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Influence of joint anisotropy on the fracturing behavior of a sedimentary rock

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ABSTRACT

Fracture toughness (FT) and tensile strength (TS) indicate a rock's susceptibility to fracturing. Past studies showed that mechanical properties and FT of homogeneous rocks can be correlated well. In the present study, this capability has been extended to the jointed sedimentary rocks. Sandstone with a wide combination of analogue joints were tested in the laboratory, and the control of joint geometrical properties on the FT, TS, and development of fracture process zone (FPZ) were investigated. A FT prediction model was developed based on the TS of the jointed specimens. Multifractal scaling law (MFSL) was utilized to extend the laboratory results to the field scale. Further, the interaction of propagating crack with the already existing joints were investigated and post-peak behavior were studied. Results show that FT and TS decrease with decreasing joint spacing, but they are more sensitive at higher joint spacing. It is also possible to construct a linear prediction model between the FT and TS of rock. FPZ of jointed rock is less sensitive to joint orientation and more related to joint spacing. A negative correlation between the FPZ size and joint spacing is established in this study. Post-peak behavior of the jointed specimens indicate that crack-joint interaction increases the frictional resistance and dissipated fracture energy of the specimens. Further, comparison of mixed-mode fracture criteria with the experimental results show that Maximum Tangential Stress (MTS) criterion can successfully predict the mixed-mode fracture behavior of jointed sandstone.

1. Introduction

Jointed rocks and fractured rock mass possess a greater complexity than the homogenous rocks in designing the hydraulic fractures, rock cutting, drilling and blasting, and slope stability analyses. The direction and extent of fracture propagation in such cases are strongly controlled by the joint spacing and orientation. Since a rock is much weaker under direct tension than under any other kind of stress, the knowledge of FT and TS of the jointed rocks are essential for modelling purposes. A large number of research have been done on the effects of temperature, confining pressure, strain rate, humidity, fluid alkalinity on the FT and TS of homogeneous rocks, but little attention has been paid to the effect of heterogeneity (Al-Shayea et al., 2000; Aliha et al., 2010; Vishal et al., 2011; Yin et al., 2012; Nara et al., 2012; Zhang and Zhao, 2013; Guha Roy and Singh, 2016; Guha Roy et al., 2016; Mahanta et al., 2016; Gautam et al., 2016). Although, the fracture mechanical characterization of anisotropic rocks has been discussed by several researchers and standards (Nasseri and Mohanty, 2008; Dai et al., 2013; Dai and Xia, 2013; Kuruppu et al., 2014; Ghamgosar et al., 2015), they failed to incorporate the effects of rock joints in their findings. Only limited work has been undertaken to address this issue (Funatsu et al., 2012). It has long been accepted that the increasing number of joints could significantly weaken the rock mass strength (Tien and Tsao, 2000; Nasseri et al., 2003; Park and Min, 2015; Wasantha et al., 2015). But, no such findings on the effects of rock joints and their orientations on the FT of the sedimentary rock has been reported.

It can be expected that the fracture properties of the intact and jointed rock will not be similar if the effect of joints are taken into account. Furthermore, measurement of FT is a very complex and cumbersome process. It becomes more difficult if natural joints are present. Therefore, development of a FT predictive model is essential for practical applications. Multiple past research have confirmed the strong inter-relation between the fracture toughness and geomechanical properties of dry and saturated rocks (Zhang, 2002; Jin et al., 2011; Guha Roy et al., 2017a, 2017b). Also from a practical point of view, determination of the TS of subsurface beds is easier than the measurement of the FT using well-logs. Hence, in the present paper the relationships among the pure-and mixed-mode FT and TS were

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investigated and predictive models were developed. Further these results were upscaled to the field scale using multifractal scaling laws (MFSL).

In order to investigate the effects of the number and the orientation of joints on the fracture properties of sandstones, a systematic experimental investigation was undertaken. Since any natural anisotropic rock type can only have a definite number of joints, a single rock with systematically varying joint spacing cannot be found. Using different types of sandstones with different number of joints would cause undesired effect of different physical properties on the FT and TS results. Therefore, a number of artificial joints with varying number and orientations were created in an otherwise homogenous Dholpur sandstone. This process ensured that all the key physical properties remain similar in all the specimens and only the number of joints and orientation vary. These artificially jointed specimens were then tested for their mode-I, mixed-mode and mode-II fracture properties and tensile strength. The experimental results were compared to examine the effect of the increasing number of joints (i.e. decreasing joint spacing) and the changing joint orientation on the FT and TS of the rock. The increasing number of joints or decreasing joint spacing in the specimen has been expressed as the "non-dimensional joint spacing", which is the ratio of "average joint spacing" to the "maximum dimension" of the specimen. In FT and TS specimens, the "maximum dimension" is the diameter of the specimen. Therefore, with decreasing joint spacing in a specimen, the "non-dimensional joint spacing" decreases.

