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Damage Mechanism of Rock Fatigue

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ABSTRACT

An understanding of the mechanics and mechanisms of brittle rock fracture is a key element in the solution of many engineering problems that involve rock structures. Some rock structures, such as bridge and dam abutments and foundations, and tunnel walls, undergo both static and cyclic loading caused by drilling and blasting, and vehicle-induced vibrations. This type of loading often causes rock to fail at a stress lower than its static strength, due to the effect of rock fatigue. While the mechanical behaviour of rock under static loading has been thoroughly investigated, rock behaviour under cyclic and repetitive loading has generally been neglected. Disc specimens of Brisbane tuff, the main rock type encountered during the excavation of the CLEM7 tunnel in Brisbane (Queensland, Australia), have been tested to investigate their Indirect Tensile Strength (ITS) response to both static and cyclic loading. Two different cyclic loading methods were used; namely, sinusoidal cyclic loading and cyclic loading with increasing mean level. The maximum reduction in ITS was found to be 33% on sinusoidal loading and 37% on increasing cyclic loading. In order to examine the major characteristics of the damage process at the microscopic level, Scanning Electron Microscopy (SEM) was used to view the surface of the main tensile fracture in specimens tested under both static and cyclic loading. The paper describes the results of the testing and SEM imaging.

Keywords: cyclic loading, indirect tensile strength, rock fatigue, static loading

1 INTRODUCTION

The tensile strength of rocks is much lower than its compressive strength. Rock is a brittle material and because all brittle materials are weak in tension, the tensile strength of rock becomes one of the most important parameters influencing its deformability and fracture toughness. The difficulties associated with performing a direct uniaxial tensile test on a rock specimen have led to a number of indirect methods for assessing its tensile strength. In 1978, the Brazilian test was officially proposed by the International Society for Rock Mechanics (ISRM) as a suggested method for determining the tensile strength of rocks (ISRM 2007).

Rock masses normally consist of blocks of intact rock separated by joints, faults or interfaces. Even intact rocks are categorised as inhomogeneous and discontinuous, on both small and large scales, because they contain cracks, voids and pores, normally induced by historical thermal, mechanical and/or chemical actions and reactions. The study of brittle fracture and its relationship to damage, fatigue and strength is central in many rock engineering disciplines, including rock fracture and damage mechanics, rock cutting, and drilling and blasting. Research on understanding rock cracking, fracture and fatigue behaviour under various loading conditions, such as static, cyclic and impact loading, has attracted many investigators in recent years (Celestino and Bortolucci 1995, Petros et al. 2003, and Zhenyu and Haihong 1990). The mechanical behaviour of rock under static loading has been thoroughly investigated. However, rock behaviour under cyclic, repetitive stresses resulting from dynamic loading, has generally been neglected, with the exception of a few rather limited studies (Attawel and Farmer 1973, Gatelier et al. 2002, Haimson 1978, and Halcomb 1979). It is known that cyclic loading often causes brittle materials, such as ceramics and rocks, to fail at a stress level lower than their strength under monotonic conditions (Attawel and Farmer 1973, Burdine 1963, and Evans et al.1974). This phenomenon is commonly termed “fatigue”. Faults, joints, bedding planes, tunnel walls, excavation roofs and ribs, bridge abutments and dam and road foundations are only a few of the natural and manmade rock structures that can be weakened by the repetitive loading caused by such stressors as vehicle-induced vibrations, drilling and blasting, and traffic.

There is very limited research on the response of the tensile strength of rocks to cyclic loading (as opposed to dynamic loading, such as explosive loads and impact loading). Moreover, relatively little attention has been given to investigating the damage mechanisms of rock fatigue. The novel research described herein describes the effect of indirect tensile cyclic loading on the ITS of rocks and the mechanisms of rock fatigue damage.

