International Journal of Rock Mechanics and Mining Sciences 106 (2018) 1–13

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics and Mining Sciences

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

Cohesion degradation and friction mobilization in brittle failure of rocks

Hossein Rafiei Renani*, C. Derek Martin

Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada T6G 1H9

ARTICLE INFO

Keywords:
CWFS model
Damage-controlled test
Plastic strain
Stress path
Parameter estimation

ABSTRACT

The progressive process of brittle failure was studied using the results of laboratory damage-controlled on the samples of Lac du Bonnet granite and Indiana limestone under uniaxial and triaxial loading conditions. A similar trend of decreasing crack damage stress, peak stress and cohesion and increasing friction angle with increasing damage was observed for both rocks which confirmed the previous findings from the results of uniaxial tests. While the absolute strength of Lac du Bonnet granite is much higher than Indiana limestone, the normalized crack damage stress curves for both rocks were similar. It was shown that cohesion degradation is mainly a function of accumulated damage and is not sensitive to confining stress. Friction mobilization, on the other hand, dependents on both the damage level and confining stress and decreases with increasing confinement. A non-linear Cohesion Weakening Friction Strengthening (CWFS) model was proposed to capture the process of brittle failure at the laboratory scale. The results of the model were in reasonable agreement with experimental stress-strain curves at different levels of confining stress. A simplified version of the CWFS model was proposed for in situ applications and implemented in the finite difference code, FLAC3D for numerical modeling of four underground excavations at the Underground Research Laboratory in Canada. In all cases, the CWFS model closely captured the observed zone of brittle failure around the excavation. The proposed in situ CWFS model eliminated the problematic behavior of the current linear CWFS models by using identical plastic strain thresholds for residual cohesion and residual friction angle. It was shown that the proposed CWFS model offers sufficient versatility to be applied to a wide range of geomaterial with strain softening and strain hardening behavior. Empirical guidelines were proposed for estimating the parameters of the proposed in situ CWFS model for good quality rock masses.

1. Introduction

Strength of materials has long been a subject of interest in engineering design and numerous strength theories have been proposed over the years. While modern day theories often become increasingly complex, the fundamental components which contribute to the overall strength of materials can be explained in simple terms.

Starting from the simplest system where there is a contact between two separate bodies, Amonton's law of friction states that the shear force required to cause the slip is proportional to the normal force acting on the surface and the coefficient of proportionality is the friction coefficient. Adding some bonds between the contacting bodies, Coulomb criterion states that there is still a direct relationship between the critical shear force and the applied normal force. However, there is finite shear strength even at zero normal force in a bonded system. This is the cohesive component of strength which entirely depends on the bonds between the contacting surfaces. The system of bodies with bonded contacts is similar to the microstructure of rocks composed of mineral grains attached together and provides a useful model to study the strength of brittle rocks.

Researchers[1,2] have shown that during a standard compression test that follows the ISRM suggested methods,[3] brittle rocks go through five distinct stages shown in Fig. 1. In stage I, existing cracks are closed under relatively low stresses causing low initial stiffness. Following crack closure, stage II starts with linear elastic deformations in axial and lateral directions. In stage III, stable axial cracks are initiated causing acoustic emissions and departure from linear expansion in the lateral direction. As loading continues, the length and number of microcracks within the material increase to a point where axial microcracks begin to coalesce together and form shear cracks. This marks the start of stage IV, unstable crack growth, and the corresponding stress level is called the crack damage stress. Aside from a sharp increase in the number of acoustic emissions, crack damage stress can also be identified using the volumetric stress-strain response and denotes where the sample ceases to contract and starts to dilate. Crack damage stress also corresponds to the long-term strength of the material[4] as higher loads can only be

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* Corresponding author.
E-mail address: rafiaire@ualberta.ca (H. Rafiei Renani).

https://doi.org/10.1016/j.ijrmms.2018.04.003
Received 11 September 2016; Received in revised form 22 March 2018; Accepted 5 April 2018

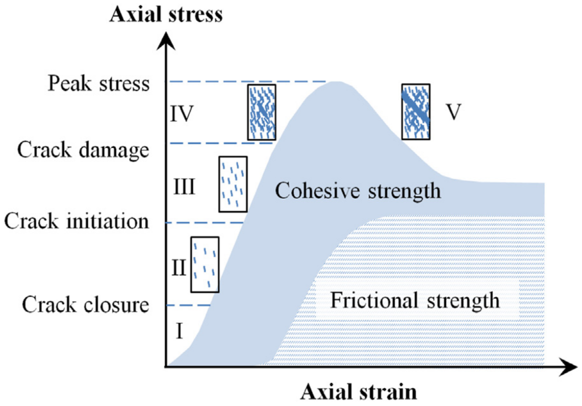

Fig. 1. The process of brittle failure of rocks under compression[1] and the possible development of the cohesive and frictional strength components, modified after.[5].

sustained for a short period of time and cannot be relied on for the long term.[2] By increasing loading, the peak stress is reached which marks the start of post-peak stage V associated with a macro shear failure and drop of stress level.

