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Influence of the geometry of partially-spanning joints on mechanical properties of rock in uniaxial compression

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ABSTRACT

As jointed rocks consist of joints embedded within intact rock blocks, their behavior depends on the behaviors of the joints and the intact rock blocks. In a jointed rock, there are two levels of heterogeneity within the jointed rocks due to the differences in properties between the rock blocks and the joints at a macro-scale, and within the intact rock blocks due to difference in the randomly-distributed flaws at a meso-scale. In this paper, numerical tests on plane stress numerical specimens with an embedded, partially-spanning joint are reported. The individual influence of three parameters relating to the geometry of partially-spanning joints: joint location, joint orientation and trace length was studied. In the simulations, the joints were modeled by elements with low moduli and strengths, whereas the heterogeneity of the rock properties of the intact rock block was taken into account by assuming that they obey the Weibull distribution. The numerical simulations not only agreed well with the experimental results, but also duplicated the complete rupture process of samples with the stress evolution and tempo-spatial distribution of damage events. The numerical results show that there is an approximately linear relationship between the location of the terminus of the partially-spanning joint with respect to the end of the sample (joint location) and the compressive strength of the partially-cut sample, whereby failure stress increases with increasing joint location value. With respect to joint orientation, the simulations show that the minimum compressive strength occurs for a joint angle of 45°, and that compressive strength increases with both increasing joint angle and decreasing joint angle from this critical value of 45°. In relation to the joint trace length, the numerical results reveal that the compressive strength of partially-cut specimens is correlated with the joint trace length using an approximately linear relationship.

1. Introduction

Geotechnical engineers are actively engaged in the search for solutions to complex problems involving the behavior of jointed rocks. Jointed rocks are heterogeneous and discontinuous containing joints and/or bedding planes with varying degrees of strength along these planes of weakness. The behavior of a jointed rock is governed not only by the properties of the intact rock block, but also mostly by the presence and properties of discontinuities such as joints and/or bedding planes within the jointed rock. For example, it is essential to know if and how existing joints and/or bedding planes connect with each other to form a continuous discontinuity surface for the stability of rock slopes or tunnels (Brekke and Selmer-Olsen, 1965; Chakraborty et al., 1994). In this case, the geometry of joints such as their location, orientation and joint trace length can heavily influence the deformability and strength of jointed rocks, which is highly relevant to fields including mining engineering, underground excavation and petroleum engineering. Therefore, it is of paramount importance to know how the geometry of joints influences the deformability and strength of jointed rocks.

Extensive experimental and numerical research has been done on the mechanical behavior of rock-like materials from a single pre-existing flaw such as a joint, weakness plane or fracture in compression. For example, Lajtai (1975) experimentally examined the influence of a single plane of weakness on shear strength in direct shear loading and found that the total shear strength of rock was determined by fundamental shear strength (cohesion) and internal friction in solid bridges and by joint friction along the separated parts of the weakness plane. Petit and Barquins (1988) studied crack propagation in sandstone from a single flaw subjected to uniaxial compression. Huang et al. (1990) performed uniaxial compression tests on marble plate with an inclined central slot, observed the initiation and propagation of primary tensile cracks and secondary tensile cracks up to ultimate failure, and identified four types of ultimate failure. Ramamurthy and Arora (1994) conducted a series of uniaxial and triaxial compression tests on

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Paris, Jamrani and Agra sandstones with joints varying in number and inclination and proposed a strength criterion for jointed rocks. Shen et al. (1995) performed a series of uniaxial compression tests on gypsum specimens with pre-existing fractures to study the failure mechanism of fractures and rock bridges in fractured rock masses. Bobet and Einstein (1998a) also performed uniaxial and biaxial compression tests on pre-fractured gypsum specimens, investigated the crack initiation, propagation and coalescence of two parallel flaws in gypsum specimens and observed two types of cracks: wing cracks and secondary cracks. Similar observations have been reported by Wong and Chau (1998) on model sandstone and Wong et al. (2001) on model specimens. More recently, Prudencio and Van Sint Jan (2007) performed experimental tests on physical models of rock with non-persistent joints and found that the failure modes and maximum strengths of rock samples were dependent on the geometry of the joint systems, the orientation of the principal stresses, and the ratio between intermediate stress and intact material compressive strength. Chen et al. (2012) investigated the combined influence of joint inclination angle and joint continuity factor on the deformation behavior of jointed rock mass for gypsum specimens with a set of non-persistent open flaws in uniaxial compression and revealed that the deformation behavior of the jointed rock mass was correlated to the closure of pre-existing joints, the development of fractures in the rock matrix and teeth shearing of the shear plane. Wasantha et al. (2012a) developed constitutive models to describe the influence of joint geometry on the uniaxial compressive strength of rock containing partially-spanning joints using existing experimental data from uniaxial compressive strength tests. Numerical methods have also been employed in the study of the mechanical properties of quasi-brittle rock-like materials with pre-existing fractures or joints. Ingraffea and Heuze (1980) performed finite element modeling for a numerical specimen with a single inclined flaw loaded in compression and duplicated the stable and unstable propagation of primary and secondary crack growth observed in experiments. Tang and Kou (1998) carried out numerical simulations on samples of brittle materials containing multiple pre-existing flaws using the finite element method and observed the propagation and coalescence of wing cracks in either tensile or shear mode, or a combination of both modes. Bobet and Einstein (1998b) performed numerical modeling of fracture coalescence in a model rock material using a hybridized indirect boundary element method. Using the discontinuous deformation analysis method originally proposed by Shi (1988), Lin et al. (1996) further extended the use of discontinuous deformation analysis in the study of crack growth in jointed rock. Vásárhelyi and Bobet (2000) studied crack initiation, propagation and coalescence in uniaxial compression using the displacement discontinuity method. Zhang and Sanderson (2001) evaluated the effects of fracture geometry and loading direction on the instability of fractured rock masses using a distinct element method, while Giacomini et al. (2008) investigated the flow anisotropy within a natural joint subjected to mechanical shear. Deb and Das (2009) provided a numerical example of the application of the extended finite element method (XFEM) in jointed rock samples with varying joint inclination angles. More recently, Zhang and Wong (2012, 2013) studied the cracking and coalescence behavior in a rectangular rock-like specimen containing two parallel pre-existing open flaws under uniaxial compression load using a parallel bonded-particle model. Ma et al. (2009) and Zhang et al. (2010) modeled complex crack propagation using the numerical manifold method. Wu and Wong (2012, 2013) studied the effects of the friction and cohesion on the crack growth from a closed flaw under compression using numerical manifold method.

