Engineering Geology 199 (2015) 74–90

Contents lists available at ScienceDirect

Engineering Geology

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

Crack coalescence between two non-parallel flaws in rock-like material under uniaxial compression

Xiao-Ping Zhang [a,1], Quansheng Liu [a,*], Shunchuan Wu [b], Xuhai Tang [a]

[a] School of Civil and Architectural Engineering, Wuhan University, Wuhan 430072, China
[b] School of Civil and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083, China

ARTICLE INFO

Article history:
Received 19 October 2013
Received in revised form 15 October 2015
Accepted 19 October 2015
Available online 24 October 2015

Keywords:
Crack coalescence
Joint
non-parallel flaws
Bonded-particle model (BPM)

ABSTRACT

Crack coalescence between parallel flaws has been extensively studied in brittle rock and rock-like materials. Due to the nature of rock masses that contain more than one joint set, the cracking process cannot be completely studied using specimens that contain parallel flaws. To address this area of research, crack coalescence between two non-parallel flaws is studied numerically using parallel bonded-particle models in which one flaw does not overlap or partially overlaps the other (varying α) and in which one flaw completely overlaps the other (varying β). Five types of linkage are observed between two flaws: tensile crack linkage, tensile crack linkage with shear coalescence at tip, shear crack linkage, mixed (tensile-shear crack) linkage and indirect crack linkage. The geometries of the two non-parallel flaws strongly influence the crack trajectories and coalescence patterns. At large angles of α (135°) and β (60°), coalescence occurs more easily by tensile crack(s) before the peak stress is reached. The stress distribution in bridge area of the non-parallel flaws is more complicated than that of the parallel flaws. This difference affects the stress for crack initiation as well as the pattern for coalescence.

1. Introduction

Crack coalescence refers to the linkage of pre-existing fractures (flaws) in a material due to the initiation, propagation and interaction of new and existing fractures (Zhang and Wong 2013a). Rocks contain natural fractures at several scales and with several geometries. The coalescence between these fractures will lead to damage or even failure of the rock mass, which is of great interest to engineers and scientists. The cracking of rock masses that contain natural fractures can be studied after a full understanding of the cracking between parallel ones and between non-parallel ones.

Many previous studies have focused on crack coalescence between parallel flaws (Bobet and Einstein 1998b; Li et al. 2005; Wong and Li 2013; Park and Bobet 2009; Sagong and Bobet 2002; Tang et al. 2001; Tian et al., available online; Vasarhelyi and Bobet 2000; Wong 2008; Wong and Chau 1998; Wong et al. 2001; Yang 2011; Zhang and Wong 2013a,b; Zhou and Yang 2007; Zhou et al. 2014, 2015) because sets of joints, which are composed of numerous parallel joints, are the most common and basic fracture unit encountered in rock masses at the scale of engineering.

However, joint patterns composed of more than one set are also common in nature. Pollard and Aydin (1988) defined several types of joint intersection geometries, which can be classified as orthogonal (+ intersections) and non-orthogonal (X intersections). Both types can be divided into three groups according to the persistence of the joints at the intersections:

1. All joints are persistent (cross other joints).
2. Some joints are persistent, while some are non-persistent.
3. All joints are non-persistent.

These patterns are schematically illustrated in Fig. 1. In a rock mass that contains the non-persistent joint pattern E, which is part of group 3, failure may occur due to the coalescence of joints (flaws) of two different sets; i.e., the sets are not parallel to each other. In a rock mass that contains non-persistent joint patterns C, D and F, which are categorized as group 2, failure may occur due to the coalescence of joints (flaws) of two different sets if the maximum compressive loading direction is perpendicular to the persistent joints.

Lee and Jeon (2011) studied the coalescence of a horizontal flaw with an inclined flaw located beneath it (Fig. 2). They stated that using such geometry can improve the understanding of the behavior of en-echelon cracks, which can propagate out of the fracture plane to become non-parallel to each other based on the orientation of the local stress. This study was a good start to consider the coalescence of non-parallel flaws, but it is not sufficient to only study configurations in which one flaw is partially or completely underneath the other horizontal flaw. As shown by previous studies of parallel flaws (Kranz 1979;

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* Corresponding author.
E-mail addresses: jxhkzhang@163.com (X.-P. Zhang), liuqs@whrsm.ac.cn (Q. Liu), wushunchuan@ustb.edu.cn (S. Wu).

