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Tensile strength of incipient rock discontinuities

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ABSTRACT: This paper addresses the issue of the tensile strength of incipient discontinuities in rock and presents preliminary results from a series of laboratory studies. In most rock masses rock discontinuities, as veins or incipient fractures, often retain some tensile strength that may approach that of the parent rock. This fact is of high importance to rock mass strength but is generally ignored, neglected or underestimated. Samples of incipient rock discontinuities including joints, bedding and mineral veins have been tested in direct tension. It has been confirmed that incipient, visible and discrete discontinuities, that might be recorded as 'joints' in a rock mass characterisation programme can indeed have high tensile strength, approaching that of parent rock. Others are of course far weaker. The factors contributing to tensile strength have been examined. It is concluded that the degree of incipiency of rock discontinuities needs to be differentiated in the process of rock mass classification and engineering design and this can best be done with reference to the tensile strength relative to that of the parent rock.

1 INTRODUCTION

Rock discontinuities have a controlling influence on many projects in terms of strength, deformability and permeability. Generally these fractures develop from an original incipient state with high tensile strength to fully mechanical discontinuities with zero tensile strength (Hencher & Knipe, 2007). For engineering simplification purpose, incipiency of rock discontinuities is usually neglected or underestimated. ISRM standard defines discontinuities have very low or zero tensile strength (ISRM 1978). Rock mass classification schemes such as Q system, RMR and RQD are defined on the basis of this engineering assumption which means that they all fail to resolve the issue of incipiency of discontinuities as well as varying degrees of tensile strength.

Degree of incipiency of rock discontinuities should not be neglected as it influences the overall strength of rock. Figure 1a presents an example of joint incipiency provided by Hencher when shearing a rock core. Light rock bridge segment is revealed after shearing test. Another incipient joint is shown in Figure 1b, intact rock bridges indicated by red arrows are shown after breaking along this fracture with geological hammer.

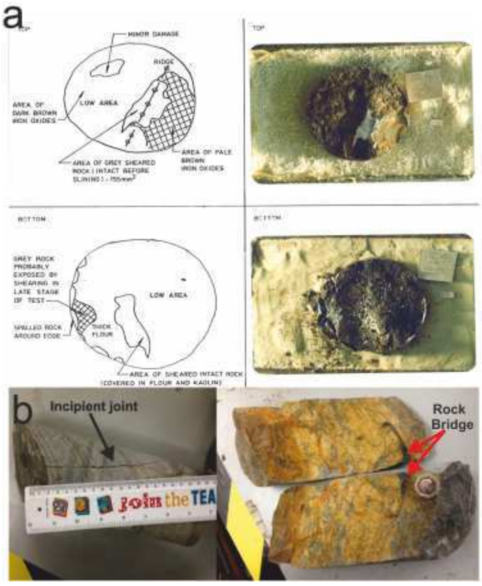

Figure1. Rock cores containing incipient rock joints. a Light rock bridge is revealed after shearing test, b incipient rock joint broken open using geological hammer; intact rock bridges are indicated by red arrows.

2 EXPERIMENT PREPARATION

2.1 Specimen preparation

To investigate the tensile strength of incipient discontinuities in the laboratory, samples were cored from large rock blocks: siltstone blocks with mineral veins were collected from Dry Rigg Quarry, North Yorkshire, United Kingdom; medium-grained sandstone blocks containing incipient bedding planes and joints were collected from Black Hill Quarry, West Yorkshire, United Kingdom. Specimens are prepared by coring perpendicular to these incipient rock discontinuities.

Specimens with horizontal incipient discontinuities including joints, bedding and mineral veins were prepared for the tests. Figure 2 illustrates the process of specimen preparation and some prepared specimens. As mentioned above, cores were drilled perpendicular to these incipient fractures as illustrated by Figure 2a. Two sets of specimens were obtained as shown in Figure 2b-d. The first sets comprised siltstone specimens (50 mm and 70 mm in diameter) containing mineral veins. The second set comprised sandstone specimens (70 mm in diameter) containing incipient bedding planes and joints.

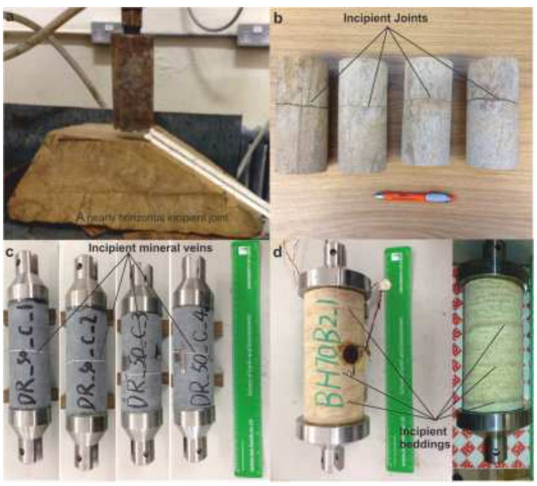

Figure 2. a Sandstone specimens drilled perpendicular to a horizontal incipient joint within a sandstone block, b prepared sandstone specimens with incipient joints, c prepared siltstone specimens with incipient mineral veins, d prepared sandstone specimens with incipient beddings.

