Assessment of Fatigue Behavior of Alvand Monzogranite Rocks

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Abstract

Comprehensive laboratory tests were performed to assess fatigue behavior of Alvand monzogranite rock subjected to uniaxial cyclic loading. A series of static loading tests was done to obtain the required data for the fatigue tests. Three maximum load levels (85, 90, 95% uniaxial compressive strength (σc)) at amplitudes 70% were used with 1Hz cyclic loading frequency. The results indicated that maximum stress level significantly influenced fatigue behavior of this rock. It was found that fatigue life decreases in a power function with increasing maximum stress level. Accumulative fatigue damage process shows three stages of behavior including crack initiation phase, uniform velocity phase and acceleration phase. Fatigue damage process were analyzed according to axial and lateral maximum and minimum strain, tangent and second modulus, toughness and hysteresis energy in both loading and unloading conditions. Among

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these parameters, lateral strain, axial strain and second modulus show the best three-stage fatigue damage behavior. Also, it should be noted that most of the cracks generated in parallel to loading direction and lateral strain are affected by more than axial strain.

Keywords: Cyclic loading, Load amplitude, Loading frequency, Fatigue life, Toughness, Alvand Monzogranite Rocks.

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Introduction

Many natural or man-made rock structures (e.g. tunnel walls, excavation roofs and ribs, bridge abutments, dam and road foundations) are subjected to both static and dynamic loads. The mechanical properties of rocks under dynamic loads varied dramatically from those under static loads. However, up to now, the nature of dynamic failure in rock remains unclear, especially in cyclic loading condition [12]. Different materials show different responses when they are subjected to cyclic loading. Some of these materials become stronger and more ductile, while others become weaker and more brittle [1]. It is well known that rock strength would decrease due to the fatigue phenomenon. Determination of fatigue characteristics of rocks under dynamic cyclic loading has more important role in prediction and control of earthquake and rock burst. A great attention has recently been focused on studying the dynamic mechanical features of rocks under different loading histories and loading conditions [4, 6-8, 11 and13]. A comprehensive literature review on

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fatigue behavior of rocks has been reported by Bagde and Petros [1]. Since 2005, other researchers have studied the effect of cyclic loadings on fatigue properties of rocks. Bagde and Petros [2] performed a series of fatigue tests to asses the fatigue and dynamic behavior of sandstone and conglomerate. They concluded that development of fatigue failure in rocks is closely related to their petrographic, physical and mechanical properties. They found that micro-fracturing is the main cause of fatigue failure. Based on the law of axial irreversible deformation development of rock Xiao et al [13] suggested an inverted S-shaped nonlinear fatigue damage cumulative model. Xiao et al [12] conducted cyclic loading tests on Heng Yang region granite rocks to find a relatively suitable damage variable to describe the fatigue damage of rocks. They reported that the residual strain method is the most ideal method for its clearly distinct physical meaning, relevant description of the degradation behaviour and consideration on the fatigue initial damage. Fuenkajorn and Phueakphum [3] evaluated the effect of cyclic loading on mechanical properties of Maha Sarakham salt. They found that the salt compressive strength decrease with increasing number of loading cycles by a power function and elastic modulus decrease slightly during the first few cycles then remain constant until failure. Liu and He [8] and Liu et al, [9] performed a series of laboratory tests to assess the effects of confining pressure on the mechanical properties and fatigue damage evolution of sandstone samples subjected to cyclic

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loading. They illustrated that with increasing confining pressure, the axial strain at failure increased and level of confining pressure has a significant influence on the cyclic dynamic deformation and fatigue damage of the rock. However, the available data on fatigue behavior of rock are not sufficient to solve the practical tasks of predicting rock bursts and earthquakes. Furthermore, the obtained results are inconclusive and sometimes have discordant. The aim of this work is to assess Alvand monzogranite rock fatigue behaviour under different maximum stress, frequency, and amplitude to describe the fatigue damage process of the granitic rock.

