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Research Paper

An application of a cohesive fracture model combining compression, tension and shear in soft rocks

Y. Gui, H.H. Bui, J. Kodikara *

Department of Civil Engineering, Monash University, Melbourne 3800, Australia

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ABSTRACT

A cohesive fracture model considering tension, compression and shear material behaviour is implemented into the hybrid continuum–discrete element method, i.e. Universal Distinct Element Code (UDEC), to simulate possible multiple fracture in soft rocks. The fracture model considers both elastic and inelastic (decomposed to fracture and plastic) displacements. The norm of the effective inelastic displacement is used to control the fracture behaviour. Three numerical examples, including Mode-I, Mode-II and Mixed-mode tests, are conducted to verify the model and its implementation in UDEC. The model is subsequently applied to simulate uniaxial compression and Brazilian disc tests on soft rocks and the results are compared with experimental results. The results indicate that the cohesive fracture model is capable of realistically simulating the combined tensile, shear and mixed-mode failure behaviour applicable to geomaterials.

1. Introduction

It is generally accepted that the linear elastic fracture mechanics (LEFM) is a useful approach for addressing fracture problems involving cracks where the non-linear process zone in front of the crack is sufficiently small [1]. In addition, LEFM assumes that the intact material behaviour is linear elastic. However, for many geomaterials, such as soils, rocks, concrete, cement-stabilised rock aggregates and soil, it may be unrealistic to consider the size of the non-linear zone to be negligible and intact materials to be linear elastic [1,2]. To overcome these shortcomings, a cohesive fracture model (also referred to as a fictitious crack model) which was first proposed by Dugdale [3], has been advanced [1,2,4–7]. In cohesive fracture model, both strength and fracture criteria are combined together offering advantages over models based on LEFM [8].

In Mode-I fracture, the cohesive fracture model and its constitutive behaviour may be described as shown in Fig. 1. The fracture is considered to consist of two components: a real crack and a fictitious crack (also known as the process zone), each of which is associated with a crack tip, namely the real tip and the virtual crack tip, respectively. The process zone is then defined as the zone between the real and fictitious crack tips, and comprises the material that is partially damaged but is still able to transfer load across the fracture [4]. The crack opening behaviour is governed by the value of the opening displacement and the strength of the material. The initial hardening behaviour is assumed to be linear elastic when the opening displacement is smaller than a critical value (i.e. w_{c1} in Fig. 1b). The crack surface traction at the critical opening displacement is the material tensile strength (i.e. σ_t in Fig. 1b). For openings larger than w_{c1}, the bridging stress across the fracture will decrease featuring softening behaviour, and will become zero at a limiting displacement (i.e. w_{c2} in Fig. 1b). Generally, the initial hardening response is relatively small in comparison to the softening response, thus softening response has therefore received more attention in the past [1]. To explain the softening behaviour, several softening laws have been proposed, including mono-linear, bi-linear and other softening laws as shown in Fig. 1.

Although there have been some advancements in cohesive fracture modelling, for example [1,2,4–7], only few models have considered Mixed-mode fracture and most are still focused on Mode-I case in geomaterials. However, some experimental and numerical evidences have shown that cohesion-softening (or sometimes referred to as decohesion) is necessary when considering the plastic/frictional dissipation in soft rocks. For example, Vermeer and de Borst [9] indicated that cohesion-softening is to be expected due to micro-fracturing and the degradation of bond between grains when material undergoing plastic deformation. Edelbro [10] also demonstrated the applicability of cohesion-softening in simulating rock mass behaviours. Therefore, it is rational to take Mix-mode cohesive fracture model in describing fracturing behaviour of soft rocks.

* Corresponding author. Tel.: +61 3 9905 4963.
E-mail address: jayantha.kodikara@monash.edu (J. Kodikara).

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Most existing cohesive models in the literature are based on damage theory and do not take into account the plastic/frictional dissipation [8]. In addition, it has been realised that although pure damage model is more efficient in terms of computation than plasticity/damage coupled model, coupled plasticity/damage cohesive model can have true predictive capability as friction and fracture are both dissipative mechanisms which contribute to interface damage process [8]. In tensile loading, the plastic deformation during loading–unloading is contributed from two aspects: (1) the rock fracture cannot be fully healed (i.e. there is an increase of porosity locally) due to the mismatch of the interface and the loss of rock grains at the rock fracture, especially, the rock fracture is under shearing. (2) There is cohesive zone in front of real crack tip which contributes to the plastic deformation. This plastic deformation cannot be reversed even if the load on the fracture has been removed. In fact, some experiments on concrete (e.g. [11]), soft rock (e.g. [12]), and soil (e.g. [13]) have demonstrated the existence of the plasticity during loading–unloading through bending tests. Kazerani et al. [5] proposed a cohesive fracture model considering the cohesive behaviour of tensile, compressive-shear in rocks. First, the hardening stage of the load–displacement response was simulated using an exponential law instead of a linear law adopted in most cohesive models. In fact, there has been no strong experimental evidence that can show the initial elastic behaviour is exponential. In addition, the plasticity dissipation was not considered in this model. The unloading/reloading path was treated as elastic, where the unloading/reloading path went through the origin of stress-displacement space (i.e. state with zero displacement and zero stress), assuming that the cohesive process zone behaves fully elastically. Moreover, there is no cohesive effect actually included in the compressive-shear behaviour as the cohesion decreases to a constant residual value immediately once the initial strength has been reached.