2.2 Apparatus set up and verification

A servo-controlled loading machine with the capacity of 250 KN was used for the direct tension tests (see Figure 3). Steel chains were used to connect rams and prepared specimens to reduce bending and torsion effects. Sandstone specimens were cemented to metal caps using araldite resin with tensile strength of more than 20 MPa. For each test, specimens were loaded uniformly at a constant rate of 40 N/s until he sample failed following the direction of ISRM (1978).

In order to verify the validity of apparatus setup, preliminary work was carried out similar to the work of Okubo (1996) and Hashiba (2014). Four strain gauges were affixed to intact sandstone specimens as illustrated by Figure 4. Figure 4 also presents curves of micro-strain vs. time demonstrating consistent strain at the four measurement locations, which provides some confidence in the alignment of the testing set-up as used for the subsequent uniaxial tension tests.

Figure 3. a General view of apparatus set up, b specimen containing an incipient joint during the process of direct tension, c failure pattern of this specimen after direct tension test.

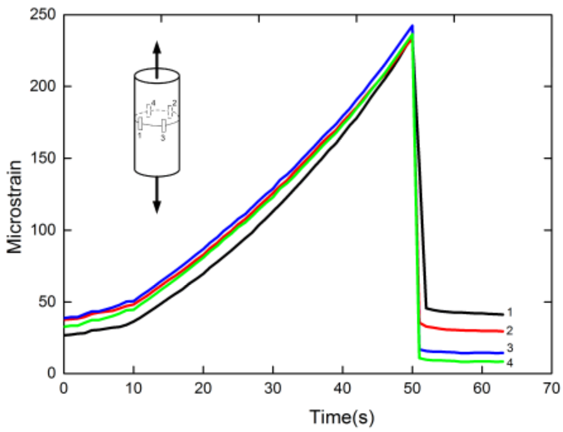

Figure 4. Apparatus setup verification.

3 PRELIMINARY TEST RESULTS AND INTERPRETATION

3.1 Tensile strength of incipient rock discontinuities

Table 1 lists laboratory test results. It can be seen that incipient discontinuities have varying tensile strength.

For incipient geological bedding, average uniaxial tensile strength is 1.45 MPa. After specimen BH1-1 was broken during a direct tension test, the two broken parts were cemented together using Araldite and reused as specimen BH1-2. Specimens 1-3 and 1-4 were obtained in a similar manner. It was found that the UTS of these specimens increased from 0.67 MPa to 1.82 MPa with decreasing specimen height. The same was found for specimens BH2-1 and BH2-2. It can be concluded that the weakest incipient bedding plane in a sample breaks first during direct tension (then that 'weak link' is strengthened artificially by glue in the testing methodology adopted here). The variation in bedding discontinuity strengths can be attributed in part to differences in original sedimentary process but also reflects subsequent geological history, including weathering. Incipiency of these bedding planes can be distinguished by using the value of percentage to UTS of intact parent rock (2.08 MPa). Percentages vary from 32.2% to 87.5% for the tested incipient bedding planes.

Incipient mineral veins were tested with diameters of 50 mm and 70 mm. It can be seen from Table 1 that average UTS of veins with a diameter of 50 mm was 0.84 MPa but 0.28 for veins with a larger diameter (70 mm). It should be note that UTS of specimen DR50C5 and DR70C4 were much greater than for other specimens (7.13 MPa and 6.68 MPa respectively). This finding might be attributed to differences in vein structures as well as general geological variability - there is no generic conclusion to be drawn; sample variability is a complex matter. These two values were discarded in the process of averaging UTS for the tested veins.

In terms of incipient rock joints, UTS of tested specimens varied from 0.48 MPa (23.1% of parent rock) to 1.34 MPa (64.4% of parent rock) with an average value of 0.75 MPa.

Table 1. Tensile strength of incipient rock joints, mineral veins and bedding.