2 EXPERIMENTAL PROCEDURE

2.1 Sample preparation

The tests were carried out on Brisbane tuff, a host rock of Brisbane's (Queensland, Australia) first motorway tunnel, the CLEM7, from which core samples were obtained. Brisbane tuff was chosen since it is a massive rock type with no bedding (being an ash deposit), making it easy to handle and prepare for testing, and giving less test result variability. In addition, it is a targeted rock type in the Brisbane area for its strength and stability for tunnelling and excavation applications. The sample preparation and testing procedure conformed to the requirements of the ISRM (2007). For the determination of the ITS, samples were cored and trimmed to form disc specimens that met the ISRM (2007) recommendations (Figure 1a); that is, cylindrical specimens 52 mm in diameter and 26 mm in thickness, to give a thickness to diameter ratio of 0.5. The Brazilian disc specimen in Figure 1b has two strain gauges attached to its perpendicular faces; one vertical (at right angles to the applied force) and the other horizontal. The vertical strain gauge measures the vertical diametral strain, while the horizontal strain gauge measures the horizontal diametral strain.

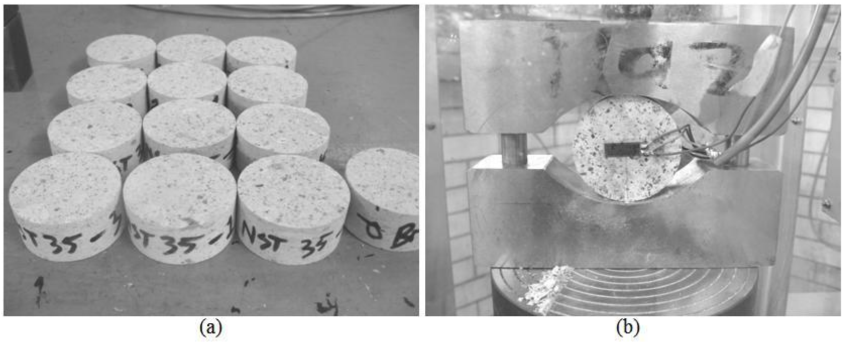

(a) (b)

Figure 1. (a) Prepared Brazilian disc specimens; (b) disc specimen with strain gauges placed between Brazilian loading jaws

2.2 Static and cyclic loading tests

For the static loading tests, the two steel standard Brazilian loading jaws are designed to make contact with the disc-shaped rock specimen at diametrically opposed surfaces over an arc of contact of approximately 10° at failure (see Figure 1b). The static loading was applied by a stiff hydraulic Instron loading frame, at a loading rate of 200 N/s, as suggested by the ISRM (2007). The tensile strength of the five rock specimens tested was calculated using the formula given by the ISRM (2007).

Two types of cyclic loading were used in this research; cyclic loading with constant mean level and constant amplitude, termed sinusoidal cyclic loading (see Figure 2a); and cyclic loading with increasing mean level and constant amplitude, termed increasing cyclic loading (see Figure 2b). Loading amplitudes are constant in both types of cyclic loading. However, the mean level of each cycle increases at a constant rate in the increasing cyclic loading tests, whereas the mean level of each cycle is constant in the sinusoidal cyclic loading tests. The cyclic loading used in these tests was a ramp waveform type of cyclic compressive loading. The loading frequency was 1 Hz for all tests. The amplitude is expressed as an absolute (± value) equal to the total range. Four different amplitudes were chosen to investigate the effect of fatigue on the ITS value of Brisbane tuff: 2.3 kN, at 10% of the static ultimate load (SUL), 4.6 kN (at 20% of the SUL), 6.9 kN (at 30% of the SUL), and 9.2 kN (at 40% of the SUL).

The sinusoidal cyclic loading tests were carried out to obtain the S-N curves illustrative of the continuous weakening of rock with increase in the number of cycles (N) required to fail a specimen loaded to a certain upper peak stress (S). This research presents for the first time the S-N curve for ITS degradation due to fatigue under cyclic loading.