In this paper, a cohesive fracture model originally presented in Ref. [17] that takes into account tensile, shear and compressive behaviour combined with an evolutionary failure model applicable to general Mixed-mode rock fractures is investigated using a hybrid continuum–discrete element method. Implementation of the model in the hybrid method has the advantage of handling multiple fracture and deformation problems in materials over other methods, such as finite element method (FEM) and discrete element method (DEM). More specifically, FEM has problem of handling multiple fractures. In conventional DEM, the block deformation is not possible to be considered. The original work on this model was developed for applications in concrete primarily for single crack simulations. However, our implementations catered for multiple crack formation as needed for rock and soil fragmentation where both shear and tension modes can be prevalent. In this model, elastic–plastic-damage is coupled together. Therefore, the dissipative mechanism (i.e. plasticity during unloading–reloading) has been taken into account in the model. In addition, the definition of elastic stiffness is based on fracture energy which eases the selection of parameters. The applicability of the model is tested through the verification of the implementation and then applying to real soft rock experimental data. For other cohesive fracture models, the implementation can be time-consuming. LEFM cannot easily simulate the development of multiple interacting cracks and disintegration of elements. Therefore, in this paper, the verification of implementation is only tested through the simulation result with the data obtained from model equations. The paper is organised as follows: in Section 2, the 2-dimensional hybrid continuum–discrete element model is introduced; the cohesive model framework is illlustrated in Section 3. In Section 4, the cohesive model is implemented and verified using uniaxial tension and compressive/shear tests. In addition, the model is applied to simulate geomechanical test examples, including uniaxial compression and Brazilian disc tests.

2. Hybrid continuum–discrete element modelling

In this section, the hybrid continuum–discrete element method is presented. The method can model the interaction of discrete materials, the solid continuum within discrete bodies and the fracturing process. A distinct element numerical scheme needs to allow for finite displacements and rotations of the discrete bodies,

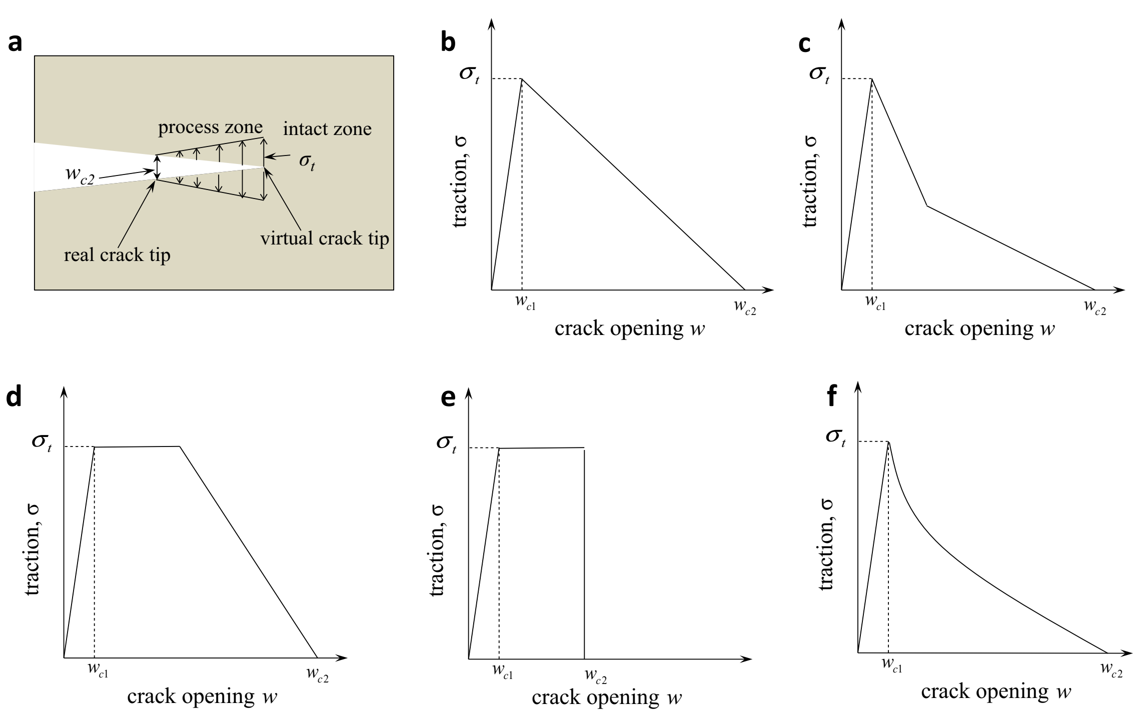

Fig. 1. Mode-I cohesive fracture model and its consititutive behaviour.