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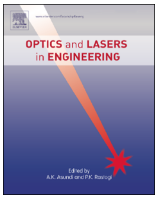

An experimental investigation on the damage of granite under uniaxial tension by using a digital image correlation method

Ge Yang [a], Zongxi Cai [a,*], Xiaochuan Zhang [b], Donghui Fu [a]

[a] *Department of Mechanics, Tianjin University, Tianjin 300072, China*
[b] *School of Mechanical Engineering, Tianjin University of Commerce, Tianjin 300134, China*

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ABSTRACT

This paper presents an experimental investigation of the damage mechanisms of granites under uniaxial tension. The displacement distribution and surface tensile strain of the specimens were measured by using a digital image correlation (DIC) method. A substantially large strain localization region emerged on the surface of the specimens before the tensile stress approached its ultimate value; subsequently, this strain localization region coincided with the final crack. Based on the measured tensile strain, a parameter was proposed to describe the average gradient of the tensile strain. This parameter was found to be much larger near the crack than in the other regions. Experimental results showed that the damage was related to the strain as well as to the strain gradient. These results may provide a practical foundation for a new gradient damage theory for rocks under tensile loading.

1. Introduction

Knowledge on the damage mechanisms of rocks is an important basis for the study of mechanical excavation engineering. In recent years, many damage theories have been proposed based on quasi-brittle materials [1–3]; a lot of experimental papers have been published [4,5]. However, most of the experimental studies focus on the damage evolution of the rock material under compressive or shear load.

Tensile failure of rock plays an important part in engineering, such as impact crushing, surrounding rock collapse, and tunnel excavation [6–8]. Since the tensile strength of rocks is far lower than the shear strength or compressive strength, tensile breaking is the most energy-saving crushing manner [9–12]. Study of the rock damage mechanisms under tensile load can provide an important practical basis and indispensible guide to the parameter design of crushing devices. Generally, the rock material does not lose its entire load-carrying capacity at the initial stage of damage. This behavior is commonly referred to as quasi-brittle fracture. Gradient damage models are powerful tools to investigate damage processes in quasi-brittle materials [13–15]. Usually, the gradient damage models of quasi-brittle fracture can be grouped into three categories: micro-mechanical models, macro-mechanical models and continuum damage models [16–21]. However, these studies are mainly theoretical or numerical for quasi-brittle materials. To our best knowledge, no experimental studies are reported on the relationship between tensile damage and the tensile strain gradient in rock materials.

Because of the difficulty associated with direct tensile tests, indirect methods, such as Brazilian disc test and splitting tension test [22–24], were used as convenient alternatives to measure the tensile strength of rock materials. From the Brazilian test, we can determine the ultimate tensile strength of a rock material. However, it is difficult to establish a relationship between the stress and strain from this test since both the stress and strain of the specimen are non-uniformly distributed. Another method of measuring the tensile strength of rock materials is the Hopkinson bar test. From such a test, we can also determine the ultimate tensile strength of a rock material. However, the strain on the specimen surface cannot be accurately captured under the high-speed impact employed in this test. Hence, it seems impossible to establish a unified constitutive model by using the indirect methods. In a uniaxial compressive loading test, tensile cracks may appear on the surface of rock specimens because of Poisson's effect [25]. However, no tensile stress exists in this case, and the tensile strain is not the primary strain.

In recent years, some ingenious traction devices were designed [26,27] to study the tensile strength of rocks. However, because of the use of cylindrical specimens, it became difficult to measure the strain on the curved surfaces of the specimens. Nonetheless, by using a suitable clamping device and by carefully preparing a specimen, the feasibility of direct tensile experiment was verified.

The digital image correlation (DIC) method can be used to study the surface field information of the object. It possesses many advantages, such as simple experimental steps, high accuracy and high computational efficiency [28–34]. DIC has been extensively applied to

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* Corresponding author. Tel./fax: +86 22 27407513.
E-mail address: zxcai@tju.edu.cn (Z. Cai).

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measure the full-field information of quasi-brittle materials by an increasing number of researchers currently. For example, Leplay [35] used DIC to analyze the crack growth behavior of ceramics; Dai [36] employed DIC to measure the fracture process of the cast iron. Zhang [4] used DIC to investigate the fracture mechanism of sandstone under indentation. Ma [37] used high-speed DIC to analyze the damage evolution of the granodiorite disc in Brazilian test. Hence, this sophisticated technique is capable of capturing the surface field information of the rock specimens under quasi-static tensile loading [38,39].

This paper presents an experimental investigation of the damage mechanisms of granites under uniaxial tension. A number of images are captured for calculating the full-field distribution of displacement and tensile strain on the surface of the specimen during the whole evolution process. Then, the qualitative relationship between the tensile damage and strain gradient is discussed. Finally, the tensile damage formation mechanisms are discussed based on the scanned micro-structure images of the fracture's surface.