Experimental set up and rock properties

Granite is the most common intrusive igneous rock. Due to its high strength it has been widely used in construction industry. In addition, escalated deep mining operations in recent years are often conducted in the vicinity of granitic rocks. Therefore, it is crucial to understand its mechanical behaviour, in partuclar, under dynamic loading conditions. In order to perform cyclic loading, rock samples were chosen from Alvand batholith outcrops, west of Iran. It is one of the largest plutonic bodies in the Sanandaj-Sirjan Metamorphic Belt. Alvand batholith consists of a mafic part (gabbro-diorite-tonalite), intermediate (granite-granodiorite porphyroids), and hololeucocratic granitoids [10]. The main part of this batholith is consisted as porphyroid monzogranite. A mineralogical and textural feature has been revealed by using thin section analysis. Mineralogical studies indicated that the monzogranite is coarse grained (>5 mm) with a subhedral granular texture and porphyritic fabric (Figure 1a) Mineral assemblages include quartz (25%), orthoclase (25%), plagioclase (25%), biotite (20%), and minor minerals (5%). The mineral composition was also investigated by XRD analysis. As shown in Figure 1b, the results of XRD analysis confirmed the mineral composition of the thin sections study.

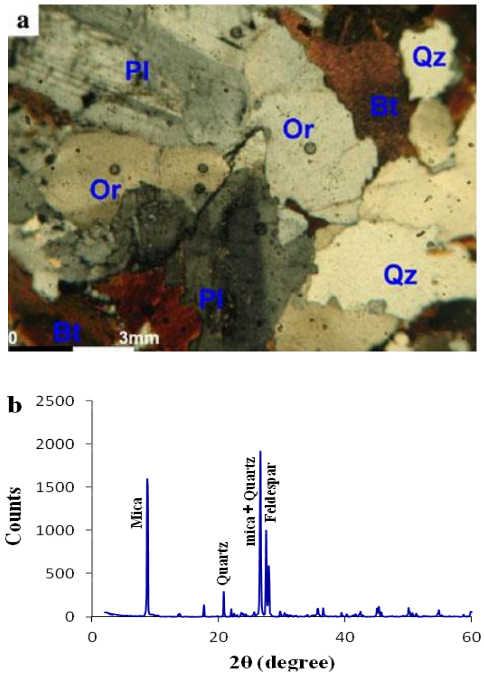

Figure 1. Mineralogical features of the Alvand monzogranite, a: photomicrograph of thin scetion, b: typical results of XRD analyses. (Pl: plagioclase, Qz: quartz, Bt: biotite, Or: orthoclase)

Fatigue tests were conducted using Instron 1342 servohydraulic fatigue testing Machines with 300 kN capacity (Figure 2a). The tests

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were performed under sinusoidal cyclic loading. The Instron controller consists of hardware components and software applications that provide closed-loop control of servo-hydraulic test equipment. This machine consist a compression loading frame, an axial dynamic loading system and a data acquisition system. The data acquisition system consists of a signal conditioning, and an acquisition unit interfaced with a computer. Multiple or single data acquisition processes can collect data on all channels. The equipment is facilitated with an automated dynamic control mode switching between any connected transducers. This machine is able to perform cyclic test in both load and displacement control modes.

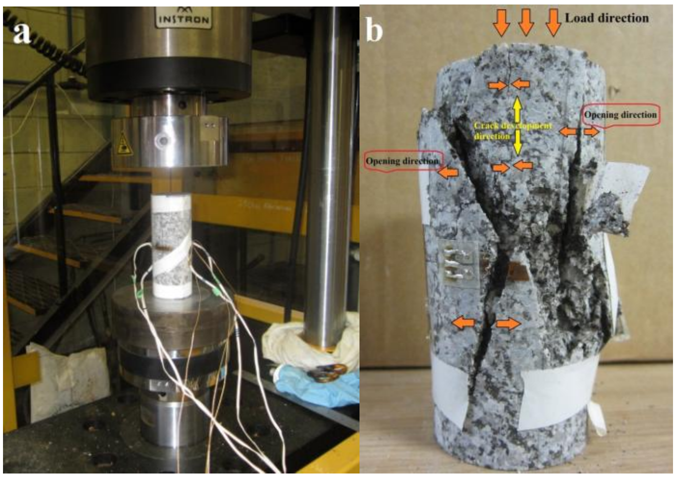

Figure 2. a. Granite specimen placed in the Instron 1342 testing machine in uniaxial cyclic loading test, b. Crack features in core sample after failure