[1] Xiao-Ping Zhang was formerly Key Laboratory of Shale Gas and Geoengineering, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China.

http://dx.doi.org/10.1016/j.enggeo.2015.10.007

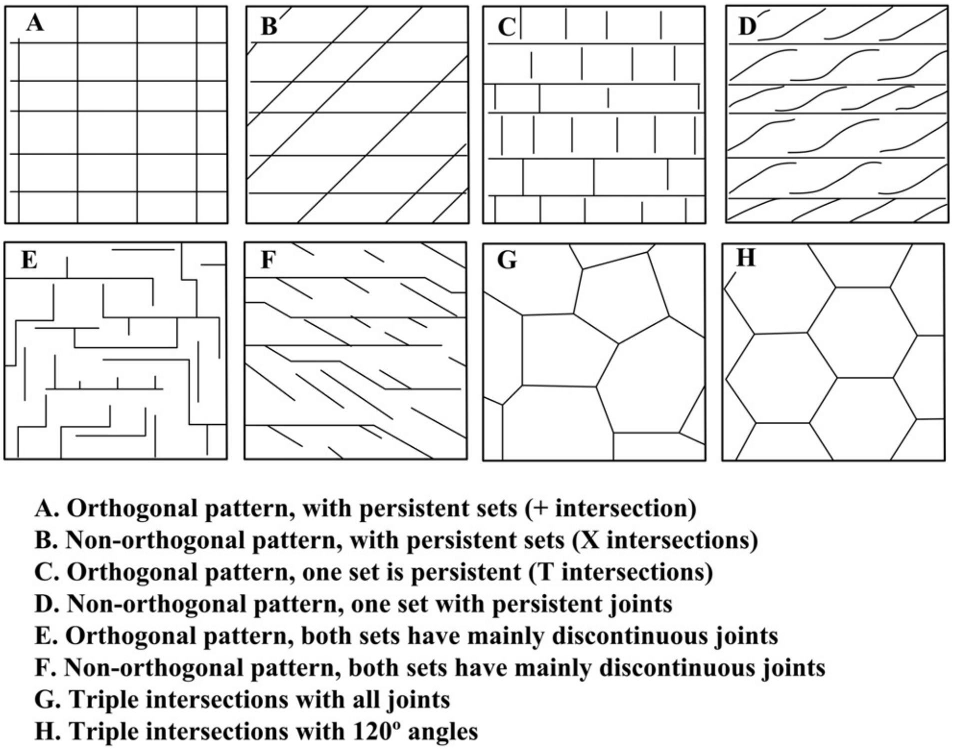

Fig. 1. Schematic illustration of typical joint patterns (from Pollard and Aydin, 1988).

Li et al. 2005) and non-parallel flaws (Lee and Jeon 2011), stress shielding occurs in the flaw that is below the other. To increase the understanding of cracking between non-parallel flaws, it is necessary to study cases in which one flaw is not underneath the other (as J2 and J6 in Fig. 3 along vertical direction). Fig. 4 illustrates the possible combinations of non-parallel flaws. Fig. 4 (a) shows cases in which one flaw is not underneath or is partially underneath the other, while Fig. 4 (b) shows cases in which one flaw is completely beneath the other. This paper will study the cracking processes of specimens containing these geometries with non-parallel flaws.

2. Geometries and parameters of the numerical specimens

The bonded-particle model (BPM), which is a distinct element-based model, has been widely used for rock failure analysis for the past decade. The interaction between cracks occurs because the breakage of individual bonds induces global stress redistribution. The capability of the BPM that is available in the Particle Flow Code 2D (PFC2D) (Itasca, 2004) for modeling the cracking process in rocks was demonstrated in our previous studies (Zhang and Wong 2012, 2013a). The BPM has advantages in simulating the initiation positions of cracks observed in physical experiments, which are not necessarily located at the flaw tips but can be located in the intact part of the specimen away from the tips (Zhang and Wong 2013a).

This study used the parallel bond BPM, which can resist tension, shear and rotation. The tensile and shear stresses that act on the parallel bond periphery are calculated from beam theory. If the maximum tensile stress exceeds the tensile strength of the parallel bond ($\overline{\sigma}_c$) or the maximum shear stress exceeds the shear strength of the parallel bond ($\overline{\tau}_c$), the bond will break. Tensile stress can also be induced in the bonded area due to rotation between two neighboring particles. If the rotation-induced tensile stress exceeds the tensile strength of the parallel bond ($\overline{\sigma}_c$), the parallel bond will break.

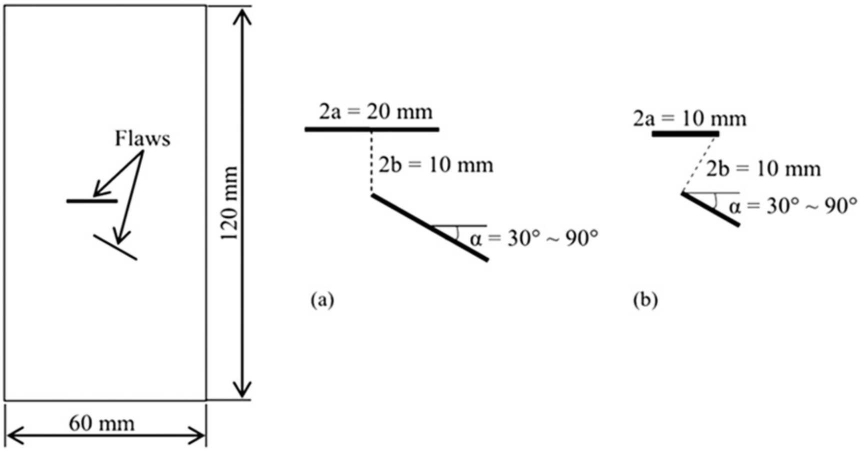

Fig. 2. Two geometries of non-parallel flaws studied by Lee and Jeon (2011).