Engineering Fracture Mechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Numerical simulation of rock failure under static and dynamic loading by splitting test of circular ring

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ARTICLE INFO

Article history:
Received 29 May 2017
Received in revised form 13 August 2017
Accepted 13 August 2017
Available online xxxx

Keywords:
Numerical simulation
Splitting ring test
Failure mode
Indirect tensile strength
FDEM

ABSTRACT

The fracture propagation and failure process in rock are subjects of great interest in rock mechanics. In the present study, an approach combining the finite element method (FEM) and the discrete element method (DEM), named ELFEN, is adopted to simulate and investigate the failure process of a typical hard rock (Carrara marble) under static and dynamic splitting ring tests. The FDEM software is firstly validated by simulating the test of a Brazilian disk under static loading. Then, the failure of circular ring specimens is numerically studied under static and dynamic loading, with the ratio of internal to external diameter (represented by λ) of the specimen groups varying from 0.1 to 0.6, with increments of 0.1. Under static loading, with the increase in internal diameter, the failure mode is transformed from diametrical splitting to four-fan-shaped failure (when $\lambda \geq 0.4$). Under dynamic loading, four-fan-shaped failure occurs from geometric axial symmetry to axial asymmetry, which means that, with increasing internal diameter, the tensile cracks along the horizontal diametrical direction gradually deviate toward the top loading platen. The peak load of the circular ring has a descending trend with the increase in internal diameter under both loading conditions. A rational load value (peak load or crack initiation load) is suggested to calculate the tensile strength of circular rock ring specimens under the splitting ring test. Finally, the numerical results are compared with previous experimental results. The good agreement between the two sets of results, in terms of the failure modes and variation trend of the indirect tensile strength with increasing internal diameters, verify the accuracy and applicability of the FDEM approach.

1. Introduction

The failure process of brittle and hard rock has always been of great interest in rock mechanics and rock engineering, especially regarding the rock failure modes and strength criteria. Tensile and shear fractures are the two main failure modes for hard rocks [1]. The Brazilian test, deemed as a simple indirect testing method, has been used extensively to obtain the tensile strength and measure the toughness of brittle materials such as rocks, rock-like materials, and concrete [2–4]. However, the conventional Brazilian test has also its own disadvantages and shortcomings in terms of the test principle and the reliability of results, particularly for soft rocks. The splitting ring test, a disk with a small central hole, was proposed by Hobbs to determine the indirect tensile strength of a rock [5]. It can ensure that the crack initiation starts from the periphery of the hole in the ring specimen and thus avoid stress concentration close to the loading platen. Over the past 20 years, extensive

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http://dx.doi.org/10.1016/j.engfracmech.2017.08.022
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Nomenclature

A	cross-sectional area of test specimen
B	area of the element
d	internal diameter of ring specimen
D	external diameter of ring specimen
E	Young's modulus
E^d	elastic damaged secant modulus
E_t	tangential softening modulus
f_t	tensile strength of the material
G_f	fracture energy
K_{Ic}	fracture toughness in mode i
l_c	local control length in finite element context
nn	local coordinate system associated with the principal stresses
P	peak load
P_n	normal penalty in FDEM approach
P_t	tangential penalty in FDEM approach
r	internal radius of circular ring
R	external radius of circular ring
t	thickness of the test specimen in laboratory tests
σ_i	principal stress invariants
σ_t	tensile strength of Brazilian disk
σ_{tr}	indirect tensile strength of circular ring
σ_{trs}^E	static tensile strength of circular ring based on previous experimental results
σ_{trs}^N	static tensile strength of circular ring based on FDEM approach
σ_{trd}^E	dynamic tensile strength of circular ring based on previous experimental results
σ_{trd}^N	dynamic tensile strength of circular ring based on FDEM approach
σ_θ	loading rate
ω	damage parameter
$\psi(\varepsilon)$	function of the total strain
λ	ratio of internal diameter to external diameter of the circular ring
μ	Poisson's ratio
γ	friction of newly generated cracks in FDEM approach

experimental and numerical studies have been carried out with the splitting ring test [6–11]. The boundary element method (BEM) approach was used by Chen and Hsu to model the ring test for determining the indirect tensile strength of anisotropic rocks [6]. The results showed that the tensile strength of anisotropic rocks determined by the ring test was influenced by their elastic properties, the angle between the planes of rock anisotropy and the loading direction, the diameter of the central hole, and the contact condition of loading. Zhu et al. [7] adopted the rock-failure process analysis (RFPA) software to model the ring specimen, and proposed a new test scheme in which the crack initiation load was used rather than the peak load to determine the indirect tensile strength of a rock based on the Hobbs' equation. You et al. [8] found that the peak load for the rock rings decreased exponentially with the increase in internal diameter, and the Hobbs' equation based on the elastic mechanics has great difference compared with the experimental results. In the splitting ring tests, the critical factor to determine the tensile strength of a rock is the ratio of ring's radii. Li et al. [10] experimentally studied the static and dynamic failure characteristics of the splitting test of circular rings. It was found that the tensile strength of rock ring specimens is dependent on the ratio of ring's radii.

The fracture process of brittle materials such as rock and glasses has been a critical issue in fracture mechanics for some decades [12,13]. Many researchers employ experimental, analytical, and numerical approaches to study the failure processes of rock and rock-like materials. Numerical approaches, such as the finite difference method (FDM), finite element method (FEM), discrete element method (DEM), and discontinuous deformation analysis (DDA) are the main tools used for simulating the fracturing processes of a rock and rock mass. Wong and Wu [14] used the numerical manifold method to investigate the progressive failure in rock slopes. They found neither the continuous nor the discontinuous approaches, but a hybrid method that combines both continuous and discontinuous methodologies can provide a comprehensive analysis. Based on the physical observations of fracturing processes in brittle rocks, Li et al. [15] proposed numerical modeling schemes that, based on the finite difference method, considered the material heterogeneity and initial microflaws at the element scale. Wen et al. [31] studied the influence of different height to diameter ratio on the acoustic emission characteristics of coal rock damage evolution using a microparticle flow PFC2D software platform.

Please cite this article in press as: Li X et al. Numerical simulation of rock failure under static and dynamic loading by splitting test of circular ring. Engng Fract Mech (2017), http://dx.doi.org/10.1016/j.engfracmech.2017.08.022