A complete description of the fracture behavior of any rock requires identification of a useful and applicable mixed-mode fracture criterion. Nearly eleven mixed-mode fracture criteria have been proposed in the literature to describe the fracture propagation, but only three have found prominence in the scientific community. These fracture criteria are – the maximum tangential stress criterion (Erdogan and Sih, 1963), the maximum energy release rate criterion (Hussain et al., 1974), and the minimum strain energy density criterion (Sih, 1974). The current paper examines the suitability of these three criteria to the jointed sandstone by means of K_{IIC}/K_{IC} ratio of the specimens.

2. Experimental procedure

The FT and TS measurement of the sandstone specimens were performed according to the standards of the International Society of Rock Mechanics (ISRM). Pure- and mixed-mode fracture property measurements were carried out using semi-circular Bend (SCB) specimens (Kuruppu et al., 2014). This core based technique requires preparation of the semi-circular specimens and a three-point compressive loading set-up. The TS of the rock was measured by using NX (54.7 mm) sized discs and a Brazilian cage as suggested in the ISRM standard (I. S. R. M., 1978).

2.1. Test material

The FT and TS experiments were performed on the Dholpur sandstone of Rajasthan, India. P-wave and petrographic analysis indicate this sandstone to be homogeneous and free from any structural discontinuity. X-ray diffraction analyses show that the sandstone is mostly composed of high amount of SiO_2, and a small amount of Al_2O_3, Fe_2O_3, and CaO. The plane- and cross-polarized optical microscopy confirms that Dholpur sandstone is monomineralic, medium grained and well-sorted. Overall this sandstone is largely uniform, highly durable and shows high compressive strength. The average geomechanical and physical properties of the sandstone are shown in Table 1.

Table 1
Geomechanical and physical properties of Dholpur sandstone.

Compressive strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)	Poisson's Ratio	Porosity (%)	Density (kg/m^3)
39	6.2	26.78	0.24	10	2198

2.2. Specimen preparation

Since Dholpur sandstone is mostly homogenous and isotropic, NX-sized cores (54.7 mm diameter) were first retrieved from the sandstone blocks by using a diamond core bit. Drilled cores were thoroughly examined visually for any visible cracks or fractures and defective cores were discarded. All competent cores were dried for 48 h in the room temperature (28 °C). Dried cores were then used to prepare Brazilian tensile discs and semi-circular bend (SCB) specimens. For the tensile test, the disc specimens were prepared by maintaining a length/diameter ratio of 0.75. The SCB specimens were prepared by cutting the disc specimens into halves. A straight notch with an a/R ratio 0.4 was introduced in the SCB specimens using a thin diamond circular saw. The angle of the notch with respect to the loading direction was chosen as required by the different modes of test.

To incorporate the joints into the SCB and TS specimens, the discs were cut into the required number of pieces using a thin diamond cutter. Subsequently, those pieces were joined using an epoxy type ceramic substrate adhesive. The adhesive was chosen such that the analogue joints behave similar to the actual rock joints. This was verified by calculating the normal-stiffness, shear-stiffness, and tensile strength of the analogue joints, and comparing them with the values reported in literature. The stiffness properties were calculated using the rock mass properties as prescribed by Barton (1972). The normal- and shear-stiffness of analogue joints vary between 393 and 456 GPa/m, and 133–177 GPa/m, respectively. These values are well within the range of those reported for different types of rock (Pells and Bertuzzi, 2002; Wines and Lilly, 2003). Further the tensile strength of the adhesive joint was calculated through indirect Brazilian tensile test. To conduct this test, a tensile disc with a single joint at the middle was used. Such configuration ensures that maximum indirect tensile stress concentrate only along the joint surface. Thus a single tensile fracture is created along the joint upon failure. Tensile strength of this analogue joint is then compared with the results of Shang et al. (2016), who reported similar results for natural joints and bedding planes of sedimentary rocks. Overall, a good agreement is found between these two results. The relatively lower tensile strength of the incipient joints of Shang et al. (2016) is because those joints were partially weathered. The results are shown in Table 2.

These results confirm that the present analogue rock joints can successfully emulate the behavior of natural rock joints. Thus, up to five joints were incorporated into the SCB and TS specimens. The angle between the loading direction and the rock joint was taken as the 'inclination angle' and was used to describe the orientation of the specimen (TS and SCB) for all the experiments. The details of the TS and SCB specimen are shown in Fig. 1a and b. Only the SCB specimens that have 4 and 5 sets of joints that are oriented at a 90^0 inclination angle could not be prepared due to the difficulty in the cutting process and the specimen size.

Table 2
Joint tensile strength of the analogue joints and natural rocks.

Joint tensile strength (MPa)	Bedding tensile strength (MPa) (Shang et al., 2016)	Incipient joint tensile strength (MPa) (Shang et al., 2016)
1.68	0.67	0.63
1.82	1.22	0.48
1.4	1.69	0.9
1.88	1.82	0.55
1.5	1.51	1.34
	1.79	0.6
Average	Average	Average
1.65	1.45	0.75