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Anisotropy and directionality of tensile behaviours of a jointed rock mass subjected to numerical Brazilian tests

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ABSTRACT

Strong anisotropy of tensile behaviros and spatial anisotropic deformation have been found in transversely isotropic rock discs. There is seldom attention paid for the insightful analysis of anisotropy and spatial variability of tensile behaviours for jointed rock masses. In the paper, an index termed as the "directionality" was proposed to quantitatively assess both the directionality and spatial variability of tensile strength of jointed rock masses. Experimental Brazilian tensile tests were carried out on stratified biotite granulite rocks. Corresponding to the configurations of laboratory tests, numerical simulations of rock specimens with different joint distributions and discrete fractures network (DFN) models were then performed using PFC2D code. The results indicated that the stratified rock discs displayed distinct anisotropy and directionality in tensile strength, manifested by the decreasing strength with inclination angle. The maximum directionality of the stratified rocks measured in laboratory was 2.40/0°, which was perpendicular to the layered discontinuities, while the tensile strength determined by DFN models showed a lower anisotropy and directionality (1.38/30°). Obvious anisotropic characteristics were observed in the fracture patterns of failure in DFN models. This paper implies the necessity of consideirng the anisotropy and directionality for the study of failure mechanisms of surrounding rocks in underground tunnels.

1. Introduction

Deformation and strength of the surrounding rock of underground tunnels is a key issue in the stability analysis of tunnel engineering. The intrinsic discontinuities such as faults, fractures, joints, and cracks render rock masses highly heterogeneous and their mechanical behaviours discontinuous and anisotropic (Amadei, 1996; Jiang et al., 2006; Fortsakis et al., 2012; Xu et al., 2013; Yu et al., 2014; Wasantha et al., 2015; Li et al., 2016; Johansson, 2016). Generally speaking, the tensile behaviours of rock materials are relatively weaker than other mechanical behaviours such as compressive or shear behaviours. Such weak planes can result in much lower levels of tensile strength and can contribute significantly to the anisotropic behaviours of rock masses. Thus, it is necessary to explore the anisotropy of tensile behaviours of jointed rock masses in the field of geotechnical engineering.

Brazilian (indirect) tensile tests of rock discs have been widely performed to investigate the tensile behaviours of rock materials (Vervoort et al., 2014; Dan and Konietzky, 2014; Duan and Kwok, 2015; Wang et al., 2016a,b,c; Khosravi et al., 2017; Xia et al., 2017; Yuan and Shen, 2017; Zhang et al., 2018). Effects of anisotropy on the indirect tensile strength of stratified rocks determined by Brazilian tests have been investigated by Wu et al. (2010) in reference to dolostone; by Cho et al. (2012) in reference to gneiss, shale and schist; by Liu et al. (2013) in reference to coal; by Dan et al. (2013) in reference to slate; and by Tavallali and Vervoort (2010) and Khanlari et al. (2015) in reference to sandstone. Overall, the tensile strength is apparently affected by rock anisotropy. Rock samples have been found to fail along the loaded diameter irrespective of the orientation of joint planes. The total lengths of cracks of anisotropic rocks vary and certain relationships with inclination angles have been reported. Khanlari et al. (2015) found two major modes of failure in fractured specimens. For lower inclination angles with respect to the horizontal ($< 60°$), fractures occur parallel to the loading direction with or without branching (fractures are independent of lamination), whereas for higher angles of inclination ($> 60°$), a failure mode along laminations dominates. Ma et al. (2017a,b) discussed the anisotropy of tensile strength in the analysis of fracture pressure. And the anisotropy ratio in tensile strength was found to have a great influence on fracture pressure. The importance of the

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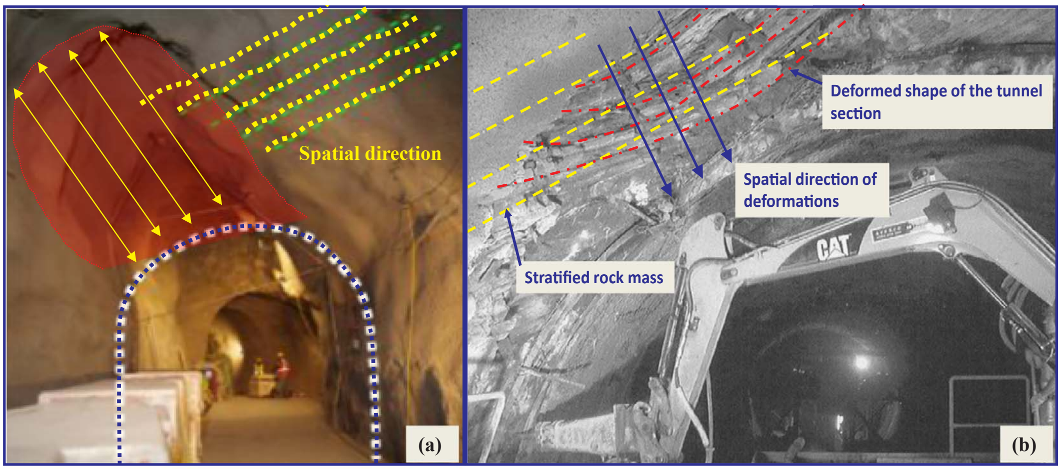

Fig. 1. The spatial distribution of geological structure and corresponding fracture patterns. (a) Is reported by Li (2013) and (b) is by Seingre (2005).

