam, 1986 Kemeny & Cook, 1987	Dragon & Mroz, 1979 Costin, 1985 Ofoegbu & Curran, 1992	Scholz, 1968 Hudson & Fairhurst, 1969



Examples of hybrid approaches	
DMM/CDM	Shao and Rudnicki, 2000
DMM/SM	Reuschle, 1998; Simpson et al.,2001
CDM /SM	Hudson & Fairhurst, 1969; Tang et al, 2002 Fang and Harrison, 2002; Yuan and Harrison, 2005
DMM/CDM/SM	Wong et al, 2005

Fig. 1. Framework of the contents of this review.

2. Discrete models based on fracture mechanics

According to Irwin and de Wit (1983), fracture mechanics "provides a quantitative treatment, based on stress analysis, which relates fracture strength to the applied load and structure geometry of a component containing defects." [10]. In this theory, the defect—which is usually modelled as a crack, although it could be another non-linear defect such as an equant pore—is regarded as a stress concentrator and accorded an appropriate importance in controlling brittle fracture. The influence of applied loads on crack extension can be related using parameters that characterise stress and strain intensity near the crack tip [5].

Rock material is typically heterogeneous in terms of it containing initial defects such as grain boundaries, cleavage, microcracks and pores. Fracture mechanics theory has become one of the most popular methods used for the study of fracture behaviour of rock materials under compression, and, during recent decades, extensive experiments have been carried out on rock samples with predefined artificial "cracks". These experimental observations have identified the specific mechanisms for the formation and growth of cracks from pre-existing defects, and a number of models for these have been proposed. These models provide a basis for relating the applied loads to the growth of a discrete crack, and this section reviews the most popular of them.

2.1. Physical models for the extension of microcracks

Two representative models are used to explain the mechanisms for the formation and extension of cracks, namely the open crack model [11–13] and the sliding crack model [14–18].

Fig. 2 shows the open crack model, in which the defect can be in the shape of either a cylindrical pore (Fig. 2(a)) [11,12], or an elliptical open crack (Fig. 2(b)) [13]. Under external compressive loading, stresses intensify around the pore or the tips of the crack, with tensile components developing on the boundary of the pore orthogonal to the line of action of the smaller applied in-plane stress in the