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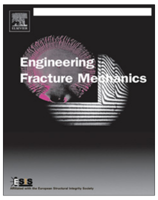

# Simulating progressive failure in brittle jointed rock masses using a modified elastic-brittle model and the application

Jin-Wei Fu [a,*], Xin-Zhong Zhang [a], Wei-Shen Zhu [b], Kui Chen [c], Jun-Feng Guan [a]

[a] *School of Civil Engineering and Communication, North China University of Water Resources and Electric Power, Zhengzhou 450046, China*
[b] *Geotechnical & Structural Engineering Research Center, Shandong University, Jinan 250061, China*
[c] *State Key Laboratory of Shield Machine and Boring Technology, Zhengzhou 450001, China*

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ABSTRACT

To analyse the damage evolution process of jointed rock masses, a modified numerical model on the basis of secondary development in fast Lagrangian analysis of Continua (FLAC3D) is proposed to simulate the fracture development of jointed rock mass. To validate the feasibility of this numerical model, numerous case studies on 2-D and 3-D cracking problems are conducted. The progressive failure processes of rock specimens with two pre-cracks under uniaxial and biaxial compressions are simulated and compared with the results obtained from the lab experiments, and they are found to be in good agreement. The failure processes of heterogeneous rock specimens with four pre-cracks are studied for further analysis. When applied to 3-D cases, the numerical results consistently match lab test results. Moreover, it is also used to analyse the failure process of a 3-D Weibull distribution specimen with an internal crack. Finally, it is used to investigate the crack propagation and stability of a slope project, presenting an excellent effect. It is concluded that this numerical model is effective and efficient in dealing with 3-D and numerous element cases.

## 1. Introduction

Rock masses normally contain a great number of fractures. To a great extent, it is the nearly ubiquitous presence of fractures that makes the mechanical behaviour of rock masses different from that of most engineering materials. These fractures have a controlling influence on the mechanical behaviour of rock masses, since existing fractures provide planes of weakness on which further deformation can more readily occur. The crack initiation, propagation, coalescence and failure mode of brittle jointed rock mass have always been studied as a hot issue in the field of rock mechanics and engineering. As the Chinese economy gradually grows, the Chinese government will begin to construct numerous huge engineering projects, such as mining, tunnels, hydropower stations, large-scale underground caverns for energy storage, etc. Therefore, the related problems in jointed rock mass will be encountered in the future. Physical experiments are the most popular method to study the mechanism problems of rocks. A series of physical studies have been carried out to investigate the crack initiation, propagation and coalescence of pre-existing cracks in pre-cracked specimens of different materials, including rock-like brittle/semi-brittle materials and natural rocks: glass, ceramics, moulded gypsum, sand-stone-like material, granite, marble, etc. Meaningful results were obtained [1–11]. Meanwhile, multiple geophysical methods have been adopted to study the fracture

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* Corresponding author.
*E-mail address:* fujinwei1987@126.com (J.-W. Fu).

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### Nomenclature

| | |
|---|---|
| $D_1, D_2, ldots, D_5$ | damage factors |
| $K$ | bulk modulus |
| $G$ | shear modulus |
| $\sigma_t$ | tensile strength |
| $c$ | cohesion |
| $\phi$ | internal friction angle |
| $K'$ | bulk modulus of post-failure elements |
| $G'$ | shear modulus of post-failure elements |
| $\sigma'_t$ | tensile strength of post-failure elements |
| $c'$ | cohesion of post-failure elements |
| $\phi'$ | internal friction angle of post-failure elements |

propagation and failure modes for rocks, such as the electric resistance method, CT scanning and the acoustic emission method. However, due to the complexity of experiments on rocks with pre-cracks and the difficulty in real-time observation of opaque rock-like materials, there are limitations in researching the interactions of pre-cracks by physical experiment.

Numerous numerical methods have also been used to simulate the fracture development. These methods could be divided into two types: continuous and discontinuous numerical methods. Specifically, these numerical methods include the finite element method (FEM), boundary element method (BEM), and displacement discontinuity method (DDM) [12]. Over the last few decades, various criteria have been proposed for crack initiation and propagation at the flaw tips. For practical purposes, three criteria are mainly applied [13,14]: the maximum tangential stress theory [15], maximum energy release rate theory [16], and minimum energy density theory [17]. The damage model [18] and F-criterion [19] have been evolved specifically for crack coalescence in the rock bridge area through secondary cracks. Recently, a numerical simulation code, RFPA2D (Rock Failure Process Analysis), was used to simulate crack propagation and coalescence in a rock bridge area. It successfully modelled the global failure of a rock specimen as well as local cracking at the flaw tips [12,20,21]. In addition, the DEM (Discrete Element Method) developed by [22] was used to simulate the cracking process in brittle specimens [23,24] and revealed a good agreement with the experimental results. [25] used their discrete element model - the lattice solid model - to study how cracks propagate when different force-displacement laws are employed.

FLAC$^{3D}$ (Fast Lagrangian analysis of Continua in three dimensions), which is an explicit finite difference method (FDM), has been used by many researchers [26–28] to simulate the 2-D crack propagation process in real rocks. However, due to deficient reform of the software's function, the simulated pre-crack was invariably surrounded by a group of irregular plastic zones, which is inconsistent with the threadlike crack propagation observed during experiments. Furthermore, regarding 3-D cracking problems, it can be more complicated and difficult, and there are only large plastic volumes around the pre-cracks [29,30]. In this paper, to simulate the fracture development of jointed rock mass, we propose a modified numerical model on the basis of secondary development in FLAC$^{3D}$, which successfully overcomes this difficulty. The criterion is based on element failure types, which makes this numerical model effective and efficient in dealing with 3-D and numerous element cases.

## 2. Numerical model and elastic-brittle theory

In this section, the numerical model and modified elastic-brittle theory are illustrated.

The numerical model is 70 mm in length and 140 mm in height. Its front and back planes are fixed, and rolling constraint is applied on the bottom. Thus it is a plane strain issue according to all boundary conditions. It contains two types of media, the intact rock and pre-cracks. The two parallel pre-cracks are arranged centrosymmetrically in the centre of the model, each of which is 20 mm long and 1 mm thick, making a 45° angle with the horizontal line. The spacing of pre-cracks is 20 mm, as shown in Fig. 1. The whole model is divided into 15,320 hexahedral elements and they must be extremely superfine. The pre-cracks are assumed as null model and displacement-controlling loading is employed. Table 1 lists the mechanical parameters of the intact rock.

The elastic-plastic model and strain-softening model could not effectively simulate the failure development of rock materials; even some microscopic problems are difficult to solve due to the large plastic zone appearing in the crack tips. For the purpose of simulating brittle properties of jointed rocks, the original elastic-plastic constitutive model in FLAC$^{3D}$ is reformed into a new elastic-brittle constitutive model, i.e., the strength of elements falls sharply to an extremely low residual strength after peak strength (as shown in Fig. 2). According to the curves of elastic-brittle stress-strain relations, a piecewise function could be used to express the whole process of the stress-strain relations. Additionally, the numerical calculation flow is displayed in Fig. 3. The method of transforming the original elastic-plastic model in FLAC$^{3D}$ is as follows. The analysis process includes two aspects: stress analysis and failure analysis. The stress analysis adopts the Mohr-Coulomb constitutive relationship, while the failure analysis is on the basis of element failure types in FLAC$^{3D}$, shear failure or tension failure. When failure

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