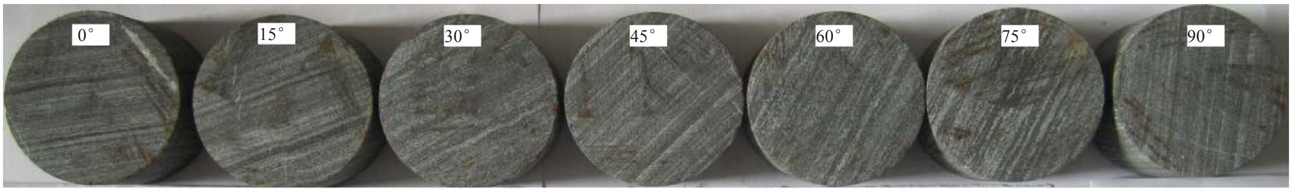

Fig. 2. Rock samples for Brazilian tests with different joint angles.

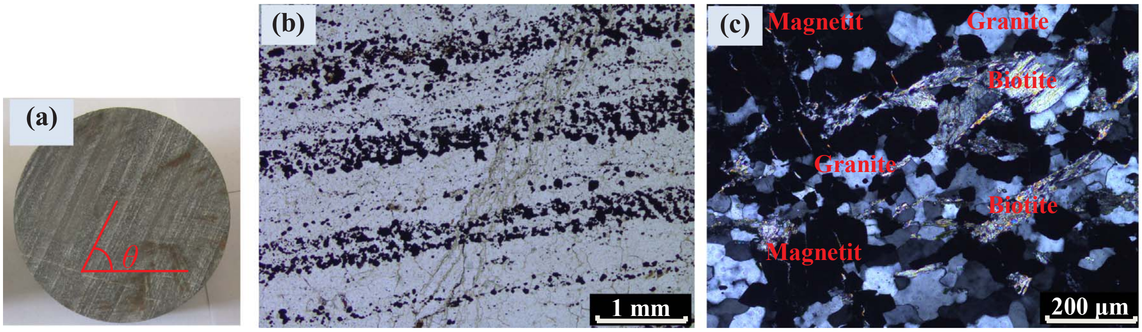

Fig. 3. Cored rock samples and thin sections of stratified granulite. (a) Is the cored rock samples. (b) and (c) Show the thin sections of rocks (Wang et al., 2017).

influence of anisotropy in the prediction of fracture pressure was emphasized. Zhang et al. (2018) investigated the failure patterns of layered shale discs under Brazilian test using acoustic emission (AE) technique. The AE spatial distribution relating with the bedding angles was discussed, which provides a better understanding of the anisotropic failure mechanism.

It has been reported that fracture network systems play a significant role in determining the compressive strength (Min and Jing, 2003; Jia and Tang, 2008; Wang et al., 2012; Wang et al., 2016a,b,c; Yang et al., 2017; Zhou et al., 2018) or shear strength (Bahaaddini et al., 2014; Bahaaddini et al., 2016a,b; Wang et al., 2017) of rock masses. The anisotropic tensile behaviours of stratified rocks have been widely studied. However, results regarding anisotropy induced by the presence of complex discontinuities are rarely reported. Li (2013) has found a typical failure pattern for an underground excavation (Fig. 1) resulting from the presence of natural joints. Tensile fractures were observed in the in-situ survey area. Lisjak et al. (2015) observed a strong anisotropic response from a tunnel cross-section measured with average convergence. It was found that displacement in the direction perpendicular to the bedding orientation is approximately 4 times greater than that measured parallel to the bedding. Seingre (2005) has reported the deformations observed in the stratified Lias limestone in Lötschberg tunnel. The deformed steel sets and surrounding rock masses were greatly influenced by the orientation of discontinuities. The deformed shape of the tunnel section from many numerical analyses (Jia and Tang, 2008; Fortsakis et al., 2012; Wang et al., 2012) considering the anisotropy is always perpendicular to the discontinuities direction in the transversely isotropic rock masses, which is in very good agreement with the deformations observed in tunnel excavation case studies (Seingre, 2005; Li, 2013; Lisjak et al., 2015; Yang et al., 2015). The anisotropy of the jointed rock mass should be a key influencer of to the study of the development of deflections. Many researchers have carried