Engineering Geology 187 (2015) 113–121

Contents lists available at ScienceDirect

Engineering Geology

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

Crack propagation and coalescence of brittle rock-like specimens with pre-existing cracks in compression

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ARTICLE INFO

Article history:
Received 14 September 2014
Received in revised form 18 December 2014
Accepted 25 December 2014
Available online 30 December 2014

Keywords:
Rock-like material
Multiple pre-existing flaws
Crack propagation and coalescence
Uniaxial compression

ABSTRACT

Fracture coalescence, which plays an important role in the behavior of brittle materials, is investigated by loading rock-like specimens with two and three pre-existing flaws made by pulling out the embedded metal inserts in the pre-cured period. Different geometries are obtained by changing the angle of the flaws with respect to the direction of loading and the spacing. With reference to the experimental observation of crack initiation and propagation from pre-existing flaws, the influences of the third pre-existing flaw on the cracking processes was analyzed. It was found during the test that: with the increase of the angle of the rock bridge, the rock specimen takes a turn from wing crack propagation failure to crack coalescence failure, and it will be more obvious with the increase of the prefabricated crack angle. According to the different geometries of pre-existing cracks, seven types of coalescence have been identified based on the nature of the cracks for the specimen with two pre-existing flaws. The multi-crack interaction results in the continuous degradation of the macroscopic mechanical properties of the rock mass. On one hand, it weakens the trend of relative sliding of the coplanar cracks, and on the other hand, it changed the coalescence patterns of the fractured specimen. The research reported here provides increased understanding of the fundamental nature of rock mass failure in compression.

1. Introduction

Rock masses contain a number of joints that appear in sets or groups with similar orientation and characteristics. Such discontinuities are found at any scale, from grain boundaries to joints and regional faults. The existence of discontinuities, joints, or cracks in rock has two effects (Lajtal et al., 1990; Bobet and Einstein, 1998; Hoek and Martin, 2014): (1) they decrease the strength and stiffness of the rock mass; and (2) they are a source of initiation of new discontinuities which in turn may propagate and link with other cracks and further decrease the strength and the stiffness of the rock. Damage induced by micro-cracks is an essential mechanism in many brittle rocks subjected to compressive stress, which will induce stress concentration on the tip of the crack and lead to the initiation and splitting propagation of the wing crack (Wong and Chau, 1998; Tang et al., 2001; Yang and Jing, 2013). It is currently recognized that damage initiates primarily in the form of extensile micro-cracks that originate from local stress concentrations. Due to the difficulties of in-situ tests, the laboratory loading test of rock-like materials was an effective research method and widely used by scholars. On the premise that the material was brittle, mechanical property was stable, and machining was easy, different materials which were used to make prefabricated fissures were selected in accordance with different purposes of experiments. Many researchers have studied the mechanism of fracture evolution from pre-existing flaw(s) (Horii and Nemat-Nasser, 1985; Ashby and Hallam, 1986; Bobet, 1997; Yang and Jing, 2011). Significant advances have been achieved in understanding the failure process of brittle rock. The crack patterns generally observed in previous investigations of rock specimens with a single pre-existing fracture loaded in uniaxial compression are shown in Fig. 1, and two types of cracks can initiate from the tips of a pre-existing discontinuity (Shen et al., 1995; Wong et al., 2001; Dyskin et al., 2003; Park and Bobet, 2009; Camones et al., 2013): (1) wing cracks; and (2) secondary cracks. Wing cracks appear first, which are tensile cracks that initiate at an angle from the tips of the flaw and propagate in a stable manner towards the direction of maximum compression. Secondary cracks appear later and are responsible, in most cases, for specimen failure. Secondary cracks are shear cracks that also initiate from the tips of the flaws and propagate coplanar to the flaw or at an angle with the flaw similar to the wing cracks but in the opposite direction.

Coalescence occurs by the linkage of two flaws through a number of combinations of tensile or shear cracks. Crack coalescence in rock materials has been extensively studied (Sagong and Bobet, 2002; Li et al., 2005; Ko et al., 2006; Wong and Einstein, 2009). Previous work provides a good understanding of the coalescence patterns obtained from specimens with two initial flaws. However, rock masses usually contain a

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http://dx.doi.org/10.1016/j.enggeo.2014.12.010
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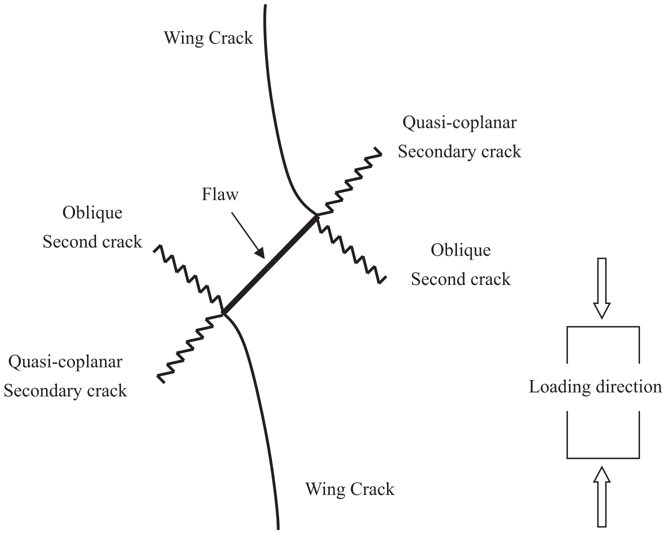


Fig. 1. Crack patterns observed in pre-cracked specimens in compression.

