Theoretical and Applied Fracture Mechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

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

Dynamic damage localization in crack-weakened rock mass: Strain energy density factor approach

X.P. Zhou *, H.Q. Yang

State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400044, PR China
School of Civil Engineering, Chongqing University, Chongqing 400045, PR China

ARTICLE INFO

Article history:
Received 14 March 2017
Revised 3 May 2017
Accepted 3 May 2017
Available online xxxx

Keywords:
Damage localization
Crack-weakened rocks
Pseudo traction method
Bifurcation of crack growth pattern
Strain energy density factor approach

ABSTRACT

The key failure mechanism of rock mass subjected to compressive loads is due to the damage localization. Conventional methods can not be applied to study the dynamic damage localization physical behavior of crack-weakened rock mass. The strain energy method has the capability to investigate the dynamic damage localization feature in crack-weakened rock mass. Therefore, in order to analyze the dynamic damage localization behavior, strain energy density factor approach is adopted in this paper. A two-dimensional model with periodic rectangular noncollinear array of cracks is established. Then, the onset condition of periodic distribution cracks in rock mass is obtained using strain energy density factor approach. By analyzing the bifurcation of crack growth pattern, the critical length and stress of damage localization of crack-weakened rock mass is determined as well as the location of damage localization. In addition, parameters sensitivity analysis is carried out, the effects of the length of crack, friction coefficient, fracture toughness, confining stress, velocity of crack growth, inclination and spacing between lines and rows on the onset condition for damage localization and bifurcation pattern of rocks are discussed. It can be concluded that onset condition of damage localization is mainly affected by its distribution of initial cracks.

1. Introduction

There are many discontinuities, such as bedding planes, joints, shear zones and faults, which are contained in rock mass. In many cases, the broken of rock mass is mainly controlled by the distribution of discontinuities in the rock mass. The key factor of rock failure is the damage localization process of microcracks in rock mass under compressive stress. Therefore, damage localization can serve as a precursor to the failure of rock mass.

It is pointed out that the failure process of rock mass consists of the following three major stages, as shown in Fig. 1. Firstly, the steady state of stress accumulation appears, in which all cracks uniformly grow. Secondly, the alternative evolution of periodic microcracks occurs when they uniformly grow to some extent. That is to say, the crack growth pattern bifurcation is characterized as only parts of cracks keeping propagation while others keeping still. Thirdly, some cracks coalesce with each other until rock mass fails. This process is called damage localization of rock mass.

Based on these above observations, it can be concluded that damage localization of rock mass results from the bifurcation of crack growth pattern. Consider an infinite array of two-dimensional cracks of the same size in Fig. 1, all cracks grow simultaneously under far field applied loads when crack interaction is neglected. However, the bifurcation of crack growth pattern occurs when the effect of crack interaction is considered. Therefore, crack interaction is key factor for the occurrence of bifurcation and the onset condition for damage localization. That is to say, a bifurcation of the crack growth pattern emerges as soon as the critical condition is reached [2,3].

Various theoretical models were developed to analyze damage localization, these models can be simply classified into three kinds. The first kind of these models is based on the statistical microdamage theory. In order to reveal the underlying mesoscopic mechanism governing the experimentally observed failure in solids

* Corresponding author at: State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400044, PR China.
E-mail addresses: zhouxiaopinga@sina.com, cqxpzhou@hotmail.com (X.P. Zhou).

http://dx.doi.org/10.1016/j.tafmec.2017.05.006
0167-8442/

Please cite this article in press as: X.P. Zhou, H.Q. Yang, Dynamic damage localization in crack-weakened rock mass: Strain energy density factor approach, Theor. Appl. Fract. Mech. (2017), http://dx.doi.org/10.1016/j.tafmec.2017.05.006

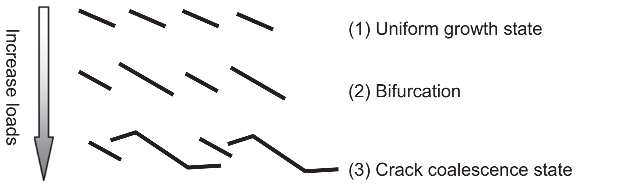

Fig. 1. A typical observation of bifurcation of the growth pattern in experiments [1].

subjected to impact loads, some researchers [4,5] put forward a model of statistical microdamage evolution to analyze the macroscopic failure. The second kind of these models was derived from the strain-gradient-enhanced plastic theory. A strain-gradient-enhanced damage model was proposed by Zhao et al. [6,7] to analyze the localization of rock-like or concrete-like brittle materials. The third kind of these models was known as the micromechanical damage model. Many efforts were done on this field. For example, considering the rapid stress drop and strain softening of material, the fracture process zone near the tips of a mode-I crack in a brittle damaged material was studied using the Dugdale-Barenblatt model [8]; the complete stress-strain relation for rock-like materials were investigated [9–16]. Although these three kinds of methods can reflect some characters of damage localization in crack-weakened rock mass, the mechanism of damage localization and the onset condition for damage localization still need to be investigated. In this paper, more general equation for noncollinear microcracks is derived based on a simplified analytical model for the bifurcation of collinear microcracks.