1. Testing methodology

Several core samples were prepared in order to perform this research. The core samples were prepared within L/D ratio of 2.5 with an average diameter of 54 mm. The end faces of the core samples were prepared according to ISRM [5] standard. Before doing the fatigue tests, physical and mechanical properties of the rocks were measured as shown in Table 1. The tests conducted to obtain physico-mechanical parameters of the rocks in static loading condition provided a reference for subsequent dynamic tests. All cyclic tests were performed by stress control mode. Despite the fact that there was a change in material properties and crack growth, the load amplitude was kept constant. Cyclic load path with time and fatigue parameters are schematically illustrated in Figure 3. The fatigue tests have been done in three different maximum load and amplitude levels with four frequency levels. The maximum stress level (the ratio of maximum cyclic stress to static strength) was varied in ranges from 0.95, 0.90 and 0.85. The amplitude level (the ratio of amplitude stress to static strength) was used at 0.70 UCS. The specimen was loaded up to the mean stress level (Sm) in the load-control mode with a 1.6 kN/s loading rate. Then the fatigue test was performed with a given amplitude and 1 Hz frequency. It should be noted that the defined stress amplitude for the machine is equal to one-half of the total range (Am= ±Sa). Finally, the results of the fatigue tests have been analysed

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according to strain spectrum, tangent and second modulus, toughness and hysteresis energy.

Table 1. Physico-mechanical properties of Alvand monzogranitic rock

Parameters	UCS (MPa)	Tangent modulus (GPa)	Second modulus (GPa)	Toughness (J/m^3)	Density (gr/cm^3)	Porosity (%)
Maximum	112.98	29.95	23.12	0.27	2.74	1.40
Average	112.35	29.37	22.92	0.25	2.71	1.24
Minimum	111.63	28.63	22.58	0.23	2.69	1.06

Table 2. Summary of the fatigue tests characterestics

Sample No	Max. stress level	Amplitude level	Frequency (Hz)	Failure cycle No
A22	0.90	0.70	1	271
A47	0.95	0.70	1	104
A20	0.85	0.70	1	2365
A12	0.79,0.83,0.88,0.93	0.68	1	12412

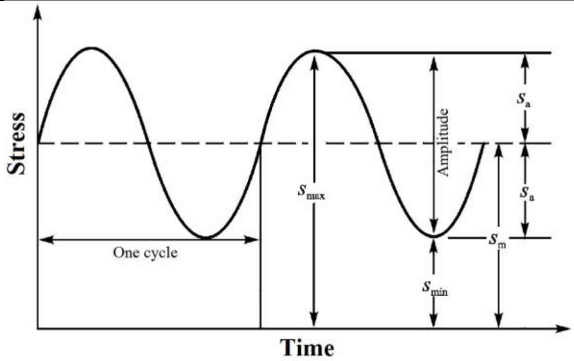

Figure 3. loading path with time in a sinusoidal wave form

Results and discussion

For a clear understanding of the effect of rock fatigue on damage mechanisms, a comparison between static and dynamic cyclic loading tests is shown in Figure 4. This figure highlights how failure occurs below of maximum strength loading condition as a result of accumulative damage process. Analysis of the fatigue test results illustrated that the fatigue failure consisted of three stages as: fatigue crack formation (initiation phase I), stable crack propagation (uniform velocity phase II) and unstable crack propagation resulting in a sudden breakdown (accelerated phase III). Figure 5 shows fatigue damage steps in axial and lateral strain point of view. Fatigue process is related to accumulative damage. This accumulative damage leads to the changes of many engineering properties of materials. In fact, the rock is not the intact one for the next cycle because of weakness due to microfracture occurrence. It can be concluded that lateral deformation is more sensitive in fatigue process in comparing with axial deformation as shown in Figs 4 and 5. It is reported that the elastic modulus, hardness, ultrasonic wave velocity, density, residual strength decrease and the residual strain, electrical resistance and energy dissipation increase with the damage accumulation [12]. Variation of these parameters with time or cycle number may be showing the three steps of fatigue accumulative damage. Damage variables used in this study include tangent modulus, second modulus, energy hysteresis, toughness, maximum strain and residual strain. These variables are discussed in different maximum stress conditions.