Table 1
Rock bridge fracture failure modes under axial compression.

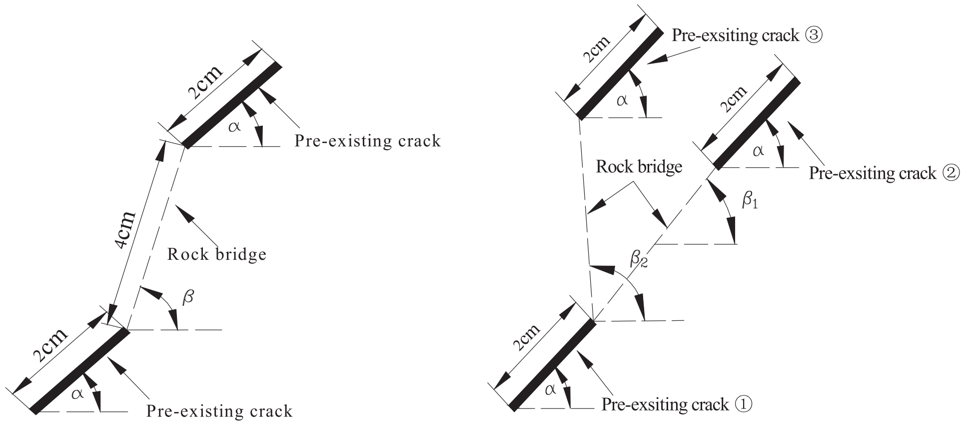
Number of flaws	Inclination angle of pre-existing crack/°	Inclination angle of rock bridge β (or β_1, β_2)/°
Two flaws	$\alpha = 25$	25
		45
		75
		90
		105
	$\alpha = 45$	45
		75
		90
		105
	$\alpha = 75$	75
		90
		105
Three flaws	$\alpha = 25$	25, 45
		25, 75
		25, 90
		25, 105
	$\alpha = 45$	45, 75
		45, 90
		45, 105
	$\alpha = 75$	75, 90
		75, 105

number of joints that appear in sets or groups with similar orientation and characteristics. The question is whether the observations made from specimens with two flaws can be extrapolated to specimens with multiple flaws. In multiple flaw systems under uniaxial loading, wing cracks and secondary cracks also occur and eventually lead to coalescence, but observations made from one or two flaws may provide a limited understanding of a much more complex behavior of the rock mass due to the large number of possible interactions among the discontinuities. Coalescence appears to be a rather complicated process. It is not just material related, but it is also dependent on the geometry of the flaws. In this investigation we present experimental observations from a number of rock model specimens with two and three flaws loaded in compression, intending to contribute to the understanding of the cracking processes in rock materials with different geometries by investigating the crack pattern and coalescence processes, and the influence of the third crack on the coalescence process is presented. The results obtained were of significance in studying the failure mechanism of fractured rock masses.

2. Specimen preparation and experiment

To study the initiation and growth of wing and secondary cracks, crack coalescence, and the macro-failure of a brittle material, many scholars choose resin, organic glass or gypsum as a similar rock material for indoor experiments. These experiments can study the crack evolution law of the crystal matrix rock material during the failure process very well. For the material composition of some other rock mass in the natural state, the solid particles are the major constituent parts of the framework of the rock mass, and the silicon, calcium, and argillaceous adhesive materials are the cementing material of the particles. Using resin or organic glass material as the model specimens, the friction enhancement effect on the failure surface hardly appears. Using the combination of gypsum and fine sand material, the friction effect of the grain body can be met, but owing to the limited bond strength of the gypsum body, the model specimen will produce relatively large deformations under the action of stress. Considering all these deficiencies, some scholars choose cement mortar material to simulate the fracture damage characteristics of a fractured rock mass. For this type of model, fine sand is used as the skeletal material, and cement is used as the cementing material to bind the grain fine sand together. In this way, not only the brittle feature is satisfied, but also it is possible to observe the friction phenomenon of the particles on the surface. The obtained experimental results compared with other materials are more close to the deformation and damage characteristics of rock masses.

Based on similar mechanical properties with natural rock masses, cement mortar specimens were used in this study. The rock-like materials



(a) Geometries with two pre-existing flaws (b) Geometries with three pre-existing flaws

Fig. 2. Physical test specimen. (a) Geometries with two pre-existing flaws. (b) Geometries with three pre-existing flaws.