2. Experimental set-up

2.1. Preparation of specimen

Granite used in this study came from Shandong province, China. It is a common type of rocks in crushing engineering. Specimens were prepared to a flat dog-bone shape by the latest ceramic processing technique, which was supported by the Key Laboratory of Advanced Ceramics and Machining Technology at Tianjin University. The whole specimen was 135 mm × 35 mm × 5 mm (length × width × thickness); the effective experimental section was 40 mm × 20 mm × 5 mm (Fig. 1). Surfaces of the specimens were painted with random black paints in order to make better artificial speckles.

2.2. Experimental procedure

The tensile tests were performed at an electronic universal testing machine with a pneumatic fixture that could firmly clamp the specimens without breakdown (Fig. 2). The machine model is Instron E10000, which had the maximum load capacity of 10 kN. During the tests, a hydraulic actuator was loaded at a speed of 0.02 mm/min under displacement-controlled loading. Images were recorded during the test at a frequency of 10 Hz by using a Grasshopper CCD camera (Grasshopper 2011, Point Grey, Canada) placed in front of the specimen. The images were 2448 pixel × 2048 pixel with a 8-bit dynamic range. At the same time, an extensometer was set on the back surface of the specimen to record the elongation of the current experimental section. Due to the impact of a non-pneumatic camera alignment to the specimen's surface [40], two measures have been taken. First, a horizontal calibration instrument was set on the camera support to ensure that the camera was in a horizontal plane. Second, a preload of 50 N was applied on the specimen by the pneumatic fixture to ensure the axis of the specimen along the vertical direction. The two measures can also reduce the out-of-plane effect, which is an inevitable defect of 2D-DIC. After the test, an image of the 100th step (the 10th second) was chosen as the reference image in DIC analysis. Also, a number of images were chosen, which had a calculation region of about 20 mm × 15 mm for subsequent processing by commercial software called Vic-2D (Vic-2D 2009, Correlated Solutions, Columbia, SC, USA). Vic-2D has been used for the evaluation of the full-field displacement or strain of the solid materials; its reliability has been proven [41]. Considering the characteristics of inhomogeneous deformation in rocks, a small calculation subset size (15 pixels × 15 pixels) and step length (5 pixels) were chosen to increase the spatial resolution of measurement. The apparent strain fields were obtained using a strain windows size of 15 pixels × 15 pixels. In order to verify the accuracy of the DIC, a zero deformation experiment was conducted under the same conditions (magnification factor, speckle size, illumination conditions, etc.). The resolution of the images was 0.019 mm/pixel. The displacement measurement accuracy in the same experimental environment was at least 1 μm based on our calibration. To observe the microscopic structure of the specimen surface, a field emission scanning electron microscope (FE-SEM) (Nanosem 430, FEI, USA) was used.

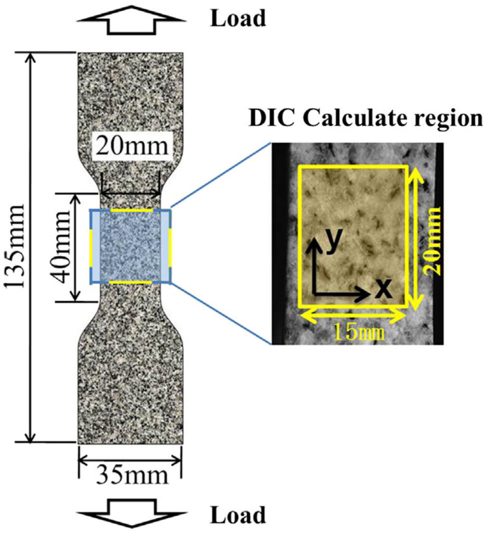

Fig. 1. Specimen schematic and the ROI (region of interest) for DIC calculation measurement (note: the thickness of the specimen is 5 mm).

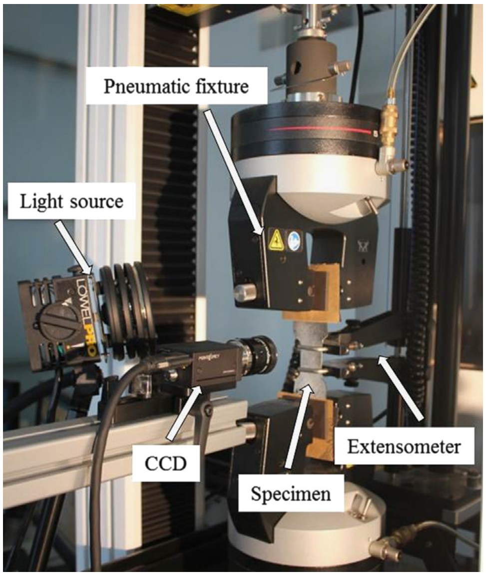

Fig. 2. Experiment set-up.

3. Results and discussion

Four identical specimens were tested in the experiment. Similar results were obtained for the different specimens. Specimen no. 2 is selected as an example to illustrate the experimental results due to its good image quality.