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Experimental and numerical study on the strength and hybrid fracture of sandstone under tension-shear stress

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ABSTRACT

Hybrid tension-shear fracture of rock usually occurs in underground openings, rock slopes, transtension faults, and en echelon cracks. To investigate the tension-shear strength and the transition between tensile and shear fractures in rock, experimental and numerical tension-shear tests were carried out using an auxiliary device and particle flow code (PFC^{2D}), respectively. The deformation and shear strength of a sandstone under tension-stress were analyzed. The initial crack (the first micro-crack) and the shear failure ratio (the proportion of shear cracks in the total number of cracks) were proposed and used to describe the mechanical properties of hybrid fracture. In addition, the force chains of parallel-bonds in the PFC model were investigated. The results show that the initial crack is a tensile crack if the normal tensile stress is large, whereas it is a shear crack when the normal tensile stress is smaller. The shear failure ratio decreases linearly with increasing normal tensile stress, and the micro-cracks are all tensile cracks in the uniaxial tensile simulation, which suggests that the transition from tensile to hybrid and shear fracture is continuous and linear. Most of the bonds between particles are subjected to tension-shear stress, while some bear compression-shear stress. In the tension-shear tests, shear micro-cracks may be formed under either tension-shear stress or compressive-shear stress. A new tension-shear failure criterion was proposed, which is more accurate than the existing failure criteria and is associated with the features of microscopic fractures. The proposed criterion can account for the microscopic physical significance of the parameter in the Hoek–Brown criterion.

1. Introduction

Tensile and shear fractures are two basic types of brittle rock failure [1,2]. Hybrid tension-shear fracture (i.e., transitional-tensile fracture) occurs widely in underground openings [3,4], rock slopes [5–7], transtension faults [8,9], and en echelon cracks [10].

Hybrid fractures are commonly formed under tension-shear stress. However, a direct shear test under normal tensile stress is very challenging to carry out owing to technical limitations in applying the tension-shear stress to brittle rock samples. As a result, researchers have developed several experimental methods and testing devices to perform tension-shear tests. Aimone-Martin et al. [11] designed a testing device on a MTS system via a symmetrical four-link mechanism to examine the deformation and strength of rock salt under tension-shear loads. The device could transform the vertical compressive load from the testing machine into a tensile stress on the sample in the vertical direction and a shear stress on the sample in the horizontal direction. However, the normal tensile stress and shear stress are proportional to each other (Aimone-Martin et al. [11]) despite three pin connectors in the design. Ramsey

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and Chester [12] conducted axial tensile tests under confining compression on a dog-bone-shaped marble to investigate hybrid fracture and the transition from extension to shear fracture. In testing the tension-shear strength and deformation, this method showed a similar limitation as the method developed by Aimone-Martin et al. [11] due to the dependency between the tensile and shear stresses. To determine the shear strength of kaolinite clay under different normal tensile stresses, Suits et al. [13] used bowtie-shaped specimens. This allows the normal tensile stress and shear stress to be applied independently. However, it is very difficult to process a bowtie-shaped rock specimen. Recently, an important breakthrough was made by Cen and Huang [14]; they designed a double bracket-shaped device to test the mechanical behavior of sandstone under tension-shear stress using a direct shear testing machine. This device overcomes the difficulties regarding the dependence of normal tensile and shear stress.

For the tension-shear failure criterion, the Mohr–Coulomb (M − C) criterion is widely used. According to Handin and Hager [15] and Ferrill et al. [16], the M − C criterion has three typical envelopes to describe the tension-shear strength: (1) a linear M − C envelope; (2) a linear envelope and break at tensile strength; and (3) a nonlinear envelope in the tensile region. The Hoek–Brown (H–B) criterion, also widely used as a tension-shear strength criterion, is considered the third type of envelope. Cen and Huang [14] discussed the suitability of other failure criteria, e.g., the two-parameter parabola failure criterion (Paterson and Wong [2]), three-parameter parabola failure criterion, and hyperbolic failure criterion, for tension-shear failure of rock. In addition, Zhu [17] derived a new failure criterion for brittle rock, which is based on micromechanical unilateral damage–friction coupling analyses.