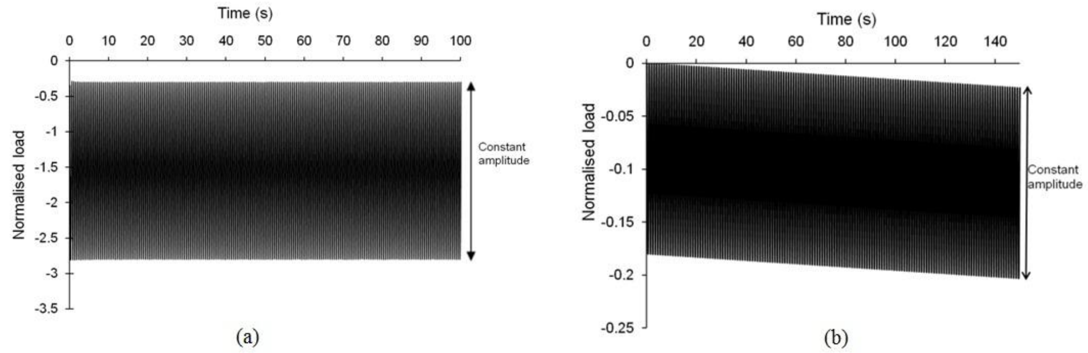


Figure 2. (a) Sinusoidal cyclic loading; (b) increasing cyclic loading

3 RESULTS

3.1 Test results

The tested Brisbane tuff specimens are shown in Figure 3a. In the static tests on Brisbane tuff disc specimens, loading with the Brazilian jaws caused central tensile cracking, with several fractures branching from the diametral plane. On the other hand, it is obvious that much more crushed rock and debris was produced under cyclic loading than under static loading (Figure 3b). The mechanisms of rock fatigue under cyclic loading induce many more micro-cracks compared with the failure mechanism under static loading, as explained in the literature (Costin and Holcomb 1981 and Hadly 1976). This experimental outcome is key to understanding the effect of fatigue on the damage mechanisms of rocks.

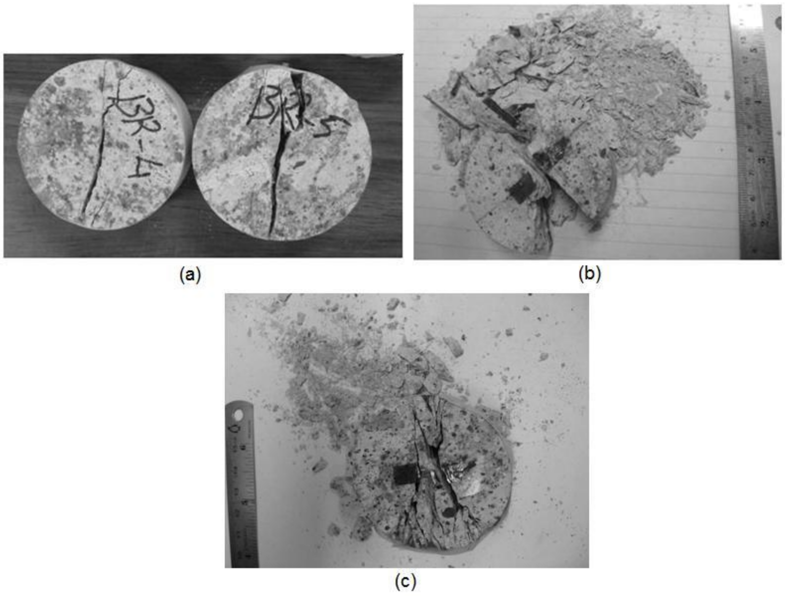


Figure 3. Tested Brazilian disc specimens under (a) static loading, and (b) and (c) cyclic loading

Under static loading, the ITS value of Brisbane tuff was found to be 11.17 MPa (the average of five replicates). Figure 4 shows the S-N curve for Brisbane tuff. The failure load under sinusoidal cyclic loading was, at 7.5 MPa, 33% lower than the static value, while the failure load under increasing cyclic loading was, at 7 MPa, 37% lower.