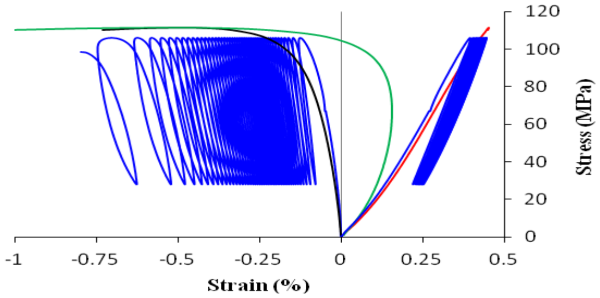

Figure 4. Stress-strain curves for uniaxial static and cyclic compressive strength tests

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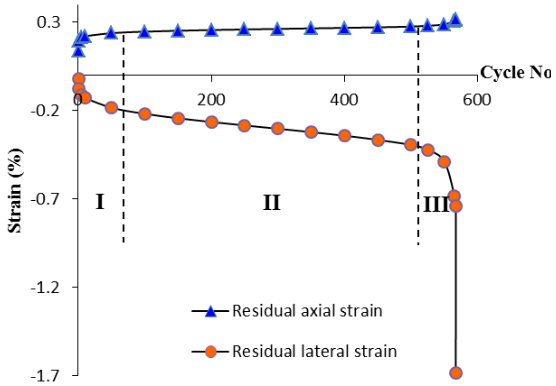


Figure 5. Three-steps fatigue damage process in residual strain point of view

1. The Effect of Maximum Stress

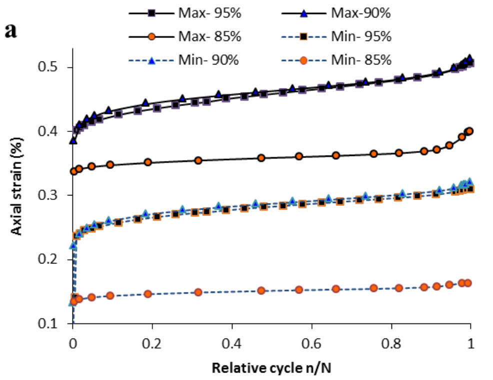
The relationship between the axial and lateral strain; fatigue damage and relative cycle at fixed amplitude level of 0.70 and three different maximum stress levels of 0.95, 0.90, and 0.85 is given in Figure 6. As can be seen from this figure, larger proportion of whole fatigue life for crack growth occurs at higher stress levels, while larger proportion of fatigue life for crack nucleation occurs at lower stress. Furthermore, slope of axial and lateral strain accumulative damage has a clear decrease with decreasing stress level. Figure 7 illustrates the elastic modulus damage curves of the granitic rock. Both reported tangent and second modulus in this study were calculated in stress level of 50% of uniaxial strength. Figure 7a shows descending trend of loading and unloading tangent modulus with a scatter pattern. It may be related with calculation method and loading condition as well as microstructure and behaviour of rock. In spite of tangent modulus results, three-stages damage process for second modulus in both loading and unloading conditions is clear (Figure 7b). This is because of calculation method and increases in axial strain with increasing number of cycles. It should be noted that both amount values and slope of accumulative damage for second modulus increase with increasing stress level.

The toughness curve for the granitic rock in three maximum stress levels is given in Fig 8a. It should be noted that, the toughness and hysteresis energy reported here are calculated from maximum and minimum stress levels. There is a dramatic decrease of these parameters in first few cycles. This trend is because of closing pre-existing micro fractures. In fact, in the initial cycle, the rock behaves more ductile in comparison with the next cycles. The granitic rock is generated in a very different thermal and pressure conditions comparing the earth surface which can generate some microfractures as a result of unloading thermal expansion and pressure (relaxation fracture). Furthermore, some part of the per-existent microfracture may be generated by the past complex loading history. After closing the microfractures, toughness started to increase slowly which is related to crack initiation phase. This phase is followed by a steady increasing in toughness. Finally a rapid increase was occurred in the acceleration phase. A similar behaviour was seen for hysteresis energy as well (Figure 8b).