Specimens	Type of incipient discontinuity	Diameter (mm)	Uniaxial Tensile Strength (UTS) (MPa)	Percentage to UTS of parent rock (%)	Average tensile strength (MPa)
BH1-1	Incipient geological bedding	70	0.67	32.2	1.45±0.40
BH1-2		70	1.22	58.7	
BH1-3		70	1.69	81.3	
BH1-4		70	1.82	87.5	
BH2-1		70	1.51	72.6	
BH2-2		70	1.79	86.1	
DR50C1	Incipient mineral vein	50	0.49		0.84±0.29
DR50C2		50	0.62		
DR50C3		50	1.15		
DR50C4		50	1.09		
DR50C5		50	7.13		
DR70C1		70	0.89		0.28±0.19
DR70C2		70	0.44		
DR70C3		70	0.11		
DR70C4		70	6.68		
BH70J1	Incipient rock joint	70	0.63	30.3	0.75±0.72
BH70J2		70	0.48	23.1	
BH70J3		70	0.90	42.3	
BH70J4		70	0.55	26.4	
BH70J5		70	1.34	64.4	
BH70J6		70	0.60	28.8	

Note: Specimen DR50C5 and DR70C4 were discarded in the process of averaging UTS for incipient mineral veins

3.2 Failure patterns of incipient rock discontinuities

Figure 5 shows failure patterns of incipient geological discontinuities under direct tension. It can be seen that specimens tested normally broke along incipient discontinuities.

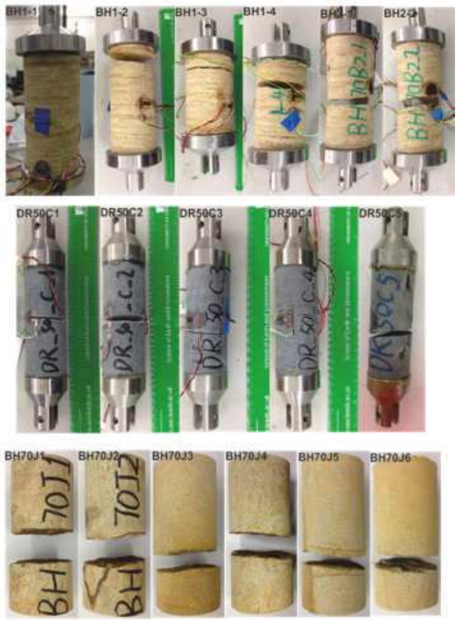

Figure 5. Failure patterns of specimens containing incipient rock discontinuities during the direct tension test. 5a Sandstone specimens broken along weakest geological bedding planes, 5b specimens broken along mineral veins, 5c specimens containing broken along incipient joint planes.

3.3 Discussions and problematic issues

Rock discontinuities are common features in rock masses. For rock engineering design, visible discontinuities are often assumed to be fully persistent - lacking any tensile strength. However this is not true in reality and sometimes this assumption may not only be over-simplistic but also problematic for rock engineering. It is immediately apparent that this conservative assumption could leads to general underestimation of overall strength of masses, which subsequently influences engineering design and excavation performance. Conversely, rock might be assumed to be readily rippable or excavated by TBM but this may prove incorrect leading to delays, changed methods of excavation and legal consequences. It is considered important that non-persistent, i.e. incipient rock discontinuities should be characterised by their tensile strength as far as possible, however difficult this might be in practice. Characterisation of rock masses in 3D is largely restricted to examination of exposed rock faces and then we are limited to observing visual traces; characterising rock masses away from exposures is extremely difficult. We generally know little of the shape and size of discontinuities at full scale (Song, 2006) and thus the degree of incipiency (including extent of rock bridges surviving the ravages of weathering) is usually unknown in full scale. This is a problematic issue in rock mechanics. Zhang and Einstein (2002) proposed a mathematical relationship between trace length and joint size, but unfortunately the issue of incipiency (true persistence) of discontinuity was not considered and the problem remains challenging.

To try to help resolve this issue or at least to make some inroads, the authors of this paper are currently carrying out field and laboratory research to investigate the extent of incipient discontinuities and to characterise the various factors controlling degree of incipiency and presence of rock bridges.

4 CONCLUSIONS

In this study, direct tension tests have been conducted on incipient rock discontinuities including bedding, mineral veins and joints. The uniaxial tension test has proved to be a straightforward and workable methodology to measure tensile strength of incipient discontinuities. Incipient rock discontinuities (visible as discontinuity traces) have been tested and found to have high tensile strength, some up to 87.5% of UTS of the intact rock. For rocks containing discontinuities (horizontal relative to the direction of applied tension), failure usually occurs along the visible discontinuity plane. It is concluded from these preliminary studies that the degree of incipiency of rock discontinuities needs to be differentiated in the process of rock mass classification and engineering design and this can best be done with reference to the tensile strength relative to that of the parent rock as proposed by Hencher (2014). The potential for interpreting, predicting and extrapolating degree of incipiency linked to an appreciation of geological history should provide a very fruitful opportunity for the future advance of rock mechanics in many fields of study

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