The propagation of tension-shear fractures and the mechanism for the transition between tensile and shear failures is still unclear [16]. Recently, however, Ramsey and Chester [12] and Ferrill et al. [16] made some important achievements in this respect. Ramsey and Chester [12] found that the fracture angle increased with increasing confining pressure, which provided the first convincing laboratory evidence for the existence of hybrid fractures. Ferrill et al. [16] reported that documented field examples of hybrid fractures are rare, and hybrid fracture is likely an indicator of a tensile minimum effective stress and low differential stress at failure. However, despite having found laboratory and field evidence, the correlation between the microscopic fracture mechanism, macroscopic fracture form, and tension-shear strength is still unclear.

In this study, laboratory double shear tests were first conducted using a simple device to reveal the characteristics of the tension-shear deformation and tension-shear strength of rock under different normal tensile stresses. Numerical simulations using particle flow code (PFC^{2D}) were also conducted to further analyze the propagation and mechanical properties of hybrid tension-shear fractures from a micro-perspective. The initial crack and shear failure ratio could effectively describe the mechanical properties of the hybrid tension-shear fracture. Finally, a new tension–shear strength criterion based on the micro-fracture characteristics was established.

2. Methods

2.1. Laboratory direct shear tests under normal tensile stress

The double shear method, which is widely used in investigations of rock and concrete mechanics [18,19], was used to perform the tension–shear tests. As shown in Fig. 1, rock samples with dimensions of 120 (length) × 60 (height) × 60 (thickness) mm were obtained for testing from an intact red sandstone block with a bulk density of 2390 kg/m^3. Displacement constraints were imposed in the *y*-axial direction on both the upper and lower boundaries of areas R1 and R2 (Fig. 1). A vertical downward shear force is applied to the upper boundary of area R3. At the beginning of the test, a normal tensile stress, σ_n, was first applied to the target level at a

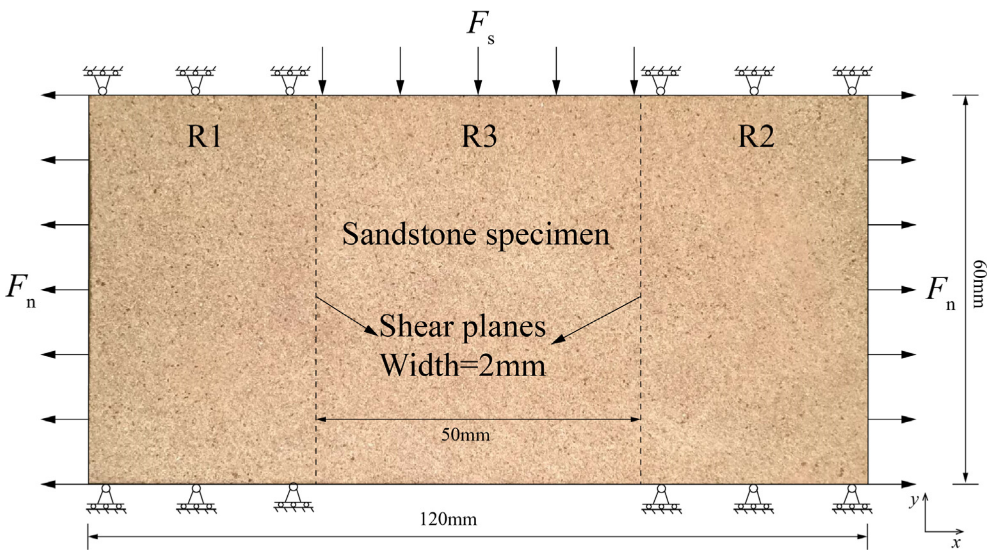

Fig. 1. Schematic of double shear test under normal tensile stress.