Assessment of the effect of maximum stress on fatigue life indicated that fatigue life increased in a power function with

[DOR: 20.1001.1.22286837.1393.8.1.3.9]

decreasing maximum stress (Fig 9). The failure load obtained from the average static tests was reduced from 258 to 217 kN because of rock fatigue damage in 2364 cycles. By using obtained equation (Figure 9) and considering 1 million cycles as infinite life, the fatigue limit stress is around 69 % of uniaxial compressive strength.



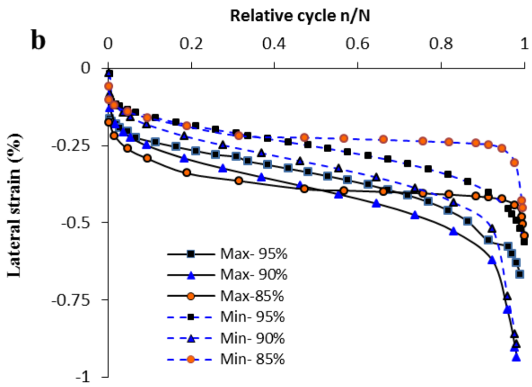
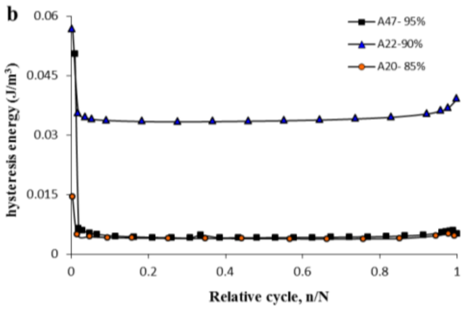


Figure 6. Maximum and minimum (residual) strain damage processes in fatigue test using different stress level. a: axial strain versus relative cycle, b: lateral strain versus relative cycle



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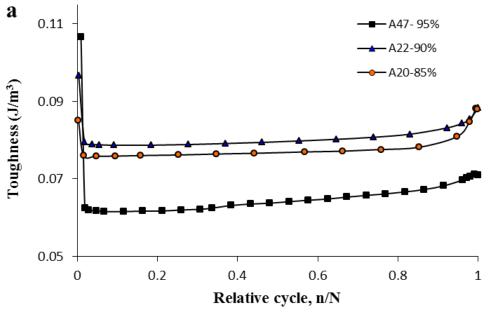
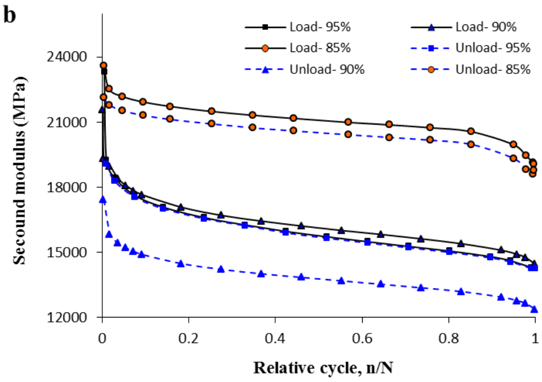


Figure 7. Loading and unloading elastic modulus damage processes in fatigue test using different stress level. a: tangent modulus versus relative cycle, b: second modulus versus cycle



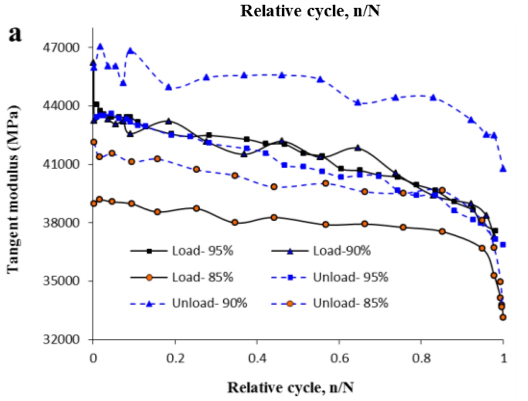


Figure 8. Energy variation in fatigue processes using different maximum load, a: toughness versus relative cycle, b: hysteresis energy versus related cycle

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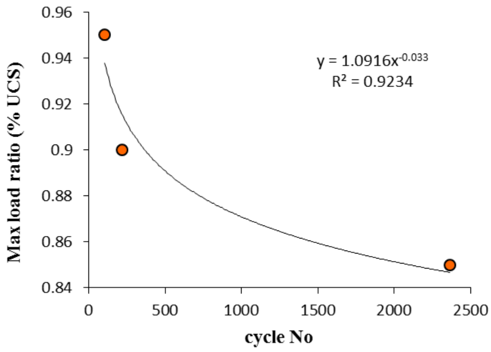

Figure 9. Correlation between applied stress and number of cycles up to failure (S-N curve).