The reduction in ITS from the static value due to increasing cyclic loading is given in Table 2. The main purpose of this comparison is to show the clear reduction in ultimate failure load, resulting in a reduction in the ITS due to rock fatigue. An attempt was made to show that tensile crack propagation causing failure is possible at lower stress values than the ITS values calculated using the ISRM suggested methods.

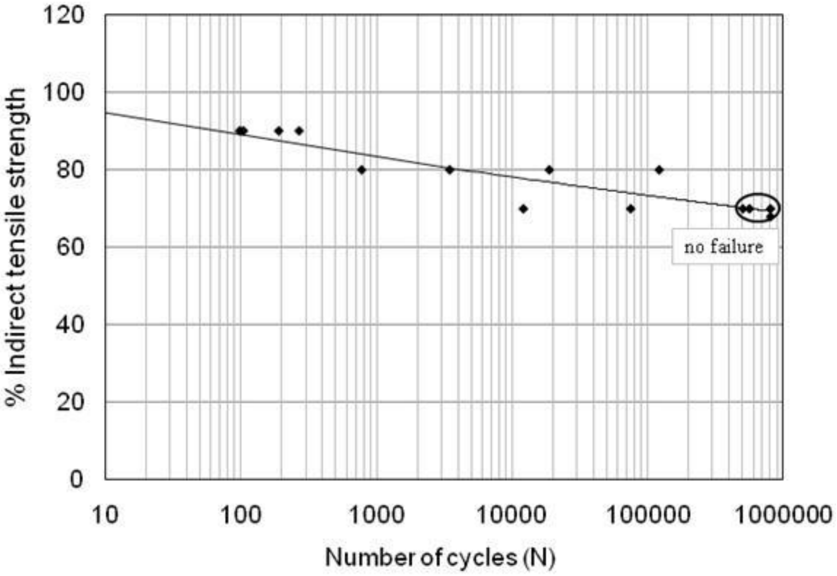


Figure 4. S–N curve for indirect tensile strength of Brisbane tuff

Table 2 Results of increasing cyclic loading tests performed on Brazilian disc specimens

Sample	Amplitude % SUL	Ultimate load (kN)	Number of cycles up to failure	Indirect tensile strength (ITS)	Reduction in ITS (%)
NST207-Rp1	10	17.4	2583	8.2	24.1
NST207-Rp2	10	15.6	2384	7.3	32.5
NST207-Rp3	10	18.1	2723	8.5	21.3
Average		*17.03*	*2563*	*8.0*	*25.9*
NST207-Rp1	20	17.5	2195	8.2	24.1
NST207-Rp2	20	15.4	1887	7.2	33.4
NST207-Rp3	20	14.6	1679	6.8	37.1
Average		*15.9*	*1920*	*7.4*	*31.5*
NST207-Rp1	30	17.3	1906	8.1	25.0
NST207-Rp2	30	15.2	1334	7.1	34.3
NST207-Rp3	30	16.1	1556	7.5	31.0
Average		*16.2*	*1598*	*7.6*	*30.1*
NST207-Rp1	40	14.0	738	6.5	42.0
NST207-Rp2	40	14.4	992	6.7	40.0
NST207-Rp3	40	16.8	1227	7.9	29.3
Average		*15.0*	*985*	*7.0*	*37.1*

3.2 Mechanism of rock fatigue damage

A comparison between the static and cyclic loading test results is shown in Figure 5 by plotting both results on the same axes. The diametral axial strain under both static and cyclic loading is greater when compared with the diametral lateral strain. However, the contribution of plastic strain to the diametral lateral strain under cyclic loading is much more than that under static loading. Moreover, diametral lateral plastic strain accumulation at the highest level is a result of the loosening of the hysteresis loop during the final cycles up to failure. During cyclic loading, the diametral lateral strain develops faster than the diametral axial strain. This behaviour indicates the development of cracking in the specimen, and is the reason for the dilatancy of the rock. The higher the stress level or the larger the cycle amplitude, the more obvious is this behaviour.