Here, the possible bifurcation of crack growth pattern in two-dimensional doubly periodic noncollinear crack arrays subjected to biaxial compression is investigated. By analyzing the bifurcation of crack growth pattern, the critical length and the critical stress for damage localization of crack-weakened rock mass are determined as well as the location of damage localization. Finally, parameters sensitivity analysis is carried out.

This paper is organized as follows. In Section 2, the pseudo traction induced by crack interaction is determined. In Section 3, a dynamic fracture criterion is adopted. In Section 4, onset condition for damage localization is derived. In Section 5, parameters sensitivity analysis is carried out.

2. Pseudo traction acting on the crack surface and stress intensity factor

2.1. The basic model

As shown in Fig. 2, a periodic rectangular noncollinear array of sliding cracks is used to analyze the damage localization of crack-weakened rock mass under biaxial compression. Similar to the works by Horii and Nemat-Nasser [17], Kemeny [18], Deng et al. [19], Li [20] and Wang et al. [21], the sliding crack array can be simplified as an array of tensile cracks subjected to a pair of splitting forces F and the far field compressive stress σ_1^∞ and σ_2^∞. For simplicity, Fig. 2 is further decomposed into configurations in Fig. 3a and b. The actual curvilinear wing crack in Fig. 2 is approximated by a straight opened crack growing parallel to the direction of the maximum principal compressive stress σ_1^∞. In Fig. 3a, an array of tensile cracks with the length of $2l$, the horizontal spacing of H, and the vertical spacing of $2w$ is loaded by a pair of splitting forces T at its center. In Fig. 3b, an array of tensile cracks is subjected to axial compressive stress σ_1^∞ and confining pressure σ_2^∞.

Considering an elastic body containing an array of cracks, which is arranged as M rows and N columns, the periodic rectangular array of cracks in Fig. 3a is labeled by its location, such as the crack at the bottom left corner labeled by (1, 1), while the crack at the top right corner labeled by (M, N). The local Cartesian coordinate system of each cracks is (o_{ij}, x_{2ij}, x_{1ij}) in Fig. 3. As shown in Fig. 3, the spacing between adjacent rows of the same column is defined as d, while the spacing between adjacent columns of the same row is defined as b.

The following three main assumptions are adopted in this model. Firstly, before bifurcation occurs, all the lengths of initial cracks are assumed to be equal to a, and all the lengths of wing cracks are $2l$. Meanwhile, the dip angle of initial crack with respect to the maximum principal compressive stress σ_1^∞ is θ. Secondly, before bifurcation occurs, wing cracks always propagate along the direction of the maximum principal compressive stress σ_1^∞. Thirdly, it is assumed that the loading rate is not fast enough to consider the effects of cracks on the transmission of stress wave. These three assumptions were also adopted by the previous literatures [16,20].

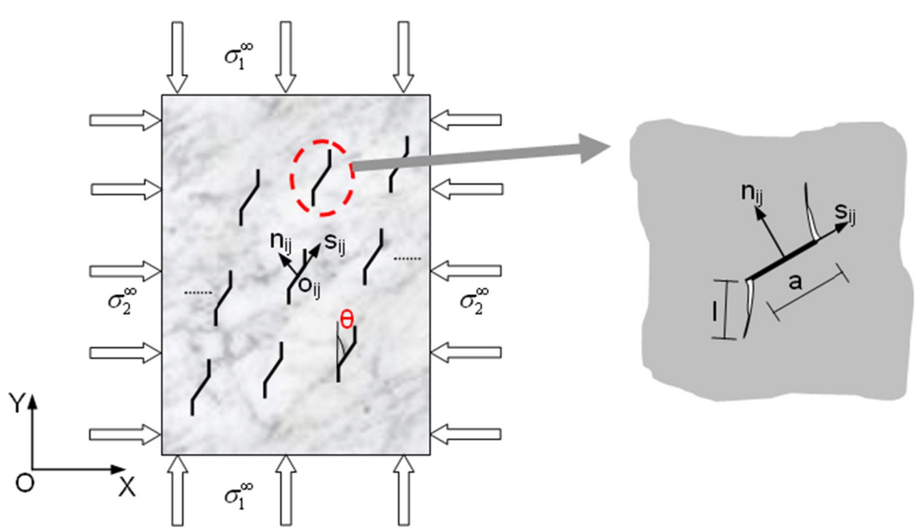

Fig. 2. The periodic rectangular array of sliding cracks.

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