2. Multi-level loading

Multi-stage fatigue test was performed in four stress level ranging from 0.79 up to 0.927 uniaxial compression stress, measured in quasistatic test. Stress was gradually increased after stabilization of deformation. Axial and lateral accumulative damages of multi-level loading are shown in Figure 10. As is clear in this Figure, for low stress level most part of fatigue life include for crack nucleation. Generally for 0.79 stress level initiation phase is dominated. For 0.835 and 0.875 stress levels both of initiation and uniform velocity phases can be realised. For 0.927 stress level all of three phases are obvious. Because of rock damage in previous levels, the initiation phase for maximum stress level is very short. It also reveals that for nearly same strain the number of cycles dramatically increase with decreasing stress levels especially for stress level below 0.80 of uniaxial strength.

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Multi-stage fatigue test as well as the previous fatigue tests showed that lateral strain constitutes a significant part of the total deformation.

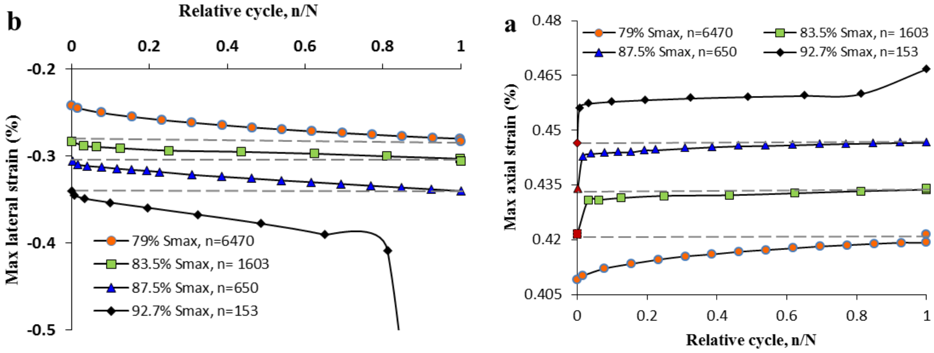

Figure 10. Maximum axial Strain (a) and maximum lateral strain (b) versus relative cyclic number during multi-stage uniaxial cyclic test

Conclusions

Alvand monzogranitic rocks were subjected to uniaxial cyclic loading under different maximum load, amplitude and frequencies to understand fatigue behaviour. The following conclusions were drawn from this research:

- Fatigue accumulative damage shows an obvious three-stage process. The result is due to microfracturing mechanism in fatigue process. By comparing axial and lateral strain damage it was found that crack propagation occurred in the loading direction and the crack opening occurred in the lateral direction.
- Analysis of fatigue damage in different load levels shows that by decreasing maximum load level large proportion of whole fatigue life is for crack nucleation, while large proportion of fatigue life for crack growth occurs at higher stress.

- Fatigue life increases in a power function with decreasing maximum stress. This is due to decrease of plastic portion in whole elastic-plastic behaviour. In addition to increases in fatigue life, the steady stage slope decrease.
- Tangent modulus accumulative damage process in different loading conditions shows a decreasing trend with scattering pattern. Whereas, second modulus shows a three stage accumulative damage in fatigue process.
- Toughness and hysteresis energy variation in different loading conditions show mostly decreasing in first few cycles and starts to increase up to failure. In fact these two parameters have short decreasing trend phase, dominated uniform increasing phase and short rapid increasing phase.
- Multi-stage incremental loading results indicated that for the first stages of most of fatigue life is spent for crack nucleation and this phase is very short for final level.
- Monitoring this rock fatigue behaviour illustrated that after few cycles in initial cycles, the rocks were almost elastic but with increasing cycle number intended to became elasto-plastic. It can be inferred that with increasing cycle numbers, the yield stress level decreases and plastic behaviour becomes dominant in each cycle.

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