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Fracture analysis of marble specimens with a hole under uniaxial compression by digital image correlation

Diyuan Li [a,*], Quanqi Zhu [a], Zilong Zhou [a], Xibing Li [a], P.G. Ranjith [b]

[a] *School of Resources and Safety Engineering, Central South University, Changsha, Hunan 410083, PR China*
[b] *Deep Earth Energy Laboratory, Department of Civil Engineering, Building 60, Monash University, Melbourne, Victoria 3800, Australia*

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ABSTRACT

To investigate the effects of pre-fabricated holes with different geometries, including size, shape and inclination angle, on the strength and fracture behavior of rock materials, a series of uniaxial compressive tests were conducted on prismatic marble specimens containing a circular or an elliptical hole using a servo-hydraulic machine synchronized with a charge-coupled device (CCD) camera. Digital image correlation (DIC) was applied to record and analyze the deformation and fracturing process of marble. Experimental results combined with theoretical analysis indicate that the geometries of the internal hole are important factors affecting the strength of marble and also the boundary tangential stress distribution. The specimen with a higher tangential compressive stress concentration coefficient will have a lower UCS values. Observations show that the evolution of deformation and fracturing process of marble specimens can be visually displayed by the apparent displacement and strain fields. The propagation of cracks is a progressive development of high major principal strain zones, and the process of damage accumulation, crack initiation and propagation of rock at different stress stages can be well reflected by DIC. When the stress increases to 78.2% of peak value, critical cracks initiate in the tensile stress concentration zones. The progressive process of "open-close-reopen" of tensile cracks was quantitatively studied by the tensile strain of the specimens. It was found that the propagation of tensile cracks surrounding the hole in marble specimens was mainly affected by the nucleation and propagation of strain localization zones.

1. Introduction

The deformation and crack behavior of rock materials is of great interest in geomechanics and rock engineering. As rock materials contain initial defects, such as fissures, pores and micro-cracks, under external loads, new cracks may initiate and propagate along these defects, and crack coalescence can lead to rock bridge fracture, which is responsible for the failure of rock and rock masses [1,2]. The circular or elliptical shapes are often utilized in tunnel and mining engineering. The diameter of circular holes, and the inclination angle and axial ratio of elliptical holes, are the main geometric parameters which can affect the strength and failure characteristics of surrounding rocks. Therefore, it is essential to study the mechanical properties and fracturing process of brittle rock materials containing a circular or an elliptical hole.

* Corresponding author.
E-mail address: diyuan.li@csu.edu.cn (D. Li).

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Nomenclature

a	major semi-axis
b	minor semi-axis
E	Young's modulus
H	height of specimen
p	vertical stress
p_{max}	peak load
q	horizontal stress
r	polar radius
T	thickness of specimen
W	width of specimen
α	inclination angle
ε_{max}	maximum tensile strain
ε_x	extensional strain
θ	polar angle
σ_c	compressive strength
σ_t	Brazilian tensile strength
σ_r	radial stresses
σ_θ	tangential stresses
$\tau_{r\theta}$	shear stresses
AE	acoustic emission
CCD	charge-coupled device
DIC	digital image correlation
ISRM	International Society for Rock Mechanics
LVDT	linear variable displacement transducer
ROI	region of interest
SEM	scanning electron microscope
UCS	uniaxial compressive strength

The study of the stress and displacement field in plates (either "infinite" or "finite") with holes (independently of their geometry) concerns engineering community long ago, starting from Kirsch [3] and Inglis [4], and more recently by Filippi and Lazzarin [5], and the solutions for a circular and an elliptical opening in a plate were deduced. Based on the solution of Inglis [4], Griffith [6] proposed a stress approach in predicting crack growth from a flaw under a remote biaxial stress, and fracture occurs when the most vulnerably oriented flaw in a population of randomly oriented flaws begins to extend under the applied stress. As being further explained and illustrated by Hoek [7] and Paterson [8], crack initiation is assumed to take place when the maximum local tensile stress at any point around the flaw reaches the critical value necessary to overcome the interatomic cohesion of the material. Meanwhile, Sammis and Ashby [9] proposed the first theoretical analysis of the brittle failure of solids containing single holes and multiple holes, and mathematical models were developed to explain and predict the processes of crack growth, interaction and rock failure [1,2].

In laboratory loading uniaxial compressive stress conditions, the fracture patterns of rock specimens containing a circular hole may involve three different failure processes: primary fracture at the tensile stress concentration zone, secondary fracture at positions inside the rock abutments, and side wall slabbing at the concentration of compressive stress [10,11]. Kobayashi et al. [12] conducted uniaxial compression test using a photoelastic material to study the crack propagation in specimen with single hole and the interaction mechanism between the hole and the crack. Using plaster models, Lajtai and Lajtai [13] demonstrated that the remote fractures combine ultimately with the failure process in the compressional zone (slabbing-crushing and shear fracture) causing the collapse of the hole. Martin et al. [14] carried out a similar test in granite and found three types of fractures around the circular hole. The breakout occurred in the maximum shear stress region around the boundary of the circular hole [15] for plane-strain conditions. However, like other classic physical models, the fracture patterns in rock samples were incapable of characterizing the entire fracture process, which involved the initiation, propagation, and coalescence of micro-cracks through the formation of a full-scale macro-crack.

The digital image correlation (DIC), as a non-contact optical method, which was first proposed in early 1980s [16,17], can provides full-field displacement and strain measurement on a specimen surface. This technique shows remarkable advantages in contrast with conventional contact measurement techniques, such as linear variable displacement transducer (LVDT), extensometer and strain gauge, by avoiding the major issues caused by direct contact measurement and generating the field of strain development relevant for insights into strain localization [18]. Thus the DIC technique has been widely used by many researches in the study of fracture characteristics. For example, the DIC was applied to detect the damage