The failure surfaces of the Brazilian discs tested under both static and cyclic loading were examined using a JEOL JSM-6460 LA brand SEM device, with a tungsten low vacuum chamber pressure. The low vacuum allowed certain specimens to be observed uncoated, which reduced damage to the specimens from the effects of a high vacuum. In addition, failure surfaces could be examined by SEM directly, without the preparation of thin sections, avoiding the creation of extra micro-cracks during the preparation of thin-sections.

On the failure surfaces of specimens tested under cyclic loading, most grains were crack-free, and the others relatively so, whereas almost all grains on the failure surfaces of specimens tested under static loading were highly cracked. The static cracking mechanism is brittle, and there is cleavage cracking through minerals (see Figures 6a and 6b). As the quartz and feldspar minerals are randomly-located in the matrix of Brisbane tuff, a mismatch in elastic stiffness at the interface between the feldspar and quartz grains, inducing a greater tensile stress in the stiffer grain, is not possible. This may mean that the cleavage mechanism, due to the high tensile stress produced in the centre of a disc specimen, causes inter-granular (inter-crystalline) cracks in a disc specimen tested under static loading (Erarslan, 2011).

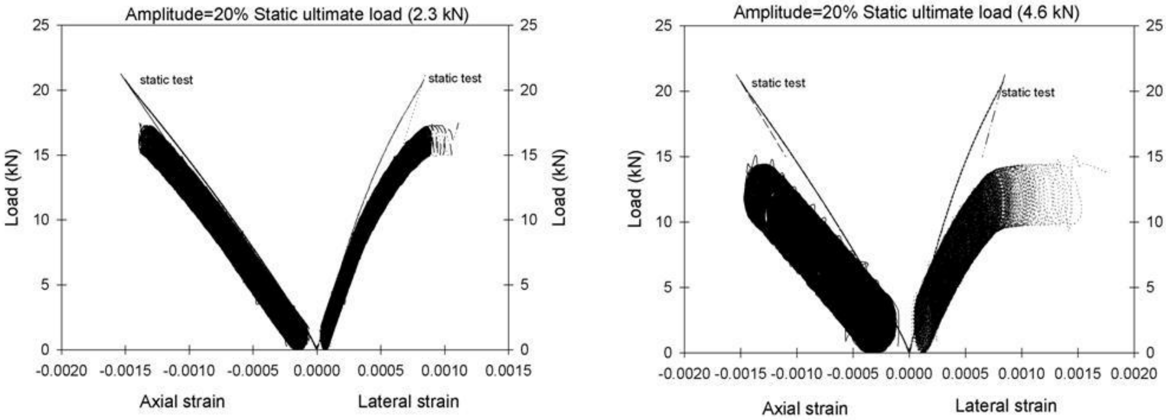
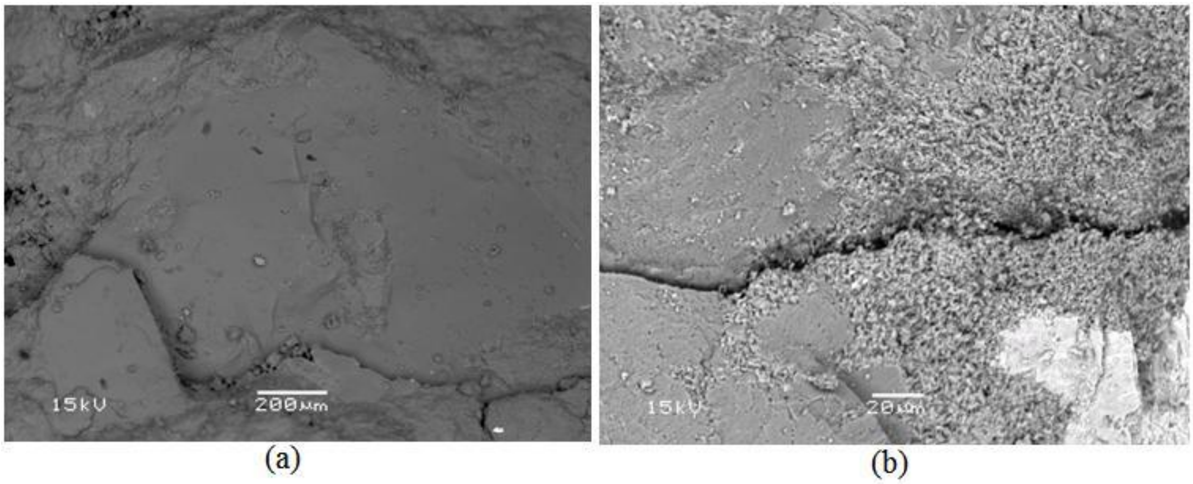


