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Failure characteristics of jointed rock-like material containing multi-joints under a compressive-shear test: Experimental and numerical analyses

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ABSTRACT

Extensive efforts have been made to gain a better understanding of the failure behaviour of rocks and rock-like materials, but crack propagation and failure processes under compressive-shear loading have not yet been comprehensively investigated. To address this area of research, the peak shear strengths (τ) and failure processes of specimens with multiple joints are studied by lab testing and particle flow code (PFC2D). Four types of failure modes are observed: (a) shear failure through a plane (Mode-I), (b) intact shear failure (Mode-II), (c) oblique shear crack connection failure (Mode-III), and (d) stepped path failure (Mode-IV). The failure mode gradually transformed to Mode-III as α (joint inclination angle) increases from 0° to 90° in the specimens. In addition, with increasing joint distance (d) in the specimens, the failure mode changes to Mode-II. As the non-overlapping length between joints (c) in the specimens increases, the failure mode changes to Mode-IV. The joint geometry has a major influence on the shear strength of the jointed specimens. The peak shear strength of specimens with different joint inclination angles is obtained when $\alpha = 45°$. Additionally, the peak shear strength increases as the joint distance (d) and non-overlapping length (c) increase.

1. Introduction

Rock masses are typically heterogeneous brittle materials containing discontinuities such as cracks, joints, and fissures. Discontinuities in the natural rock masses have a considerable influence on the strength and failure behaviour of the rock masses. During the failure process of a rock mass, the existence of many discontinuities results in an extremely complex development pattern with strong non-linear characteristics. Therefore, in most rock slope projects, it is difficult to estimate the strength and failure characteristics of a rock mass. Therefore, it is necessary to study the crack initiation, propagation and failure processes in a rock mass in a slope-induced stress environment, and the results can be used to guide the prediction of the instability slip of the slope.

The coalescence of fractures and the strength degradation of jointed rock masses are of considerable interest to engineers

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and scientists. Previous studies show that two types of cracks will initiate from pre-existing joints under loading [1–6]. However, the coalescence pattern of fissures or joints is influenced by the fracture geometry. Based on laboratory tests of gypsum specimens, Shen [1] found that pre-existing joints mainly propagate as tensile cracks, shear cracks and mixed-mode cracks. Bobet and Einstein [6] identified five types of failure patterns from uniaxial compressive tests of gypsum specimens with parallel flaws. Wong and Chau [7] carried out uniaxial compression tests on plaster specimens with two flaws and identified nine types of coalescence patterns. Park [8] categorized the crack coalescence patterns from the results of uniaxial compression tests on Diastone and Yeosan marble into seven groups. Moreover, Lee and Jeon [11] investigated the coalescence mode between two non-parallel joints, and the joints mainly coalesced via tensile cracks or tensile and shear cracks. Zhang et al. [10] also studied the coalescence behaviour of non-parallel flaws, and their results identified five types of linkage between the two flaws: tensile crack linkage, tensile crack linkage with shear coalescence at the tip, shear crack linkage, mixed linkage, and indirect crack linkage.

In specimens with multiple joints, tensile cracks and shear cracks initiate under loading from the tips of pre-existing joints. With further loading, new cracks propagate and are linked with others, which ultimately causes overall failure. Previous studies on the failure characteristics of specimens with multiple joints have primarily concentrated on compression tests. In addition, many aspects of the joint geometry were considered in previous studies, such as the joint inclination angle [11–16], joint distance [11–16], and overlap distance [13,14]. Prudencio and Van Sint Jan [14] conducted laboratory tests on physical models of rock with non-persistent joints, and the failure modes of the specimens were classified into three categories: failure through a planar surface, stepped failure, block rotation, planar failure. Cao et al. [11] identified four types of failure patterns from experimentation on rock-like specimens with multiple joints. The failure patterns of the specimen with multiple joints included mixed failure, stepped path failure, shearing failure and intact failure.

Compared with compressive tests, the failure behaviour of rock masses under shear loading has not been studied as extensively. Additionally, most existing studies are based on direct shear tests [17–21]. However, field cases such as rock slopes indicate that rock masses are commonly in both a compressive and shear environment. Both compressive and shear forces have a considerable influence on the failure of jointed specimens, and the crack initiation, propagation and failure process under compressive-shear loading will be quite different from that of either pure compressive loading or shear loading. Therefore, in this research, the crack coalescence and failure characteristics of specimens containing multiple intermittent joints under a compressive-shear test will be investigated with the aid of a rock-like material and PFC2D.

2. Experimental and numerical details

2.1. *Specimen preparation and material properties*

The specimens are made of high-strength white cement, fine sand and water at volume ratio of 3:3:2, respectively. The dimensions of the specimens are 100 mm (height) × 100 mm (width) × 30 mm (thickness). Joints are created by inserting mica sheets (0.6 mm thick and 15 mm long) into the fresh cement mortar paste at the experimental joint locations. The strength parameters (average value) for the intact materials are shown in Table 1. In terms of strength parameters, the rock-like material can be viewed as soft rock. Meanwhile, it exhibits an obvious brittleness. Because the bond strength between the cement and sand is high, deformation under loading will be minimal. In addition, as the grains in the specimen were sand, when the specimen fails, it can provide the frictional behaviour of the modelling material.

The geometrical parameters of the joints used in our experiment are shown in Fig. 1. As shown in Fig. 1, the position and number of mica sheets inserted in the mortar are varied to produce joints with different inclination angles (the angle of the pre-existing joint from the horizontal, α), joint distances (the distance of parallel joints, d) and non-overlapping lengths (the non-overlapping length of two joints, c). Table 2 provides the sample numbers and geometrical parameters of the joints placed in the specimens. For all specimens, b is 20 mm.

It can be seen from Table 2 that α varies from 0° to 90°. In addition, for increasing α, the joint distance d changes from 15 mm to 36 mm, at increments of 7 mm. The specimens with numbers 1–6 and 25–42 are used to investigate the influence of the non-overlapping length c on the mechanical behaviour of jointed specimens, while c varies from 0 to 15 mm and the other parameters are kept constant.

2.2. *Testing system and loading procedure*

As shown in Fig. 2(a), the shear box tests are positioned between the two loading platforms, and the top and bottom boundaries are unconstrained in the horizontal direction. The displacement loading rate is fixed at 0.2 mm/min. A specimen is placed between two bevelled die blocks at a certain inclination angle with respect to the horizontal direction, 45° (Fig. 2(a)). All specimens are loaded until specimen failure, and the load-displacement curves of the jointed samples are recorded simultaneously via a data acquisition system. Under loading, a jointed specimen experiences the boundary stresses shown in Fig. 2(b).

2.3. *Numerical model and micro-parameters*

Compared with in situ and laboratory testing, numerical simulation is an economical and practical method to study the failure processes of jointed rock masses. In recent years, many numerical methods have been used to simulate the failure

Table 1 – Experimental results for the macro-mechanical parameters of the intact material.

Item	Experimental result
Uniaxial compressive strength, UCS (MPa)	21.73
Young's modulus, E (GPa)	5.64
Poisson's ratio, ν (–)	0.243
Uniaxial tensile strength, σ_t (MPa)	1.355