From a microscopic point of view, the rock sample in a triaxial test starts from an initial state with some pre-existing microcracks and experience damage i.e., initiation, propagation, and coalescence of cracks. Going back to the concept of a bonded contacts model, as crack density increases the number of bonds and therefore cohesive strength decreases (Fig. 1). Frictional strength, on the other hand, develops with increasing the number of crack surfaces and will be present even after all the bonds are broken (Fig. 1). This suggests a cohesion weakening and friction strengthening (CWFS) model for brittle failure of rocks.

The commonly used continuum models based on simultaneous mobilization of cohesion and friction ignore the interrelationship between damage, deformability, and strength and have shown to be ineffective in capturing the in situ brittle failure of rocks.[5] While the CWFS model suggested by Martin and Chandler[2] and implemented by Hajiabdolmajid et al.[5] has gained wider acceptance,[6–9] little work has been carried out to develop the methodology using the results of confined laboratory tests. In this study, the results of triaxial damage-controlled tests are used to capture the evolution of cohesion and friction during the entire failure process. Equations are proposed to model the observed cohesion weakening and friction strengthening in the laboratory and in situ. The models are implemented in numerical analysis and case studies are used to verify the proposed approach.

2. Damage-controlled laboratory tests

Standard triaxial compression tests using stiff servo-controlled loading machines can provide pre- and post-peak stress-strain curves at different levels of confining stress. However, they provide little if any information regarding the gradual damage process (crack initiation, propagation, and coalescence) and its effect on the fundamental components of strength, i.e., cohesion and friction. To investigate the effect of incremental microstructural damage on the macroscopic strength characteristics, Martin[10] used the results of a series of damage-controlled compression tests on samples of Lac du Bonnet (LdB) granite from the Underground Research Laboratory (URL) and Cold Spring Quarry (CSQ) and Indiana limestone. The test specimens were prepared according to the ISRM suggested methods.[3]

In the damage-controlled tests, the axial and confining stress were initially increased simultaneously at a rate of 0.75 MPa/s to reach the desired confinement level. Axial stress was then increased at the same rate up to about 75% of the expected peak strength with unload-reload cycles. In order to ensure a controlled damage process, the unload-reload cycles after 75% of the peak strength were carries out at 0.063 mm increments of circumferential deformation. During unloading, axial stress was reduced to confining stress in triaxial tests and to 5 MPa in the unconfined tests. The results of damage-controlled tests were shown to be in agreement with standard compression tests. More details on the damage-controlled tests can be found in.[2,10]

The damage-controlled tests reported by Martin[10] provided pre- and post-peak stress-strain curves during a gradual damage process (Fig. 2) and the results are used in this study to develop theories and modeling approaches.

2.1. Tests on LdB granite samples from the URL

A comprehensive set of damage-controlled tests were carries out on the samples of Lac du Bonnet granite from the 420 level of the Underground Research Laboratory (URL) owned by Atomic Energy of Canada Limited.[10] The results under uniaxial and triaxial loading with confining stresses of 10, 20, 40, and 60 MPa have been analyzed. In order to quantify the extent of damage within the sample, volumetric

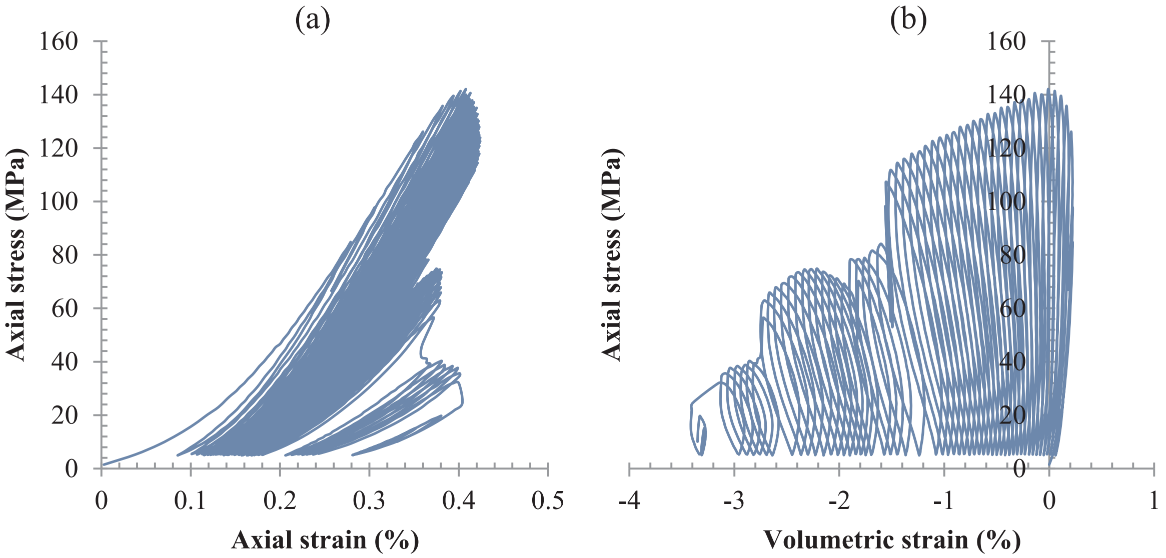

Fig. 2. Results of unconfined damage-controlled tests on a sample of Lac du Bonnet granite from the Underground Research Laboratory (URL), (a) axial stress vs. axial strain, (b) axial stress vs. volumetric strain.