Figure 5. Comparison of load–strain curves of Brazilian disc specimens tested under static and increasing cyclic loading with various amplitudes



(a) (b)

Figure 6. Typical transcrystalline cracks on the failure surfaces of Brisbane tuff disc specimens tested under static loading

On the fracture surfaces of specimens tested under cyclic loading, almost all grain boundaries are cracked along their entire length and some are cracked at small angles to the maximum stress direction (see Figures 7a and 7b). The extracted loosened minerals shown in Figures 7c and 7d show general fatigue effects. Inter-crystalline cracks were revealed as the principal cracking form on the failure surfaces.

However, it is still unknown how the loading cycles break the bonds between the grains and the rock matrix to produce inter-granular cracks around grain boundaries. Two possible mechanisms can be inferred from analysis of the SEM images: (1) stiffer grains (i.e. quartz and feldspar minerals) act on the surface of the weaker matrix as indenters under principal compressive stress; and (2) there is an effective sliding and shearing mechanism between the grains and the rock matrix during each loading and unloading cycle, under which internal stress is produced between the grains and the matrix as a reaction to the external diametral compressive stress.

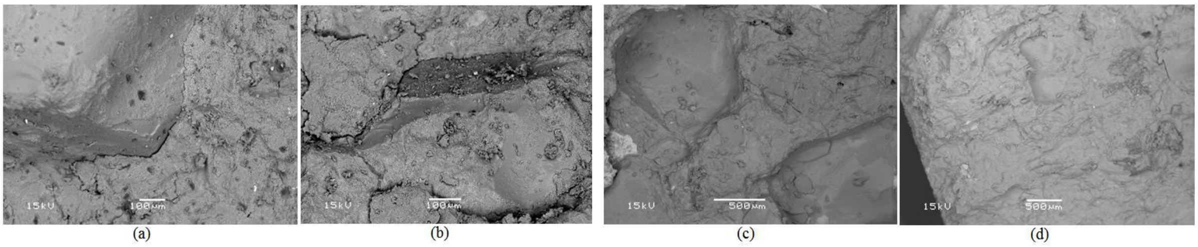


Figure 7. (a-b) loosened grains and typical inter-crystalline cracks around grains on the failure surfaces of Brisbane tuff disc specimens tested under monotonic loading

4 CONCLUSIONS

The ITS response of Brisbane tuff to cyclic loading was found to be different from that under static loading, with failure occurring at a reduced load and exhibiting fracturing mechanisms. Increasing cyclic loading is more effective in degrading the ITS of Brisbane tuff than sinusoidal compressive cyclic loading. The reduction in ITS from the static value was found to be 33% under sinusoidal loading, and 37% under increasing cyclic loading.

SEM investigations revealed that grain boundaries play an important role in rock fatigue. The largest cracks follow the grain boundaries, and micro-cracks generally start to form at the grain boundaries or voids. Grain de-cohesion seems to be the source of large cracks. Grain breakage under cyclic loading probably starts at highly-stressed grain contacts (i.e. indenters) and is accompanied by the production of very small fragments, probably due to frictional sliding within the weak matrix. Trans-granular cracks may emanate from these regions and inter-granular cracks sometimes pass through these contact points. Once cracking starts, there is a steady progression of damage and a general “loosening” of the rock, which is a precursor to the formation of inter-granular cracks.

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