Although considerable attention has been paid to the initiation and propagation of pre-existing flaws in jointed rock mass, the influence of joints on the overall mechanical properties of jointed rock mass and the underlying fracturing mechanism remain less well understood. Moreover, detailed knowledge of the effect of joints on the overall mechanical properties of jointed rock mass is fundamental to an understanding of the deformation and failure process of engineering rock mass and the design of engineering rock mass structures. Thus, in the present study, an attempt has been made to consider the most significant aspects including joint location, joint orientation and joint trace length of rock joints which are mainly responsible for the reduction in strength and are measurable in the field.

2. Brief outline of numerical model

Numerical simulation is currently the most popular method used for modeling the deformation behavior of rock-like materials before failure. Even though progress has been made in the numerical simulation of failure in rocks, a satisfactory model which can simulate progressive failure in a more visual way, including simulation of the failure process and failure-induced stress redistribution, is lacking.

The demand for new tools which may contribute to a better understanding of the failure mechanisms of heterogeneous brittle materials initiated the development of the Rock Failure Process Analysis code (abbreviated as RFPA^{2D}). RFPA^{2D} is a progressive elastic damage model. It can simulate the non-linear deformation of a quasi-brittle or brittle behavior with an ideal brittle constitutive law for heterogeneous materials by incorporating the heterogeneity of material properties into the model. It can also simulate strain-weakening and discontinuum mechanics problems in the continuum mechanics mode by introducing the reduction of material parameters after element failure.

There are two levels of heterogeneity in a jointed rock, one being the differences in properties between the rock block and the joint at a macro-scale, and the other being the heterogeneity within the intact rock blocks due to differences in the randomly distributed flaws at a meso-scale. In the model, because the system was analyzed at a meso-scale, the heterogeneity within the intact rock blocks due to the differences in the degree of weathering and the randomly distributed flaws at a meso-scale was taken into account. The stress–strain relationship can be described by an elastic damage constitutive law. Continuum damage mechanics can describe the effects of progressive micro-cracking, void nucleation, and micro-crack growth at high stress levels using a constitutive law, by making use of a set of state variables modifying the material behavior at the macroscopic level. Using an isotropic continuum damage formulation, the constitutive law for an isotropic and elastic material at instantaneous loading can be written as (Lemaitre and Desmorat, 2005):

$$\varepsilon_{ij} = \frac{1+\nu}{E}\sigma_{ij} - \frac{\nu}{E}\sigma_{kk}\delta_{ij} \tag{1}$$

$$E = E_0(1-D) \tag{2}$$

where ε_{ij} is the damaged elastic strain tensor, σ_{ij} is the stress tensor, E and E_0 are the Young's modulus of the damaged and undamaged materials, respectively, D is the isotropic damage variable, ν is the Poisson's ratio and δ_{ij} is the Kronecker symbol. In the case of a uniaxial state of stress ($\sigma_{11} \neq 0, \sigma_{22} = \sigma_{33} = 0$), the constitutive relation can be rewritten in terms of the longitudinal stress and strain components only (Lemaitre and Desmorat, 2005):

$$\sigma_{11} = E_0(1-D)\varepsilon_{11}. \tag{3}$$

Hence, for uniaxial loading, the constitutive law is explicitly dependent on the damage index D.

The model is based on progressive isotropic elastic damage. Fig. 1 shows the constitutive law for an element in uniaxial compression and uniaxial tension. When the stress on an element exceeds a damage threshold, its Young's modulus E is modified according to Eq. (2). In the beginning, each element is considered to be elastic, as defined by a specific Young's modulus and Poisson's ratio. The stress–strain curve of the element is considered linear elastic with a constant residual strength until the given damage threshold is reached. The maximum tensile strain